Pedagogical approach and collaborative learning in the implementation of PID control algorithms and Fuzzy Logic in robotics teaching with Arduino for students

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Abstract

The research explores the implementation of advanced robotic control algorithms, such as PID and fuzzy logic, in education with the aim of improving robotics education. Educational robots often use basic control systems, which limits their functionality and can make it difficult to perform more complex tasks. The evaluation of these more complex algorithms showed that they can significantly improve robot performance, facilitating student learning as well as the accomplishment of predetermined tasks. The experiments worked with 100 high school students, using Arduino-controlled robots, in which the students tested the algorithms to evaluate how the robots fulfilled the set objectives, thus indirectly measuring the students' learning process. The methodological approach focused on verification tests that measured aspects such as the robot's speed, response speed, movement accuracy and balance. The results revealed that the robots performed excellently in these key areas, meeting the control requirements, demonstrating the effectiveness of advanced algorithms in improving both robot performance and student understanding of educational robotics.

Keywords: PID Algorithm, Fuzzy Logic Algorithm, Educational Robotics, Arduino Programming.

1 Introduction

PID (Proportional-Integral-Derivative) Control algorithms and fuzzy logic are two fundamental techniques in modern robotics, used to improve the accuracy and adaptability of control systems in autonomous robots. In robotics, control systems are essential to manage the behaviour of robots according to the inputs they receive from the environment, such as position, velocity or temperature.

The PID algorithm is widely known for its effectiveness in systems where the dynamics are relatively simple and where precision control of variables is key. This algorithm continuously adjusts the outputs of a system as a function of error, cumulative error, and change in error, providing precise control. Its application in robotics includes tasks such as motor speed control, actuator positioning and maintaining stability in mobile robots.

Fuzzy logic, on the other hand, offers a more flexible and practical approach to controlling systems in more complex environments. Unlike classical controllers, such as PID, which require precise mathematical models, fuzzy logic operates using a set of linguistic rules to handle uncertainty and variability in data. In robotics, fuzzy logic is used for tasks such as autonomous navigation, real-time dynamic parameter tuning and decision making in unpredictable environments.

Both techniques, PID and fuzzy logic, can complement each other to provide more efficient and adaptive control for robots operating in varying conditions. In fact, in some advanced systems, both methods have been successfully integrated to maximise the advantages of each: PID ensures precise control under stable conditions, while fuzzy logic allows the robot to better adapt to variations and non-linear behaviours in the environment.

The combination of these algorithms has revolutionised the field of robotics, allowing robots to become more autonomous, precise and adaptable to changing environments.

1.1 Robotics learning

A learning environment with pedagogical robotics offers an experience that fosters creativity and critical thinking in students. In this environment, the teacher presents problem situations for the robots to solve, involving the implementation of control algorithms. [1] Robots are essential technological resources in basic education, as they support learning in STEM (Science, Technology, Engineering and Mathematics) areas. The integration of multidisciplinary components of robotics for educational purposes generates an active and motivating learning environment for students. In addition, it promotes the development of key 21st century skills and offers various opportunities to link mathematics and science by integrating technology into the classroom. However, despite the potential of educational robotics for interdisciplinary learning in basic education, its application in formal science and mathematics classes is neither constant nor widespread, being mostly limited to extracurricular activities. In this context, one of the main obstacles for teachers to incorporate robotics in their teaching methods is the lack of sufficient educational robots in schools, as well as inadequate preparation to connect robotics with curriculum subjects. In the same way, [2] robotics could be key for students to acquire skills in the use of technological tools and to develop logical and critical thinking. Educational robotics is an innovative interdisciplinary teaching approach that encompasses diverse areas of the curriculum, enabling active student learning through the use of mechanical, electronic and technological devices and tools. As noted by, [3] the effective incorporation of educational robotics promotes learning, as the use of the robot as a teaching tool helps to develop skills and competences by solving multidisciplinary problems. In addition, it fosters the technological skills that are essential to face today's challenges. Another advantage is that it generates expectations and increases students' motivation, facilitating the acquisition of knowledge. Similarly, the use of robots in early childhood education stimulates creativity and interest, allowing them to develop cognitive and manual skills.

1.2 Arduino in a pedagogical and collaborative approach

The use of Arduino technology in academic experiences allows students to develop algorithmic and programming skills, as well as developing basic electronics skills. Arduino technology is a computer system that directly integrates the areas of hardware and software management, facilitating the design and implementation of solutions.

There are different types of boards for use such as Arduino Uno R3, Arduino Mega, Arduino Leonardo and others with different characteristics [4]. Learning educational robotics with the arduino, a manifesto of the [5] which is a free perspective, using electronic materials, where the student can create their knowledge by initiating an idea of construction, which align with the spiral of creative learning, using the Arduino platform, hardware parts and developing an assembly of sequences, which imagines, creates, plays, shares and reflects on the process of developing robots.

1.3 Robotic study algorithms

1.3.1 Fuzzy Logic Algorithm

In his research on the application of Fuzzy Logic in robot control, [6] mentions that a robot is an autonomous device composed of integrated mechanical and electronic systems, designed to perform tasks in a given environment. They are widely used in the automation of repetitive industrial processes, as well as in marine, terrestrial, aerial and space exploration. They are also used in search and rescue missions, in office environments and in a variety of complex human activities. Today, fuzzy logic is an advanced controller model that facilitates the programming and control of electronic devices. Fuzzy controllers, which are part of Artificial Intelligence, fall into two categories: direct control and adaptive control. The structure and control scheme vary according to the process to be managed, collecting the required data for the controller. In the same way, [7] a great deal of research has been carried out on the application of fuzzy logic in the control of DC motors. In these studies, a fuzzy logic controller is proposed that uses two input parameters (error and error shift) and three output parameters (KP_PP, KI_II and KD_DD), which are associated with the three gains of a proportional-integral-derivative (PID) controller. These output parameters generate a control signal to tune the motor. The approaches vary in the rule base and in the types of membership functions applied to the input and output parameters. An advantage of these controllers is their ability to adapt to system changes, as their gains (KP_PP, KI_II and KD_DD) are self-adaptive. However, their implementation is complex. Moreover, few studies have developed a fuzzy controller with two input parameters (error and change of error) and a single output.

According to [8] it is mentioned that Fuzzy Logic is an advanced tool with relevant applications in industrial process control. Unlike the traditional feedback loop control approach and the rigorous thinking of microcomputer programs, fuzzy logic employs linguistic variables that are often considered imprecise. Despite its association with imprecision, fuzzy logic is based on a disciplined framework that allows control systems to be accurately described without the need for complicated mathematical expressions.

Within the field of Intelligent Control, fuzzy logic stands out as a form of Artificial Intelligence. It is widely used today and focuses on the control of complex industrial processes using fuzzy systems that are general, robust and user-understandable implementations.

Fuzzy control, based on vague and imprecise concepts, is often used to approximate precise and deterministic functions, which contrasts with the original focus of fuzzy logic in process control.

Fuzzy Logic Controller

The fuzzy logic controller is mainly used in management and control systems that use ambiguous expressions to define rules to manage the system. Unlike traditional control systems, a fuzzy control system makes use of expert knowledge to create a database that allows the system to make decisions about what actions to take. These systems define a set of rules that a person will use to manage a process and, from these rules, generate the required control actions. Fuzzy control can be used in both simple systems and those with complex mathematical models.

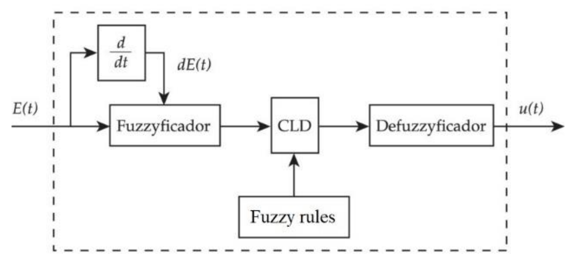

Figure 1: Structure of a fuzzy model

1.3.2 PID algorithm

In the investigation of the use of the PID algorithm [9], Robotics is one of the most exciting areas of electronics. A line-following robot belongs to the field of mobile robotics. Its main task is to move along a track, whether known or unknown. To do so, it needs to fulfil three basic functions: locomotion (physical level), perception (sensory level) and decision-making (control level). With these principles in mind, the position of the line is captured by optical sensors installed at the front of the robot, using phototransistor sensors. Therefore, the line detection process must be highly resolute and complex. This allows the robot to move parallel to the line using any type of steering mechanism. Generally, this process is performed with direct current (DC) motors, which implies the need for phase compensation to stabilise the tracking motion, applying digital filters and various types of controllers, such as PID or others, to adjust the speed according to the lane conditions. The speed decreases when cornering due to friction between the tyres and the ground. Line-following robots are able to follow a line drawn on the ground, which is commonly black on a white background.

According to, [10] A PID (proportional, integral, derivative) controller is a closed-loop control system used extensively in industrial applications. This controller determines the error by calculating the difference between the actual value of the system and the desired reference value.

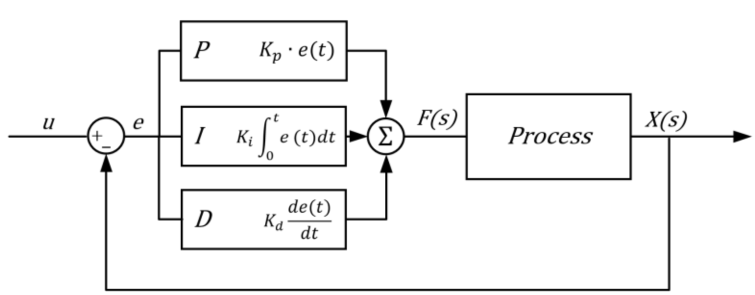

Figure 2: Diagram of a PID controller

In the PID controller calculation, three parameters are used that can be interpreted in terms of time. The proportional component (P) is related to the error at the current time, the integral component (I) is based on the accumulation of past errors, and the derivative component (D) takes into account the rate of change of the error. The interaction of these three terms allows a process to be tuned by a control element, such as the speed to be achieved by a DC motor.

$U = P + I + D$

By modifying the three constants of the PID control algorithm, the controller can be adapted to meet the specific needs of a system. The efficiency of the controller is evaluated by three parameters, which are adjusted through detailed analysis of the system.

2 Methodology

The methodology used in the experiments with Arduino-controlled robots focused on evaluating how the robots or algorithms developed by the students fulfilled the predefined objectives and tasks, thus providing an indirect measure of learning.

Firstly, this work was carried out with a sample of 100 upper level students of systems engineering, divided into two groups.

Secondly, a structured approach to data collection was adopted through the use of check sheets that allowed the performance of the robots to be evaluated according to pre-defined criteria. These criteria were instrumental in observing the performance of the robots in specific tasks, thus ensuring that the robots met the pre-defined functional requirements. Secondly, scoring from 1 to 5 quantitative values was implemented to the evaluation criteria to assess the performance if the robots meet the expectations of the control and behaviour according to the implemented PID and Fuzzy Logic algorithms. In addition, a Bluetooth module was integrated to enable communication between the robots and the computer, which facilitated real-time visualisation of the behaviour of each robot. This connection allowed constant supervision of the robot's performance during tests and experiments, thus optimising the monitoring and data analysis process.

This methodological approach not only increased the effectiveness of the tests performed, but also facilitated a more accurate and detailed evaluation of the robots' performance in various experimental conditions. In addition, it allowed for meaningful comparisons in robotics education, prioritising the development of practical skills in students without neglecting the theoretical foundations, thus promoting comprehensive and application-oriented learning.

3 Results

The experiments were conducted in an educational environment, where the robots' responses to various tasks and challenges were observed and analysed. During these tests, key factors such as accuracy of movement, the ability to adapt to changes in the environment and the ease with which students understood how the algorithms worked were evaluated.

A detailed comparison was made between a fuzzy controller and a PID controller, both implemented in the same robot engine. The objective of this comparison was twofold: on the one hand, to evaluate the effectiveness of each algorithm in controlling the robots and, on the other hand, to determine their usefulness and clarity as teaching tools in robotics.

To achieve an accurate assessment, prototype mobile robots were designed and tested, equipped with both PID and fuzzy logic controllers.

3.1 Verification tests:

Line follower cart

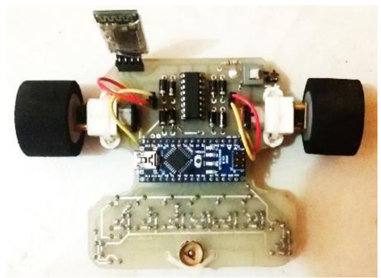

Figure 3: Construction of self-designed line follower cart

The line follower uses the PID control algorithm, implemented only with the proportional and derivative (PD) terms, to traverse different trajectories:

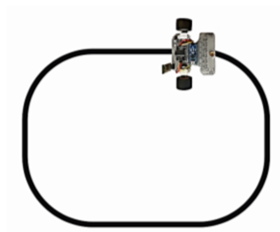

Figure 4: First test: circular circuit.

Figure 5: Second test: oval line circuit.

Figure 6: Third test: a combination of straight lines and oval strokes.

Note. In Figure 8, the results obtained by connecting the robot via Bluetooth are presented, showing its performance on the test tracks using PID (Proportional, Integral and Derivative) control. In this test, the integral term does not contribute to effective steady state (straight line) control, due to the accumulation of errors in the steady state.

```
Velocidad derivativo:0
Velocidad integral:14
Velocidad TOTAL:-186
Velocidad Proporcional:-200
Velocidad derivativo:0
Velocidad integral:9
Velocidad TOTAL:-191
Velocidad Proporcional:-200
Velocidad derivativo:0
Velocidad integral:4
Velocidad TOTAL:-196
Velocidad Proporcional:-200
Velocidad derivativo:0
Velocidad integral:-1
Velocidad TOTAL:-201
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Figure 7: Speed of the provided, integral and derivative, Arduino console

Obstacle detection cart

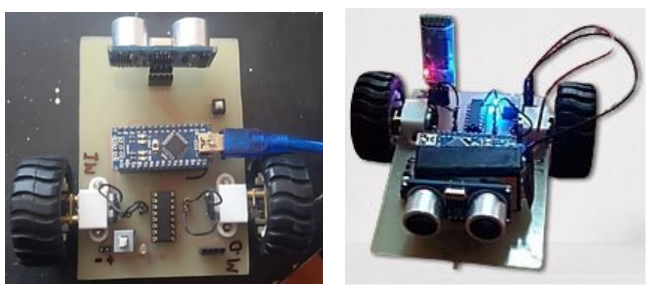
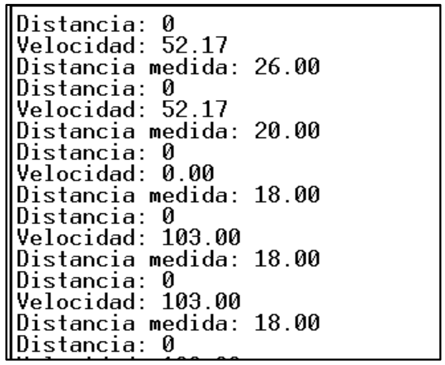


Figure 8: Construction of obstacle detection cart

Figure 9: Obstacle detection trolley route

Note. Figure 10 shows the operation of the obstacle detection robot using a Fuzzy Logic Algorithm. The robot identifies an obstacle (such as a wall) and moves backwards until it maintains a distance of approximately 30 cm. The tests were visualised on screen via Bluetooth connection, verifying the performance of the ultrasonic sensor. This sensor measures only the distance and, when it detects an obstacle in front of the robot, it adjusts its values as it moves forward.



```
Distancia: 0
Velocidad: 52.17
Distancia medida: 26.00
Distancia: 0
Velocidad: 52.17
Distancia medida: 20.00
Distancia: 0
Velocidad: 0.00
Distancia medida: 18.00
Distancia: 0
Velocidad: 103.00
Distancia medida: 18.00
Distancia: 0
Velocidad: 103.00
Distancia medida: 18.00
Distancia: 0
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Figure 10: Ultrasonic sensor distance and speed, Arduino console

3.2 Comparison of algorithms

3.2.1 Fuzzy Logic Algorithm: Obstacle detection trolley

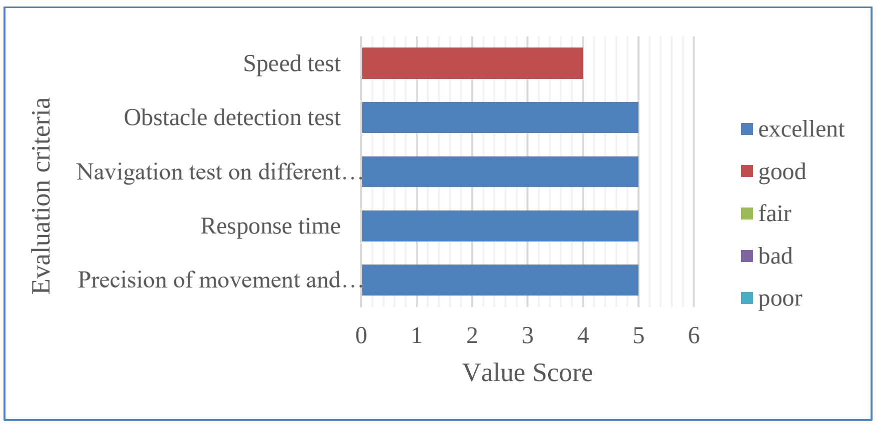

Figure 11: Evaluation result Fuzzy Logic, obstacle detection trolley

Note. Figure 11, shows that the robot demonstrates outstanding performance in most of the criteria evaluated, with outstanding results in obstacle detection, navigation on different types of surfaces, response time, and the precision and stability of its movements. This reflects its ability to adapt efficiently to the environment, react quickly to changes and maintain accurate and stable movements.

However, in the speed test, the robot received a rating of “good”, indicating that, although its performance in this aspect is adequate, it does not reach the level of excellence shown in the other criteria. Overall, the robot is positioned as highly competent in terms of accuracy, responsiveness and adaptability, but could benefit from adjustments to its speed to achieve a more balanced performance in all the parameters evaluated.

3.2.2 Algoritmo PID: Carrito seguidor de línea

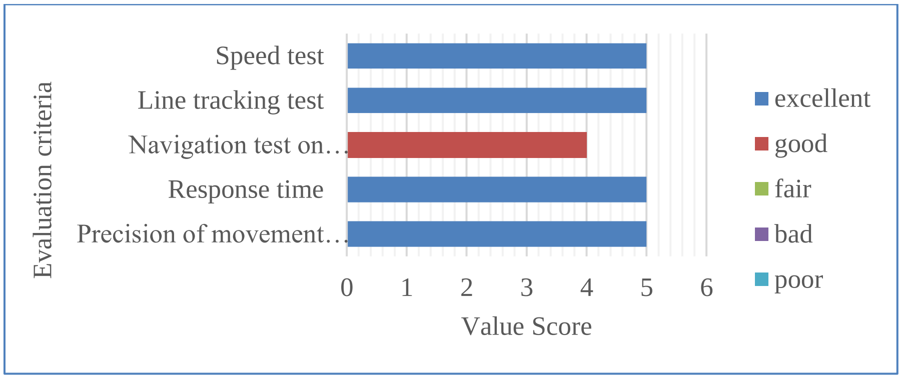

Figure 12: PID evaluation result, line follower cart

Note. In Figure 12, the evaluation of the robot shows an outstanding performance in almost all aspects evaluated. In the tests for speed, line following, response time and accuracy of movement and stability, the robot reaches the level of "excellent". This means that the robot not only moves quickly and follows lines accurately, but also responds nimbly to stimuli and maintains stability in its movements.

However, in the test of navigation on different surfaces, the robot scores "good". This indicates that, although it is capable of adapting to different types of surfaces, its performance in this area is slightly lower than in the other areas.

Overall, the robot demonstrates high efficiency and precision in its main functions, with a small opportunity for improvement in adapting to varied surfaces.

3.3 Assessment of student learning:

This methodology allowed not only to ensure a comparison of algorithms, but also to analyse the effectiveness of each approach in teaching robotics, providing students with a practical and meaningful educational experience.

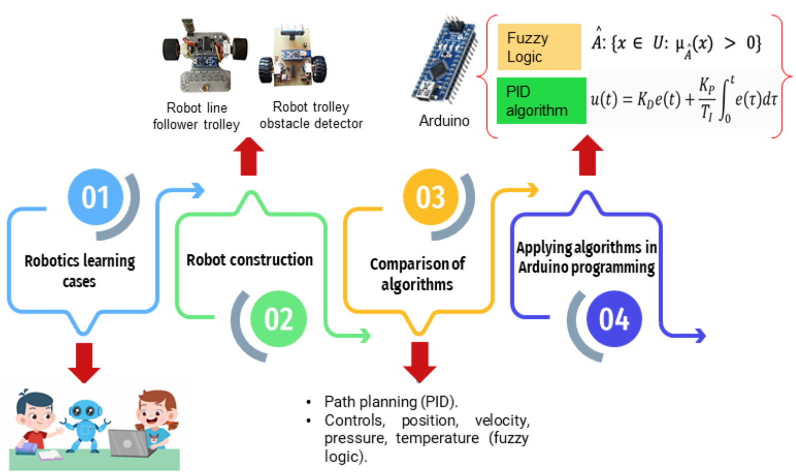

Figure 13: Proposed educational methodological outline of the robotics learning process

Note. In Figure 13, the proposed educational methodological scheme illustrates a robotics learning process, which is composed of four fundamental phases: **In the first phase**, robotics learning cases are addressed**,** here, robotics students explore and understand basic concepts, such as the fundamentals of robotics and the initial projects they can carry out. This stage aims to introduce students to the field in an accessible way.

In the second phase, they move on to robot construction**,** a hands-on stage, in which they assemble specific robots, such as a ‘robot follower cart’ and an ‘obstacle detection cart robot’. In this phase, participants develop robot assembly and preparation skills, preparing them for the implementation of control algorithms.

The third phase focuses on the comparison of algorithms**,** students analyse and compare control algorithms, such as the PID (Proportional-Integral-Derivative) controller and fuzzy logic. These algorithms allow the control of important variables in robotics, such as position, velocity, pressure and are also useful for robot path planning. Finally, **in the fourth phase**, the algorithms are applied to Arduino programming**,** in this stage, the algorithms that have been studied and compared are implemented in an Arduino microcontroller to control the behaviour of the robot. Programming on the Arduino allows the instructions of the algorithm to be carried to the robot, making it possible for it to execute specific tasks and respond to its environment.

Table 1. Distribution of points by criteria to students

Criteria	**Points**	**Description**
Understands the basic concepts of algorithms	15	Assesses theoretical understanding of PID and Fuzzy Logic.
Recognises the importance of PID functions and fuzzy rules in control	10	Checks whether they are developing their practical application correctly.
Analyses the systems	15	Defines your ability to assess and diagnose a controlled system.
Implement and test	20	Attaches greater importance to the practical implementation of algorithms.
They compare the performance of the algorithms	15	Consider the clarity and depth of the comparative analysis.
Diagnose problems in a system controlled with PID or Fuzzy Logic	10	It assesses the accurate identification of errors or weaknesses.
Adapt control algorithms for improvements	10	It is based on the creativity and effectiveness of the proposed solutions.
Clearly document the process of designing, implementing and tuning controllers	5	Evaluates the clarity of documents.
Full	**100**	Total distribution of points

Table 2. Results of the evaluation applied to the students according to criteria

Criteria	**Group 1**	**Group 2**
Understands the basic concepts of algorithms	15	15
Recognises the importance of PID functions and fuzzy rules in control	10	10
Analyses the systems	15	13
Implement and test	20	20
They compare the performance of the algorithms	15	15
Diagnose problems in a system controlled with PID or Fuzzy Logic	10	10
Adapt control algorithms for improvements	9	9
Clearly document the process of designing, implementing and tuning controllers	5	5
Total	**99**	**97**

Note. Table 2 shows a direct comparison between group 1 (99 points) and group 2 (97 points) on eight criteria related to the understanding, implementation and improvement of control systems based on PID and Fuzzy Logic algorithms.

Both groups demonstrated similar strong performance in the criteria assessed, with a particular focus on the fundamentals and practical implementation of control algorithms, such as those based on PID and fuzzy logic. They excelled in key areas such as understanding of basic concepts and the ability to implement and test algorithms. This reflects a good command of the fundamental and practical skills required to work with control systems. Although Group 1 had a slight advantage in the total score (99 versus 97), this difference is minimal and does not represent a significant contrast in skills or results. Overall, both groups showed a balanced performance, excelling in practical and conceptual aspects, but with clear opportunities for further refinement of robotic systems.

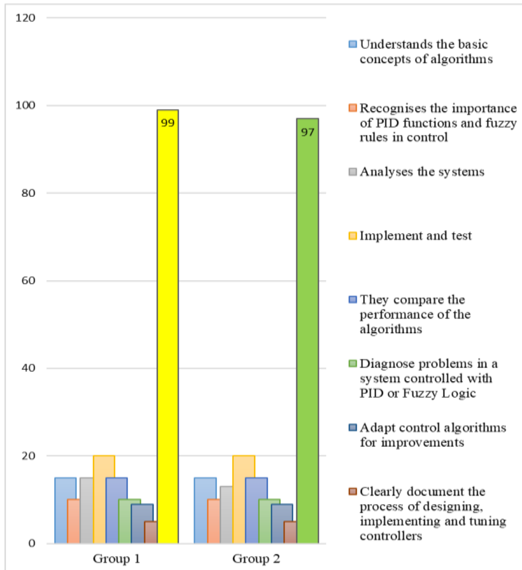

Figure 14: Graph of group evaluation results.

4 Conclusions

In conclusion, the evaluation results highlighted the robot's strengths in key areas such as speed, line following, rapid response, and accuracy of movement and stability, where its performance is consistently excellent. These capabilities demonstrated that the robot is effective in tasks that require speed, accuracy and quick response, meeting basic control and navigation requirements. Whereas, the obstacle detection robot demonstrates outstanding performance in detection, navigation, adaptability, and stability, standing out as an effective and versatile tool. Although its speed performance is adequate, it could benefit from improvements to balance its performance in all aspects.

Similarly, the evaluation and experimentation experience with the robot allowed students to learn hands-on about the use and effectiveness of various control algorithms, such as the PID controller and fuzzy logic. By observing how the robot responded in each test, students not only understood the theoretical concepts, but were also able to see how they translated into the robot's performance in real-life situations. Through the tests, students learned about the importance of factors such as accuracy, speed of response and adaptability, and how these affect the overall performance of a robot. The “excellent” evaluation on most of the criteria showed the positive impact of a well thought-out control design. However, the “good” score obtained in the experimentation test on different surfaces showed that even the most advanced algorithms may need specific adjustments to meet challenges in different environments.

These processes not only strengthened students' technical competencies in programming and robotics, but also boosted their critical thinking and analytical skills, enabling them to identify opportunities for improvement and suggest modifications to optimise robot performance.

In summary, students gained a comprehensive understanding of how to apply and evaluate control algorithms in robotics, and how this knowledge can be used to solve real-world problems and improve the design of autonomous systems.

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