Educational Robotics in Action: Development of a Line-Following Robot through STEAM Methodology to Address Traffic Issues

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Abstract

This research delves into the implementation of the STEAM (Science, Technology, Engineering, Arts, Mathematics) methodology in the Peruvian educational context, specifically addressing traffic issues affecting the school community of the Private Educational Institution Berne, in Comas, Lima. Education in Peru faces substantial challenges as a result of the gaps generated by the COVID-19 pandemic, especially in strengthening critical competencies in basic-level students. This work describes how 6th-grade students, using educational robotics, seek to offer solutions to vehicular traffic problems by designing and building a line-following robot. With a theoretical-practical approach, students engaged in understanding and applying traffic engineering concepts and route algorithms, framed within an educational proposal that seeks to promote the integral and applied development of competencies. Additionally, the project conducts a comparative study through a control group and an experimental group to evaluate the impact of this methodological strategy on student learning and competency development. The findings are discussed considering their relevance and potential for the application of the STEAM methodology in the Peruvian educational context and how it can be a viable tool to address real and close problems to students, thus promoting meaningful learning connected with their immediate environment.

Keywords

Educational robotics, STEAM Methodology, Road problems, Line following robot, Science education

1. Introduction

In contemporary Peru, the educational sector confronts distinctive challenges, predominantly instigated by the schism engendered by the COVID-19 pandemic. This global health crisis has not only impinged upon this nation but also perturbed educational systems worldwide, necessitating the suspension of in-person instruction [1]. This predicament intensified the obstacles in sustaining continuous educational advancement, particularly in the light of constrained technology access and a pronounced deficiency in teacher training in diverse methodologies. These circumstances have further amplified pre-existing educational disparities [2]. Despite the implementation of strategies by the Ministry of Education, these measures have fallen short in bridging the educational divides that have emerged in this international context [3].

Confronted with this landscape, it becomes essential to acknowledge the diminished reinforcement of competencies in pivotal areas such as Mathematics, Communication, Science, Technology, and Social Sciences among primary and secondary students in Peru [4]. Consequently, the Peruvian educational framework is tasked with manifold challenges to assure the achievement of the graduate profile delineated in the National Curriculum and to formulate responses congruent with the National Educational Project. Hence, educators in Regular Basic

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Education (RBE) schools are challenged to deploy agile and impactful methodologies that endorse a holistic approach to the cultivation and enhancement of student competencies [5].

In this context, the STEAM methodology emerges as a formidably promising and feasible option for integration into the educational system [6, 7]. It enables students to adopt a transdisciplinary perspective in devising comprehensive solutions to their targeted challenges [8]. This project, therefore, is dedicated to bolstering a range of competencies associated with STEAM fields, as well as the development of cross-disciplinary skills [9, 10].

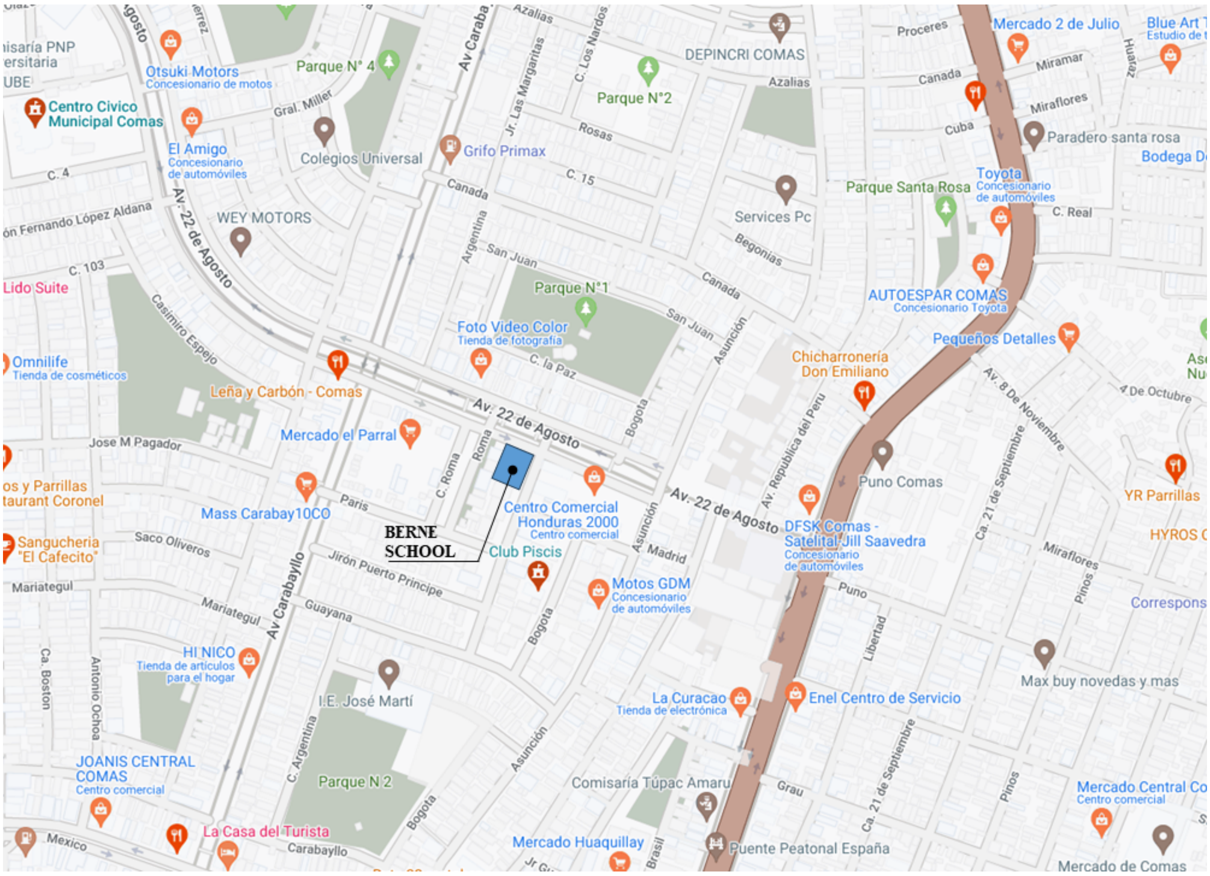


Figure 1: Geographical location of Berne School, situated adjacent to an avenue devoid of signage, proximate to a market and shopping center.

In this vein, the Private Educational Institution Berne, positioned in the Municipality of Comas, Lima, Peru, represents a unique case study. The institution's geographical location, adjacent to an inadequately signposted avenue and near a market, engenders vehicular congestion due to the movement of heavy and motorized vehicles during school hours, thereby posing safety challenges for its students (Figure 1). This scenario, infused with a culture of disarray and limited traffic education — elements perpetuated by parental and environmental influences through the social acceptance of informality — has catalyzed incidents involving several members of the educational community. In response, sixth-grade students from Cycle V of RBE have proposed the development of a line-following robot aimed at emulating effective traffic solutions [11]. Through this initiative, students gain insights into traffic engineering concepts and routing algorithms, offering a practical and technological dimension to the learning and addressing of real-life issues pertinent to their immediate surroundings.

Thus, this article emerges not solely as a testament to educational innovation and resilience but also as an illustrative example of the applicability of the STEAM methodology in addressing and potentially alleviating the tangible, day-to-day challenges impacting the school community and, by extension, the broader community.

2. Robotics and STEAM

Educational robotics, heralded as a frontier in the academic realm, has established itself as a cornerstone in the development of comprehensive competencies in students. Garcia-Fuentes [12] underscores its potential application from early childhood, not only as a didactic tool that permeates all academic areas, particularly STEAM, but also as a conducive medium for the development of computational thinking. The latter is crucial in building skills for structuring research and problem-solving, a fact highlighted by Acuña [13] in considering robotics and computational thinking as catalysts for opening strategic learning spaces.

A pivotal application in the field of educational robotics is the line-following robots, which, due to their ability to be programmed to follow a specific path, are seen as suitable tools for fostering the learning of digital and programming skills, especially at primary education levels [14]. This conjunction of robotics and education opens a spectrum where experimentation and practical application become fundamental, particularly when addressing problems of a traffic nature, which require a practical and applied approach.

In this respect, the STEAM methodology emerges as an educational approach that, by integrating science, technology, engineering, art, and mathematics, fosters a harmonious development of critical, creative, and reflective thinking in students [15]. The fundamental premise of STEAM, as described by Simesterra [16], lies in its commitment to a less theoretical and more practical education, encouraging students to explore through experimentation and creativity. This method, based on an interdisciplinarity that seeks to amalgamate different areas of knowledge to solve complex problems [17], has shown a positive impact at various educational levels, including preschool, where it has promoted the development of critical and creative competencies [18]. Moreover, in focused studies like that of Trujillo et al. [19], the implementation of a STEAM approach has revealed a specific positive impact on the development of creative thinking in children aged 9 to 11 years.

On the other hand, the implementation of STEAM and robotics projects in primary education classrooms has not only promoted creativity and problem-solving but has also opened a window towards addressing social and civic themes such as road safety education [20]. Road safety education, according to Poo [21], should focus not only on the transmission of knowledge but also on the promotion of values and behaviors that support safe, responsible, and equitable transit. This perspective of road safety education intertwines with the development of competencies that educational robotics and the STEAM methodology can offer, building a bridge between theory and practice, between learning concepts and their application in solving real problems in society.

This conceptual intertwining of educational robotics, the STEAM methodology, and road safety education presents a horizon in which education becomes a tangible and directly applicable tool in solving social and civic problems, highlighting the preeminent role of active and practical methodologies in the formation of conscious, critical, and proactive citizens in society.

3. Methodology

3.1. Participants

In this experimental research, sixth-grade students from Cycle V of RBE, attending the Private Educational Institution Berne, were involved. The selection of this educational level is based on the appropriate level of maturity and cognitive skills developed by the students at this stage, allowing for effective interaction and understanding regarding the use and development of the line-following robot through the STEAM methodology, as well as a relevant aptitude for perceiving and reflecting on the traffic issues focused on in the study.

The Experimental Group consisted of students from the sixth-grade section “A”, while the Control Group was made up of students from sixth-grade section “B”, both from the aforementioned institution. Section "A" was selected to form the sample of this study based on previously established criteria, such as availability, interest, and permission granted by guardians and the institution, ensuring that participation in the study would not negatively interfere with their regular academic activities or their general well-being. All students from experimental group actively participated in the development, implementation, and evaluation of the line-following robot in the educational context, and their interaction with it was crucial for the collection of experimental data.

On the other hand, the control group, comprising section "B", did not participate in the robot's development and implementation activities, but they were evaluated in parallel using the same measurement instruments applied to the experimental group, in order to establish valid comparisons regarding the impact of the intervention on the study variables. It should be noted that ethical considerations were rigorously respected, ensuring confidentiality, voluntariness, and the right to withdraw from the study at any time by the participants, in addition to guaranteeing appropriate and fair treatment for all students involved, both in the experimental and control groups.

3.2. Experimental Design

3.2.1. Instruments

The assessment of the impact of implementing the STEAM methodology using the line-following robot on the achievement of competencies was conducted using a holistic rubric. This rubric was designed to encompass indicators from the areas involved in the project, providing a comprehensive and coherent evaluation. To ensure precise and multifaceted assessment, clear and well-defined criteria aligned with the relevant cycle standards were established. Table 1 presents the breakdown of competencies, performances, and standards addressed, offering a clear view of the educational objectives tackled.

During the accompanying process, observation sheets, estimation scales, and checklists were used as tools for continuous monitoring and assessment. These instruments enabled not only the tracking of student progress but also the identification of areas for improvement and strength throughout the project. The use of these tools contributed to a richer and more complete formative and summative assessment.

For the final evaluation, and as part of the certification process, a specific rubric was applied. This rubric aligned with the levels of achievement established in the Peruvian educational framework: beginning, process, and achieved. This stratification allowed for a more nuanced evaluation of student performance and facilitated the identification of the levels of mastery achieved by the students in each cycle standard.

The results obtained from the application of this rubric are presented later, highlighting the comparative outcomes between the experimental and control groups. This comparison enables not only the assessment of the impact of the STEAM methodology and the use of the line-following robot but also the identification of significant differences in learning and competency development between both groups.

To complement the quantitative evaluation and gain a deeper understanding of the project's impact, a Likert scale survey [22] was applied to students from both experimental and control groups. This survey consisted of 7 questions, distributed across three essential dimensions: Motivation (Q1, Q2), Methodology (Q3, Q4), and Innovation (Q5, Q6, Q7). The survey's design aimed to gather students' perceptions and opinions on the applied methodology and project development, offering valuable insights into the educational experience from the students' perspective. The following questions were considered in the survey:

- Q1. My interest and enthusiasm significantly increased during the project's development.
- Q2. The project increased my motivation to learn and explore concepts of science and technology.
- Q3. The methodology used in the project was effective in helping me understand key concepts.

- Q4. My learning experience was enriched by working in a team during the project.
- Q5. The project helped me develop skills in creative and innovative thinking.
- Q6. The originality and creativity of the problems addressed in the project were remarkable.
- Q7. The project encouraged me to think of innovative solutions to real problems.

The combination of these assessment tools provided a holistic and multifaceted understanding of the project's impact, allowing not only to measure the achievement of competencies and standards but also to capture the perceptions and experiences of the involved students.

Table 1

Description of competencies, performances, and cycle standards of the areas integrated into the STEAM methodology.

STEAM	Curricular Areas of the National Curriculum of Peru	Competencies	Performances	Cycle V Standard
Science Technology	Science and Technology	Designs and constructs technological solutions to solve problems in their environment	Identify a technological solution alternative.	Designs and constructs technological solutions by identifying the causes of technological problems and proposes alternative solutions based on scientific knowledge.
			Design the technological solution alternative.	Represents one of these solutions, including its parts or stages, through structured diagrams or drawings. Establishes characteristics of form, structure, and function, and explains the procedure, implementation resources; executes them using selected tools and materials.
			Implement and validate the technological solution alternative.	Verifies the operation of the technological solution, detecting inaccuracies, and makes adjustments to improve it.
			Evaluate and communicate the functioning and impacts of your technological solution alternative.	Explains the procedure, applied scientific knowledge, and limitations of the technological solution. Evaluates its functioning through tests, considering the established requirements, and proposes improvements. Infers the impacts of the technological solution.
Engineering	Cross-curricular competence. Operates effectively in virtual environments generated by ICT		Personalize virtual environments. Manage information in	Navigates virtual environments effectively by coherently and organizedly personalizing their virtual space, representing their identity, knowledge, and ways of interacting with others.

	(Information and Communication Technologies).		the virtual environment. Interact within virtual environments. Create virtual objects in various formats.	Creates digital material (presentations, videos, documents, designs, among others) by comparing and selecting different activities according to their needs, attitudes, and values.
Art	Art and Culture	Create projects from artistic languages	Explore and experiment with the languages of art. Apply creative processes. Evaluate and communicate your processes and projects.	Develops individual or collaborative artistic projects, exploring alternative ways of combining and using elements, media, materials, and artistic and technological techniques for creative problem-solving. Generates ideas by researching a variety of sources and manipulating the elements of the various languages of the arts (dance, music, theater, visual arts) to assess which ones best fit their intentions. Plans and produces works that communicate personal and social ideas and experiences, incorporating influences from their own community and other cultures. Records their processes, identifies the essential aspects of their works, and modifies them for improvement. Plans presentation spaces considering their intentions and presents their discoveries and creations to a variety of audiences. Evaluates whether they effectively achieve their intentions.
Mathe-matics	Mathematics	Solve problems of form, move-ment, and location.	Explore and experiment with the languages of art. Apply creative processes. Evaluate and communicate your processes and projects.	Solves problems involving modeling the characteristics and location of objects into two-dimensional and three-dimensional forms, their properties, enlargement, reduction, or rotation. Describes and classifies right prisms, quadrilaterals, triangles, circles, by their elements: vertices, sides, faces, angles, and by their properties; using geometric language. Performs rotations in quarters and half turns, translations, enlargement, and reduction of two-dimensional shapes on the Cartesian plane. Describes paths and locations on maps.

				Uses procedures and instruments to enlarge, reduce, rotate, and construct shapes; as well as to estimate or measure the length, surface area, and capacity of objects, selecting the appropriate conventional unit of measure and making conversions. Explains their assertions about relationships between elements of geometric shapes and their measurable attributes, with concrete examples and properties.
	Personal Social	Manage space and the environ-ment responsi-bly	Understand the relationships between natural and social elements. Handle information sources to comprehend geographical space and the environment. Generate actions to conserve the local and global environment.	Manages space and environment responsibly by frequently engaging in activities for their care and reducing vulnerability factors to climate change and disaster risks in their school. Uses various cartographic and sociocultural sources and tools to locate elements in the geographical space and environment, and compares these spaces at different scales considering the action of social actors. Explains environmental and territorial issues based on their causes, consequences, and manifestations at various scales.

3.2.2. Procedures

The implementation of the STEAM methodology was conceived as an innovative proposal, aimed at strengthening abilities and competencies, thereby ensuring the achievement of the graduate profile, especially in the context of the pandemic where a slow progress in student competencies was observed.

The methodological work began in February 2023, during the school management sessions, and was integrated into the institution's Annual Work Plan. During the first bimonthly period (March, April, and part of May), a diagnostic assessment and characterization of the students were conducted, allowing for an understanding of their progress levels in relation to the competencies to be developed, their interests, and learning methods. It was identified that 80% of the students were in the process of developing four of the selected competencies for the project, and only one was at the achievement level (transversal), thus reinforcing the choice of the group. Additionally, the diagnosis revealed a tendency towards active learning in the students, preferably through integrative and collaborative activities, as opposed to passive methods or individual practices. It was also identified that the students were facing an institutional problem, already recognized in the Institutional Educational Project (PEI).

The project planning was carried out at the end of the first bimonthly period, during the school day. The implementation took place from May to July and comprised three phases:

A. Proposal: Students from both groups, experimental and control, analyzed the situation to be addressed and developed their action plan. In each group, work was conducted forming a single team with all the students in the classroom, and they were involved in the creation of a single line-following robot per group.

B. Development and Implementation: The experimental group developed the project following the STEAM methodology, guided by the teacher. This process involved continuous support and feedback, both individually and as a group, ensuring personalized attention and formative assessment. On the other hand, the control group developed a project following the Problem-Based Learning (PBL) methodology.

- Duration: 9 weeks
- Hours: 15 academic hours (45 minutes – 1 academic hour)

Considering the approach of polyteaching in the Peruvian primary educational context, where a teacher is responsible for teaching all areas, a schedule was managed that allowed working through integrated areas, promoting transdisciplinarity. Thus, the development of the project "Building a line-following robot as a proposal for improving vehicular management in our school" was carried out in an integrated manner, not in isolation. The assigned hours were dedicated to inquiry, construction of the plan, and creation of the line-following robot, following all the steps and processes involved. While the experimental group was building the line-following robot, the control group developed a 3D model proposing alternative routes, but without the ability to simulate their management, a situation that was achieved by the experimental group.

C. Closure: Students from both groups presented and exhibited their projects. The final (certifying) evaluation and the analysis of the results of the application of the implemented methodologies (STEAM and PBL) were conducted as part of the curriculum evaluation.

4. Development of a Line-Following Robot

4.1. Design

The design of the line-following robot was centered on combining engineering and technological principles with a pedagogical approach based on the STEAM methodology, thus promoting a transdisciplinary and participative integration in the educational process.

4.1.1. Conceptualization

Initially, the robot's conceptualization was based on identifying educational needs and practical applications for addressing traffic issues. Solutions were sought that would not only foster technical skills in students but also competencies related to problem-solving, teamwork, and creativity. The concept was to develop a robot that, in addition to following lines on the ground, could also serve as a tool for exploring and learning about traffic regulations and issues in a practical and playful manner. Figure 2(a) shows the design, inspired by school transportation, a familiar element to many students, thereby facilitating connection with the project. Furthermore, the choice of a school bus reinforces the idea of addressing traffic issues in an educational environment.

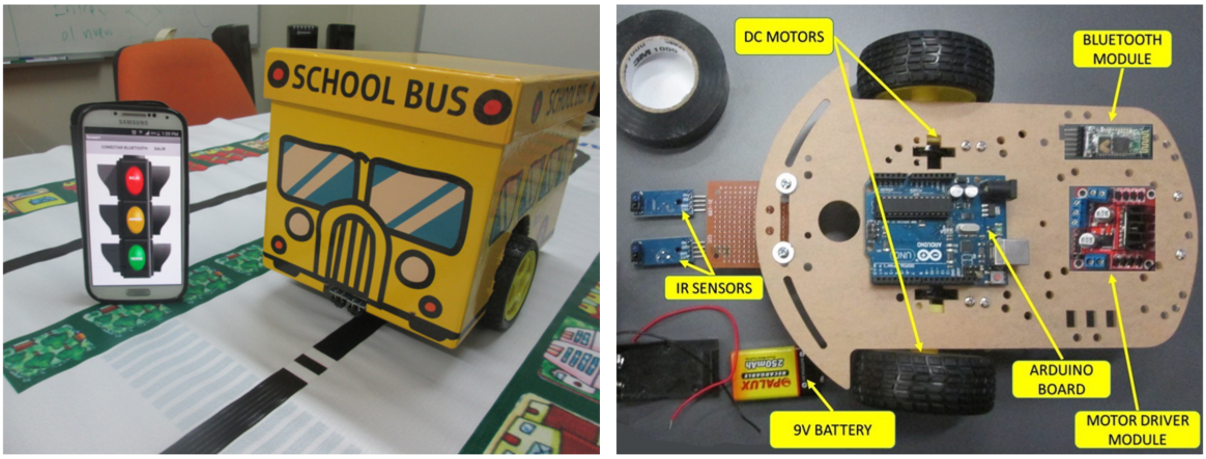
4.1.2. Technical Specifications

The electronic and mechanical parts are displayed in **Figure 2**(b). These components can be categorized as: sensors, microcontroller, propulsion system, mechanics, communication, and power.

As a sensor, the TCRT5000 infrared module was used, consisting of an infrared LED emitter that operates at a wavelength of 950nm and a phototransistor receiver to detect the color of the surface and follow lines on the ground, giving the robot the ability to navigate through different predefined and student-generated routes using insulating tape.

For control and automation, an Arduino UNO was used, a board that is easily programmable and has an active community, to facilitate learning and experimentation by students. The board has 6 pins for analog input and 14 general-purpose digital pins, 6 of these digital pins have the function of pulse width modulation (PWM).

For the propulsion system, two motors with a nominal voltage of 12Vdc, 100RPM, and a free-rotation wheel were selected. Both motors were controlled by the L298n driver module that provides up to 2A per channel, allowing the robot to maneuver efficiently through the predetermined routes.



(a) (b)

Figure 2: Development of the line-following robot (a) Traffic light app and robot design (b) Electronic and mechanical parts of the robot.

A compact and lightweight chassis was designed with MDF cutting, with a differential mobile robot configuration that allows good maneuverability and stability during movement. Incorporation of mechanical components that are accessible and safe for students. A casing with a school bus theme was adapted.

For bidirectional communication, a Bluetooth HC05 module was connected, paired with an application that functioned as a traffic light. The application was developed in MIT App Inventor.

The system was powered by a 9V Opalux battery with 250mAh. The power was supplied directly to the driver module and the ARDUINO UNO.

4.1.3. Integration with the Traffic Light Application

The robot integrates with a mobile application that simulates the functioning of a traffic light. This application presents a simple interface with traffic light colors (red, amber, and green). Each light has an associated command that the robot recognizes and acts accordingly. When the red light is on in the application, the robot will stop; with the green light, it will continue its journey. Communication between the robot and the application is achieved via Bluetooth, allowing real-time interaction without perceptible delays.

4.2. STEAM Implementation

The implementation of the STEAM methodology in the development of the line-following robot aligns transversally with the disciplines converging in this educational proposal, providing a comprehensive framework that promotes both theoretical and practical learning, while inspiring students to create innovative solutions to real-world problems.

From a scientific perspective, the laws and physical principles governing the robot's movement and orientation were explored, such as Newton's law and the principles of robotics. Research was conducted on sensors and how they can perceive changes in their environment, translating it into data that the robot can process and use to make decisions about its trajectory and speed.

In terms of technology, infrared sensor systems and motors were implemented, allowing the robot to detect and follow a line drawn on the ground. Programming software was used, enabling students to design, test, and optimize control algorithms for the robot's autonomous decision-making. Additionally, different manufacturing technologies for the robot's parts and structures, such as 3D printers and laser cutters, were explored.

Engineering was present throughout the design and construction process of the robot. Students applied concepts of mechanical and electrical engineering to design an efficient and functional robotic system. Problem-solving skills were enhanced through constant adaptation and optimization of the robot designs to improve their performance and reliability.

Art was integrated through the aesthetic and functional design of the robot. Students were encouraged to explore different shapes, colors, and arrangements of components to make the robot not only functional but also aesthetically pleasing and representative. Visual and symbolic narrative was also explored, using the robot as a medium to tell a story about solving traffic problems through technology.

Mathematics was an essential tool for the analysis and development of the project. Mathematical logic was used to create algorithms that guided the robot along the desired route. Additionally, mathematical concepts were employed to calculate distances, turning angles, speeds, and other critical parameters for precise and controlled navigation of the robot.

4.2.1. STEAM Integration in the Project

The STEAM methodology was implemented not only as a means to develop the line-following robot but also as a comprehensive educational approach. Students actively engaged in each stage, experimenting, learning, and applying knowledge from various disciplines in a practical and applied context. Moreover, this transdisciplinary approach not only facilitates the acquisition of specific knowledge from each area but also develops soft skills, such as teamwork, communication, problem-solving, and creativity, which are fundamental for the personal and professional development of students.

5. Results and Discussion

This research aimed to assess the impact of developing a line-following robot using the STEAM methodology on the acquisition of competencies and student motivation. A comparative evaluation between the experimental group (E) and the control group (C) revealed significant data.

Competencies were evaluated under five categories: design and construction of technological solutions (C1), performance in virtual environments generated by Information and Communication Technologies (C2), creation of projects using artistic languages (C3), problem-solving in form, movement, and location (C4), and responsible management of space and the environment (C5).

According to Figure 3(a), the experimental group demonstrated significant acquisition of competencies in all categories, with achievement percentages exceeding 80%, particularly notable in C1, C2, and C5 (91.7%). This contrasts with the control group, where achievement percentages were lower, notably in C1 at 60%.

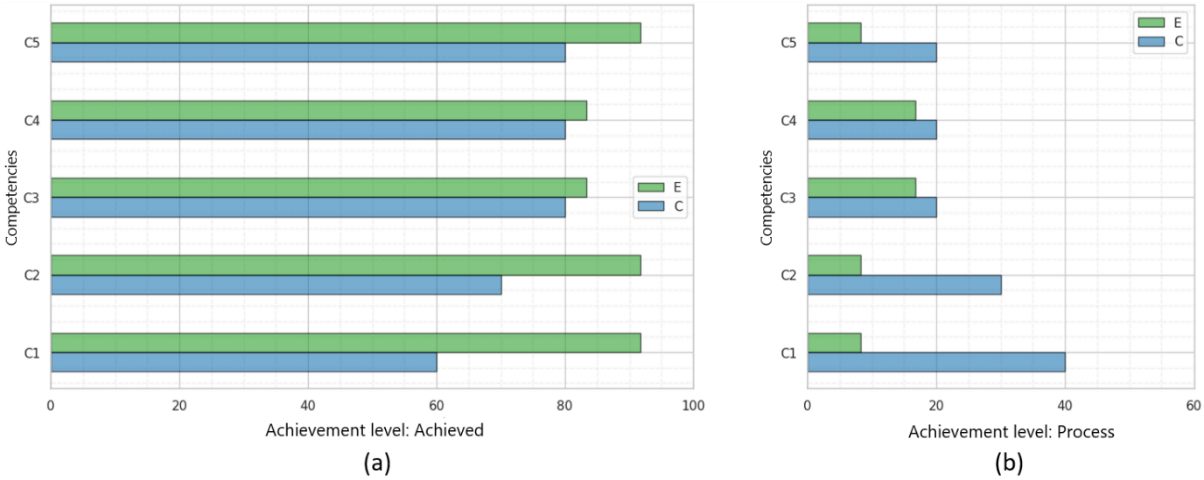


Figure 3: Achievement levels of the experimental (E) and control (C) groups: (a) Achieved (b) Process.

Regarding Figure 3(b), which represents the process level in competency acquisition, it was observed that in the experimental group, the percentages did not exceed 16.7%, suggesting a more solid consolidation of competencies. In contrast, the control group showed higher percentages, indicating a higher level of process and a less consolidated acquisition of competencies.

Figure 4 illustrates the students' perception of their learning experience and motivation, based on key questions (Q1-Q7). Here, values represent the average of responses, with 5 being the highest.

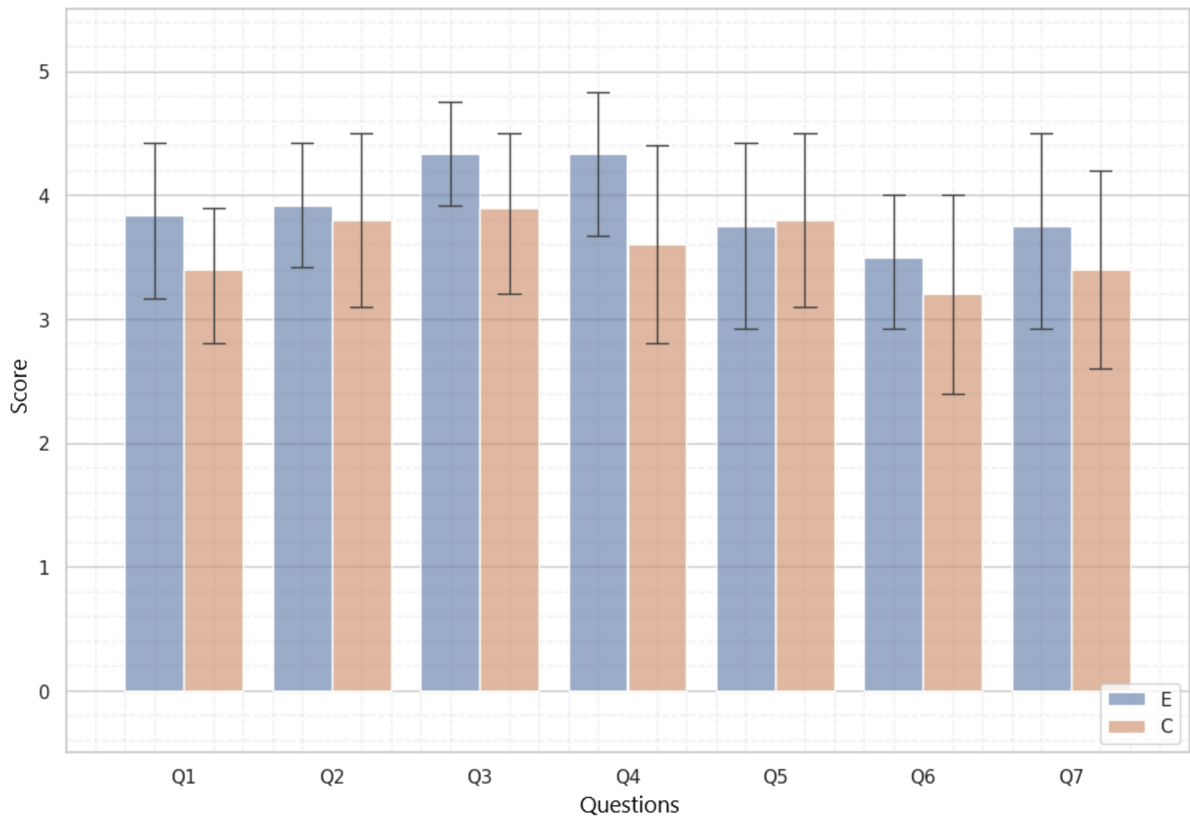


Figure 4: Survey results of the experimental (E) and control (C) groups by question.

The experimental group displayed high levels of interest and enthusiasm (Q1), with several students rating 4 or more. A similar trend was observed in the motivation to learn and explore science and technology concepts (Q2). The effectiveness of the methodology (Q3) was also highly valued, suggesting that the practical application and STEAM focus were beneficial.

The experience of teamwork (Q4) and the development of creative and innovative thinking skills (Q5) received positive evaluations, albeit with greater variability in responses. This might indicate that while the project promoted these skills, individual experience may have influenced the perception of their development.

As for the control group, while it generally showed high motivation and enthusiasm (Q1 and Q2), more significant variability in responses was observed, especially in the originality and creativity of the addressed problems (Q6) and the drive to think of innovative solutions (Q7). This may suggest that, although they were motivated, the depth and focus of their learning could have been different from the experimental group.

6. Conclusions

The outcomes of this investigation emphatically demonstrate the efficacy of the STEAM methodology in the realm of education, manifested through the significant enhancement of skill acquisition and heightened motivation within the experimental cohort. The construction of the line-following robot extended beyond the mere reinforcement of technical proficiencies such as design and assembly of technological solutions; it also cultivated pivotal transversal competencies, encompassing creativity, collaborative teamwork, and responsible environmental stewardship. This synthesis of diversified knowledge and skills accentuates the necessity of an educational paradigm that adeptly harmonizes theoretical and practical elements, thus propelling students to apply their learning in complex, real-world contexts.

The implications of these findings are profound for the formulation of pedagogical strategies in science and technology education. Implementing practical projects founded on STEAM principles not only augments the educational experience but also equips students to confront contemporary global challenges with a mindset characterized by innovation and adaptability. Hence, it is advocated that curricula incorporate analogous projects, aiming to nurture a comprehensive skillset that includes, but is not limited to, technical expertise, critical thinking, creativity, and collaborative capabilities, essential for navigating the complexities of the modern global landscape.

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