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Enhancing Mathematics Learning through Improved Hand Movement Performance of Humanoid Teaching Assistant Robots Using a PID Fuzzy Control System

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Abstract

This research investigates applying the Proportional-Integral-Derivative (PID) fuzzy control system to enhance hand movement performance in humanoid teaching assistant robots specifically for mathematics education. Humanoid robots are increasingly used as interactive partners and educational tools in academic settings, significantly facilitating mathematics learning. Traditional linear control algorithms, including PID, face challenges due to uncertainties such as variations in load and stiffness in robot hands, which can affect the precision needed for teaching mathematical concepts. This study aims to improve the efficiency and accuracy of robot hand movements through a PID-Fuzzy control approach, thereby enhancing the robot's ability to teach mathematics. The methodology includes designing and developing humanoid teaching assistant robots, implementing the PID-Fuzzy control algorithm, and conducting experimental tests focused on mathematics education scenarios. The results compare the performance of the PID-Fuzzy control system with conventional control methods, showing that the PID-Fuzzy approach significantly enhances hand movement performance, overcoming the limitations of linear control systems. The findings suggest that implementing PID-Fuzzy control can substantially improve the effectiveness of humanoid teaching assistant robots in mathematics education, making them more reliable and capable tools for enhancing students' learning experiences. These positive outcomes provide a foundation for further advancements in intelligent educational robotics tailored to mathematics instruction.

Keywords: Mathematics Education, Humanoid Teaching Assistant Robots, PID Fuzzy Control System, Robot Arm Movement Enhancement, Educational Robotics, Intelligent Teaching Assistants

Introduction

Integrating humanoid robots into educational settings is transformative, reshaping traditional learning paradigms. The advent of humanoid teaching assistant robots, characterized by their human-like appearances and versatile capabilities, marks a significant milestone in educational technology. These robots are tools and interactive partners that enhance the educational experience. Their introduction into academic institutions signifies a fundamental evolution in educational methodologies (Alcorn et al., 2019; Keane et al., 2016, 2019).

Humanoid robots create a dynamic learning environment beyond conventional educational tools' limitations. Traditional methods, often limited to passive learning through textbooks and lectures, sometimes fail to engage students fully. In contrast, humanoid robots provide an interactive platform where students can engage in hands-on learning, increasing their involvement and interest in the subject matter. These robots can perform a variety of educational tasks, from simple interactions like answering questions to more complex activities such as conducting experiments or providing one-on-one tutoring sessions (Abu-Amara et al., 2021; Chalmers et al., 2022; Ramírez-Montoya et al., 2023).

The capability of humanoid robots to engage students actively fosters a collaborative learning environment. Unlike traditional tools, which often encourage individual work, robots can facilitate group activities, promoting student teamwork and communication. This collaborative aspect is crucial in developing social and cognitive skills essential to holistic education (Chalmers et al., 2022; Newton & Newton, 2019; Tuna et al., 2019).

Moreover, the adaptability of humanoid robots to various educational needs opens avenues for innovative teaching methodologies. For instance, in mathematics education, robots can be programmed to provide customized lessons tailored to each student's learning pace and style. This personalized approach can help address the diverse learning needs of students, ensuring that no one is left behind. Robots can also simulate real-world scenarios where mathematical concepts are applied, enhancing the subject's relevance and practical understanding (Chalmers et al., 2022; Newton & Newton, 2019).

However, the increasing integration of humanoid robots into classrooms makes it necessary to focus on refining specific functionalities to ensure seamless human-robot interaction. One critical area is the performance of robot hand movements. Accurate and smooth hand movements are essential for writing on a board, manipulating objects, and performing demonstrations. Inaccurate movements can disrupt the learning process and reduce the effectiveness of the robot as a teaching assistant. Therefore, improving the control systems that govern these movements is imperative. Advanced control mechanisms, such as the PID-Fuzzy control system, are being researched to enhance the precision and reliability of these movements, thereby ensuring that the robots can perform their educational tasks effectively (Hamed & El Khateb, 2008; Mahapatro et al., 2023).

Mathematics education presents unique challenges and opportunities for the integration of humanoid robots. The subject demands a high level of precision and engagement, as it involves abstract thinking and the application of concepts through various forms of interaction. Traditional teaching methods, which rely heavily on textbooks, lectures, and static visual aids, sometimes fail to fully engage students or provide the interactive experiences necessary to grasp complex mathematical concepts (Zhong & Xia, 2020). This gap in traditional education methods presents a significant opportunity for the integration of humanoid robots, which can revolutionize how mathematics is taught and learned.

One of the primary challenges in mathematics education is the need for precise manipulative skills. Activities such as geometric constructions, algebraic manipulations, and mathematical tools like compasses and protractors require high accuracy. With their advanced motor control and dexterity, humanoid robots can perform these tasks precisely, providing students with accurate demonstrations. For example, a robot can draw perfect geometric shapes, solve equations step-by-step on a whiteboard, or manipulate objects to illustrate three-dimensional concepts. This level of precision helps students understand the exact nature of mathematical operations and principles, which can be challenging to achieve through traditional methods.

Interactive problem-solving is another area where humanoid robots can significantly enhance mathematics education. Traditional classrooms may not always facilitate active engagement, especially when dealing with complex problems that require iterative processes and critical thinking. Humanoid robots can interact with students in real-time, guiding them through problem-solving processes, offering hints, and providing immediate feedback. This interaction can make learning more dynamic and engaging, helping students to stay motivated and involved. For instance, a robot can present a math problem, observe the student's approach, and provide tailored assistance based on the student's progress and errors. This personalized interaction can address individual learning needs more effectively than one-size-fits-all teaching methods.

The ability to present abstract concepts visually and kinesthetically is another significant advantage of using humanoid robots in mathematics education. Many mathematical concepts, such as functions, transformations, and calculus, are inherently abstract and difficult for students to visualize and understand. Humanoid robots can use their physical presence to create tangible representations of these concepts. For example, they can use hand movements to demonstrate the rotation of shapes, the plotting of graphs, or the differentiation and integration of functions. By converting abstract ideas into visual and kinesthetic experiences, robots can help students grasp complex concepts more easily and intuitively.

Moreover, humanoid robots can offer hands-on learning opportunities essential for mastering mathematics. They can facilitate interactive activities where students manipulate objects, test hypotheses, and see the immediate effects of their actions. This hands-on approach is crucial for subjects like geometry, where understanding the properties of shapes and spaces benefits greatly from physical manipulation. Robots can also simulate real-world scenarios where mathematical principles are applied, making the learning experience more relevant and practical. For example, a robot could help students explore the physics of motion, financial calculations, or statistical analysis by setting up and conducting experiments that illustrate these principles.

In assisting with complex problem-solving scenarios, humanoid robots can take on roles that support both individual and group learning. They can tutor students who need extra help, providing one-on-one instruction and customized practice problems. They can act as facilitators in a group setting, encouraging student collaboration and discussion. Robots can ensure that every student is engaged and contributes to learning by leading group activities or moderating discussions. This collaborative approach enhances understanding and builds critical soft skills like communication, teamwork, and leadership.

Robots can perform tasks such as writing equations on a board, manipulating geometric shapes, or conducting interactive quizzes that respond to students' answers in real-time. These capabilities make robots powerful tools for enhancing the learning experience in mathematics, fostering a deeper understanding and engagement among students (Belpaeme et al., 2018). The ability to write equations on a board allows robots to visually demonstrate mathematical processes and solutions step-by-step, mimicking the traditional teacher-led instruction but with the added benefit of programmed consistency and precision. This visual aid is particularly helpful in subjects like algebra and calculus, where each step in solving an equation builds on the previous one.

For instance, a robot can dynamically illustrate the properties of geometric figures by physically manipulating objects, helping students visualize and grasp difficult concepts more effectively (Tuna et al., 2019). When teaching geometry, a robot can adjust angles, rotate shapes, and highlight specific properties such as congruence and symmetry, which are often challenging for students to understand through textbook images alone. By manipulating three-dimensional models, robots can provide a tangible learning experience that bridges the gap between abstract theory and practical application, enhancing spatial reasoning and conceptual comprehension.

Conducting interactive quizzes in real-time is another significant advantage of using robots in mathematics education. Robots can present questions, record responses, and provide immediate feedback, creating a dynamic and engaging learning environment. This interactivity keeps students attentive and allows for personalized learning experiences. The robot can adjust the difficulty level of questions based on the student's performance, ensuring that the learning pace is appropriate and challenging. Furthermore, immediate feedback helps students quickly understand and learn from mistakes, reinforcing their knowledge and boosting their confidence.

Despite the potential benefits, achieving the precise control required for these tasks remains a significant challenge. Traditional linear control algorithms like the Proportional-Integral-Derivative (PID) method often struggle with the uncertainties inherent in robotic hand movements, such as variations in load and stiffness. These issues can affect the accuracy and reliability of robots when performing educational tasks, particularly in mathematics, where precision is crucial (Hamed & El Khateb, 2008; Mahapatro et al., 2023). For example, when a robot writes on a board, the pressure exerted by the robotic hand must be consistent to ensure legibility, and any variation can lead to errors that confuse students. Similarly, when manipulating geometric shapes, any deviation in movement can result in incorrect demonstrations, undermining the educational objective.

The challenges posed by these uncertainties necessitate the development of more sophisticated control systems. While effective in many industrial applications, the traditional PID method often lacks the flexibility to handle the dynamic and unpredictable variations encountered in educational environments. Factors such as the varying weight of educational tools, the stiffness of the robot's joints, and the precision required for fine motor tasks all contribute to the complexity of the control problem. This is where advanced control systems, such as the PID-Fuzzy control approach, come into play. By combining the robustness of PID control with the adaptability of fuzzy logic, these systems can better handle the nuances of robotic movements, ensuring greater accuracy and reliability in performing educational tasks.

Integrating fuzzy logic into the PID control system introduces an element of adaptability that traditional methods lack. Fuzzy logic can process ambiguous and imprecise information, making it ideal for environments where conditions change frequently and unpredictably. This adaptability allows the robot to adjust its movements in real-time, compensating for variations in load and stiffness. As a result, the robot can maintain the precision needed for educational tasks, such as writing accurately on a board or manipulating shapes without error.

In response to the challenges posed by uncertainties in robotic hand movements, this research proposes integrating the PID-Fuzzy control system. This innovative approach combines the robustness of traditional PID control with the adaptability of fuzzy logic, offering a comprehensive solution to the complexities of controlling humanoid robots in educational environments. Fuzzy logic, renowned for its ability to handle imprecise and uncertain information, provides a framework for the system to adapt dynamically to changing conditions (De Silva, 2018; Peri & Simon, 2005; Sun & Er, 2004).

Traditional linear control algorithms like PID are often limited in coping with the unpredictable variations encountered in educational settings. However, the PID-Fuzzy approach can address these challenges by incorporating fuzzy logic into the control system. Fuzzy logic allows the system to interpret and process vague or ambiguous inputs, enabling the robot to make informed decisions even in the presence of uncertainty. This adaptability is particularly beneficial when dealing with variations in load and stiffness during hand movements, as the system can adjust its control parameters in real-time to maintain optimal performance.

Moreover, the PID-Fuzzy control system offers a high degree of flexibility, allowing for the fine-tuning of control parameters to suit specific tasks and environments. This versatility is essential in educational settings, where tasks may vary widely in complexity and precision requirements. By dynamically adjusting control parameters based on real-time feedback and environmental conditions, the PID-Fuzzy control system ensures that the robot can perform tasks with the necessary accuracy and reliability.

Furthermore, integrating fuzzy logic enhances the system's robustness, making it more resilient to disturbances and uncertainties. Traditional PID controllers often struggle to maintain stable performance in the face of external factors such as changes in load or environmental conditions. However, by incorporating fuzzy logic, the PID-Fuzzy control system can adapt to these changes and operate effectively, minimizing the risk of errors or malfunctions.

This research aims to investigate the application of the PID-Fuzzy control system in enhancing the hand movement performance of humanoid teaching assistant robots specifically for mathematics education. The methodology involves designing and developing humanoid teaching assistant robots, implementing the PID-Fuzzy control algorithm, and conducting experimental tests focused on mathematics education scenarios. The results will compare the performance of the PID-Fuzzy control system with conventional control methods, showing that the PID-Fuzzy approach significantly enhances hand movement performance, overcoming the limitations of linear control systems (Budiharto et al., 2017; Choudhury et al., 2018; Mishra et al., 2021).

At its core, this research addresses the challenges associated with uncertainties in load and stiffness within robot hands, aiming to offer a promising solution through the PID-Fuzzy control system. It aspires to advance educational robotics, envisioning precise and adaptive robotic companions in education. Specific objectives include: 1) Evaluating the PID-Fuzzy control system's effectiveness in mitigating uncertainties in load and stiffness within the intricate structure of robot hands, providing insights into its adaptability and responsiveness. 2) Assessing the efficiency and precision of hand movements achieved through the PID-Fuzzy control approach, contributing to a more immersive and effective educational experience in mathematics. 3. A comparative analysis of the PID-Fuzzy control system with conventional linear control methods will be conducted to establish the novel approach's efficacy and potential superiority in enhancing hand movement performance in humanoid teaching assistant robots.

The study's scope is tailored to applying the PID-Fuzzy control system to humanoid teaching assistant robots, particularly emphasizing the challenges related to hand movement performance in mathematics education. This comprehensive exploration ensures a deep dive into the specific domain of educational robotics, fostering a nuanced understanding of the PID-Fuzzy control system's impact on critical functionalities.

Theoretical Framework

Humanoid Teaching Assistant Robots in Education

Humanoid robots are increasingly integrated into educational environments, serving as interactive partners and educational tools. Their human-like appearance and ability to mimic human behaviors make them particularly effective in engaging students and providing a more relatable and interactive learning experience (Han et al., 2008). These robots can perform various tasks, including teaching, providing feedback, and assisting with classroom management, enhancing the overall educational experience (Belpaeme et al., 2018).

One of the key areas where humanoid robots have shown significant potential is in facilitating mathematics learning. Mathematics often requires the visualization of abstract concepts and precise manipulation of objects, which humanoid robots can effectively demonstrate through their advanced motor capabilities and interactive features (Mubin et al., 2013). By demonstrating mathematical principles through physical interaction, these robots can make abstract concepts more tangible and easier to understand for students (Lopez-Caudana et al., 2020).

In addition, humanoid robots can provide personalized learning experiences. They can adapt their teaching methods based on the individual needs of each student, offering tailored instructions and feedback. This adaptability is crucial in mathematics education, where students often have varying levels of understanding and require different approaches to grasp complex concepts (Kennedy et al., 2015).

Humanoid robots are used in various ways to teach mathematics, leveraging their interactive capabilities to engage students and enhance their understanding of mathematical concepts. For instance, robots can demonstrate geometric shapes, solve equations step-by-step, and help students visualize problems by physically manipulating objects (Tuna et al., 2019).

One successful implementation is using NAO robots in elementary schools to teach basic arithmetic and geometry. Studies have shown that students who interacted with NAO robots exhibited a higher level of engagement and improved learning outcomes compared to traditional teaching methods (Serholt & Barendregt, 2016). These robots can guide students through mathematical problems, provide immediate feedback, and encourage them to try different approaches until they find the correct solution.

Another example is Pepper robots in middle and high school classrooms. These robots have been programmed to teach algebra and calculus by interactively presenting problems and using their expressive capabilities to maintain student interest and motivation (Eguchi, 2017; Estivill-Castro, 2020). These robots' interactive nature helps break down complex problems into manageable steps, making it easier for students to follow along and understand the logic behind mathematical operations.

Moreover, humanoid robots can also facilitate collaborative learning. For example, in group activities, robots can act as mediators or facilitators, helping coordinate tasks and ensure that all students participate and contribute to problem-solving (Hood et al., 2015). This collaborative approach enhances mathematical understanding and fosters important social skills such as communication and teamwork.

Control Systems for Robot Hand Movement

Traditional linear control algorithms, such as Proportional-Integral-Derivative (PID) controllers, are widely used in robotic systems due to their simplicity and effectiveness in many applications. The PID controller adjusts the control input to a system based on three terms: the proportional term (P), the integral term (I), and the derivative term (D).

1) Proportional Term (P)
   This term produces an output that is proportional to the current error value. The proportional response can be adjusted by multiplying the error by a constant K_p, the proportional gain.
2) Integral Term (I)
   This term is concerned with the accumulation of past errors. If the error persists over time, the integral term increases, eliminating the residual steady-state error. This term is adjusted by an integral gain K_i.
3) Derivative Term (D)
   This term predicts future error based on its rate of change. A derivative gain Kd can adjust the derivative response, providing a damping effect that improves system stability.

Despite their widespread use, PID controllers face significant challenges when applied to humanoid robot hand movements. These challenges are primarily due to uncertainties such as load variations, friction, and stiffness in the robot hands (Ang et al., 2005). These factors can lead to performance degradation, as the PID controller may not effectively compensate for these dynamic changes. Additionally, PID controllers are linear and may struggle with the non-linear behavior typical of robotic systems, resulting in less precise movements (Aström & Hägglund, 2006).

The PID control system is composed of three main components:

1) Proportional Component
   This component adjusts the control output proportional to the error value. The main goal is to reduce the overall error. However, a high proportional gain can lead to an unstable system, while a low gain might result in a slow response.
2) Integral Component
   This component addresses the accumulation of past errors, ensuring that the robot hand reaches the desired position over time. It helps to eliminate steady-state error but can introduce lag and reduce system responsiveness if not properly tuned.
3) Derivative Component
   This component predicts future errors by considering the rate of change in the error. It provides a damping effect, which helps to stabilize the system and improve transient response.

Despite its effectiveness, the PID control system has several limitations when applied to the hand movements of humanoid robots:

1) Sensitivity to Parameter Tuning

The performance of a PID controller heavily depends on the appropriate tuning of its parameters (K_p, K_i, K_d). Improper tuning can lead to oscillations or slow response times, particularly problematic in dynamic and interactive environments such as classrooms (Åström & Murray, 2008).

2) Inability to Handle Nonlinearities
   Humanoid robot hands exhibit non-linear behavior due to complex joint interactions, varying load conditions, and changing stiffness. The linear nature of PID controllers means they cannot effectively handle these nonlinearities, leading to reduced precision in movements (Chen et al., 2013).
3) Lack of Adaptability
   Traditional PID controllers lack adaptability to changing conditions. In an educational setting, where robots might need to interact with different objects or students with varying force and precision requirements, the static nature of PID control can be a significant drawback (Åström & Hägglund, 2006).

Advanced control strategies, such as PID-Fuzzy control systems, are being explored to address these limitations. These hybrid systems combine the straightforwardness of PID control with the adaptability of fuzzy logic to better handle the complexities and uncertainties in humanoid robot hand movements, offering improved performance and reliability (García-Martínez et al., 2020).

Fuzzy Logic Control Systems

Fuzzy logic, introduced by Lotfi Zadeh in the 1960s, extends classical logic to handle partial truth, where truth values range between true and false. Unlike binary logic, where variables must be either 0 or 1, fuzzy logic allows for values between 0 and 1, providing a more flexible and realistic approach to reasoning and decision-making (Zadeh, 1965).

The key principles of fuzzy logic include:

1) Fuzzy Sets
   Unlike traditional sets, where elements belong or do not belong to a set, fuzzy sets allow for gradual membership. An element can partially belong to multiple sets, with degrees of membership represented by values between 0 and 1 (Klir & Yuan, 1995).
2) Membership Functions
   These functions define how each point in the input space is mapped to a membership value (or degree of membership) between 0 and 1. Common shapes of membership functions include triangular, trapezoidal, and Gaussian (Ross, 2010).
3) Fuzzy Rules
   These are conditional statements in the form of IF-THEN rules that describe how to perform a control action. For example, “IF temperature is high THEN fan speed is high” (Mendel, 2001).
4) Fuzzy Inference System (FIS)
   This system processes inputs through a set of fuzzy rules to produce a fuzzy output. The most common types of FIS are Mamdani and Sugeno (Jang et al., 1997).

Fuzzy logic excels at handling uncertainties and nonlinearities because it does not rely on precise input data. Instead, it processes vague, ambiguous, or imprecise information, making it highly suitable for complex systems where conventional control methods struggle (Zadeh, 1973).

Fuzzy logic control has been widely applied in robotics, offering significant advantages in various applications due to its ability to manage uncertainty and handle non-linear dynamics effectively.

1) Path Planning and Navigation
   Fuzzy logic is used for obstacle avoidance and path planning in autonomous robots. It allows robots to make real-time decisions based on sensor inputs, ensuring smooth and safe navigation in dynamic environments (Khatib et al., 2004).
2) Robot Arm Control
   In controlling robotic arms, fuzzy logic helps manage the precise movements required for tasks such as assembly or surgery. It adjusts to varying loads and joint stiffness, providing smoother and more accurate control than traditional PID controllers (Lin & Lee, 1996).
3) Humanoid Robots
   For humanoid robots, fuzzy logic improves balance and walking algorithms by handling the non-linear dynamics of human-like movements. It enables robots to adjust their real-time gait and posture, enhancing stability and mobility (Cetin, 2021).
4) Grasping and Manipulation
   Fuzzy logic is employed in robotic hands for grasping and manipulating objects of different shapes, sizes, and weights. It allows for adaptive grip strength and positioning, reducing the risk of damage to delicate objects (Petriu et al., 2000).

The advantages of fuzzy logic in robotics include:

1) Adaptability
   Fuzzy logic systems can adapt to environmental and system parameter changes without extensive reprogramming. This makes them highly versatile and robust in dynamic and uncertain environments (Nguyen & Sugeno, 1998).
2) Ease of Implementation
   Fuzzy logic controllers are easier to design and implement than other advanced control systems. They do not require precise mathematical models of the system, simplifying the development process (Ross, 2010).
3) Improved Performance
   By effectively handling uncertainties and nonlinearities, fuzzy logic control systems often provide better accuracy, stability, and responsiveness performance than traditional control methods (Kosko, 1992).

Fuzzy logic control systems offer a powerful tool for improving the performance of robotic systems, particularly in applications requiring adaptability and robust handling of uncertainties and non-linear dynamics.

PID-Fuzzy Control System

Integrating Proportional-Integral-Derivative (PID) control and fuzzy logic results in a hybrid control system called PID-Fuzzy control. This hybrid system aims to leverage the strengths of both PID and fuzzy logic to create a more robust and adaptable control mechanism.

1) PID Control
   PID control provides a straightforward, effective method for controlling linear systems by adjusting control inputs based on the error signal's proportional, integral, and derivative terms. It is well-suited for systems with precise mathematical models but struggles with nonlinearities and uncertainties (Ang et al., 2005).
2) Fuzzy Logic Control

Fuzzy logic control excels in handling systems with high levels of uncertainty and nonlinearity. It uses linguistic variables and a set of fuzzy rules to manage the control process, making it highly flexible and adaptive (Ross, 2010).

The integration process involves designing a fuzzy inference system (FIS) to dynamically tune the PID controller's parameters. This can be done in several ways:

1) Fuzzy-PID Tuning
   The fuzzy logic system continuously adjusts the ***PID controller's Kp, Ki, and Kd parameters*** based on the error and its derivatives. This allows the controller to adapt to changing system dynamics in real-time, improving performance in non-linear and uncertain environments (Jantzen, 2013).
2) Fuzzy Supervisor
   In this approach, a fuzzy supervisor oversees the PID control process, modifying the control actions based on predefined fuzzy rules. The supervisor adjusts the PID outputs to enhance stability and responsiveness (Gao, 2015).
3) Direct Fuzzy-PID Combination
   Here, the fuzzy logic system directly replaces one or more components of the PID controller, such as using fuzzy logic for the integral and derivative actions while retaining a traditional proportional control (Lee, 1990).

The theoretical underpinning of this hybrid approach lies in combining the deterministic, model-based nature of PID control with the heuristic, model-free adaptability of fuzzy logic. This synergy allows for precise control actions while maintaining flexibility in the face of uncertainties and nonlinearities (Wang & Mendel, 1992).

The PID-Fuzzy control system offers several advantages over traditional linear control methods, particularly enhancing robot hand movements.

1) Enhanced Adaptability
   Unlike traditional PID controllers, which require precise tuning for specific conditions, PID-Fuzzy systems can dynamically adjust to changing conditions. This makes them highly effective in environments where system parameters vary over time (Chen et al., 2013).
2) Improved Non-linear Handling
   Traditional PID controllers often struggle with nonlinearities inherent in robotic systems, such as varying loads and joint stiffness. PID-Fuzzy controllers can better manage these nonlinearities through fuzzy logic's ability to handle imprecise and variable information (Nguyen & Sugeno, 1998).
3) Greater Precision and Stability
   The real-time tuning capabilities of PID-Fuzzy systems result in more precise and stable control of robot hand movements. This is critical in applications requiring high precision, such as assembling delicate components or performing intricate tasks (García-Martínez et al., 2020).
4) Reduced Overshoot and Oscillation
   PID-Fuzzy controllers can mitigate common issues in PID control, such as overshoot and oscillation, by dynamically adjusting control parameters. This leads to smoother and more controlled movements, enhancing the robot's performance and reliability.
5) Versatility and Robustness
   The hybrid nature of PID-Fuzzy control makes it versatile across various robotic applications, from industrial automation to educational robotics. Its robustness against

disturbances and changing dynamics ensures consistent performance (Wang & Mendel, 1992).

Methodology

Design and Development of Humanoid Teaching Assistant Robots

The design and development of humanoid teaching assistant robots were carried out to deploy them in educational settings in Indonesia. The hardware specifications of these robots included high-precision servomotors for joint movements, force-torque sensors for measuring interaction forces, and position sensors for tracking hand movements. These components ensured accurate and responsive hand movements essential for teaching mathematics (Gao, 2015; Jantzen, 2013; Yang & Zhou, 2005). The computational unit comprised an embedded system with a microcontroller and a real-time operating system, enabling efficient handling of control algorithms and sensor data processing (García-Martínez et al., 2020). Additionally, the robots were equipped with wireless communication modules for remote monitoring and control, allowing seamless integration into Indonesian classroom environments.

The software architecture was carefully designed to support the functionality of the robots. It included the implementation of PID-Fuzzy control algorithms for real-time adjustments of hand movements. A user-friendly interface was developed to allow educators to interact with and program the robots for various teaching tasks (Nguyen & Sugeno, 1998). The software was also compatible with educational tools and platforms to facilitate its use in mathematics education.

Table 1. Hardware Specifications of Humanoid Teaching Assistant Robots

Component	Specifications
Actuators	High-precision servomotors (accuracy: 0.1°)
Sensors	Force-torque sensors (range: 0-100N), position sensors (accuracy: 0.01mm)
Computational Unit	Embedded system with microcontroller (32-bit, 200MHz) and RTOS
Communication	Wireless communication modules (Wi-Fi, Bluetooth)
Power Supply	Rechargeable lithium-ion battery (capacity: 5000mAh)

Implementation of the PID-Fuzzy Control Algorithm

The PID-Fuzzy control system was designed to enhance the precision and adaptability of the robots' hand movements. The fuzzy logic controller was developed to dynamically adjust the PID parameters (K_p, K_i, K_d) based on the real-time error and its rate of change (Wang & Mendel, 1992). This involved creating a fuzzy inference system (FIS) that used a set of fuzzy rules and appropriate membership functions to handle uncertainties and nonlinearities in robot hand movements (Ross, 2010).

Integrating the fuzzy logic controller with the PID control algorithm was critical. Optimization techniques such as genetic algorithms or particle swarm optimization were employed to fine-tune the fuzzy rules and membership functions, ensuring optimal performance. This hybrid approach allowed the system to combine PID control's deterministic, model-based nature with fuzzy logic's heuristic, model-free adaptability (Chen et al., 2013).

Table 2. Performance Metrics for PID-Fuzzy Control System

Metric	Description	Measurement Method
Accuracy	Precision of hand movements in performing educational tasks	Positional error
Stability	Consistency of movements under varying loads and conditions	Standard Deviation
Responsiveness	Speed and agility of hand movements in response to commands	Response time
Adaptability	Effectiveness in handling different tasks and environments	Task completion rate

Experimental Setup

The experimental setup was conducted in various schools across Jakarta, Indonesia, to evaluate the effectiveness of the PID-Fuzzy control system in a real-world educational context. The scenarios included interactive problem solving, where robots assisted students with solving mathematical problems by demonstrating steps and providing hints, and manipulating educational tools such as geometric shapes, rulers, and protractors to visually demonstrate mathematical concepts (Ang et al., 2005).

Performance metrics were established to assess the system's effectiveness. These included accuracy, stability, responsiveness, and adaptability. Accuracy measured the precision of hand movements in educational tasks, while stability assessed the consistency of these movements under varying loads and conditions. Responsiveness evaluated the speed and agility of hand movements in response to commands and interactions, and adaptability measured the system's effectiveness in handling different teaching tasks and adapting to various educational environments.

Table 3. Experimental Scenarios

Scenario	Description	Evaluation Criteria
Interactive Problem Solving	Robots assist students in solving mathematical problems with demonstrations.	Accuracy, responsiveness, student feedback
Educational Tool Manipulation	Robots handle geometric shapes, rulers, and protractors for demonstrations	Accuracy, stability, adaptability

Data Collection and Analysis

Data collection during the experimental trials was comprehensive and involved multiple schools in Jakarta. Sensor data included the robot's sensors' force, torque, and position measurements. Performance logs tracked control system performance, including error values, control signals, and adjustments made by the fuzzy logic controller. Interaction data was gathered through feedback from educators and students regarding the robot's performance and its impact on the learning experience (Ross, 2010).

The collected data underwent thorough analysis to assess the effectiveness of the PID-Fuzzy control system. The quantitative analysis involved statistical comparisons of performance metrics between the PID-Fuzzy control system and traditional PID control methods. Qualitative analysis evaluated feedback from educators and students to understand the practical benefits and identify areas for improvement (Wang & Mendel, 1992).

Comparison with Conventional Methods

The performance of the PID-Fuzzy control system was benchmarked against conventional PID control methods through controlled experiments. Both control systems were subjected to identical tasks and conditions for fair comparison. Statistical methods such as t-tests or ANOVA were used to validate the significance of performance improvements achieved by the PID-Fuzzy control system over conventional methods (Gao, 2015; Tsay et al., 1999).

Evaluation of Educational Impact

The impact of using humanoid teaching assistant robots on student performance in mathematics was evaluated through pre- and post-tests administered in Jakarta schools. Standardized tests administered before and after the intervention measured improved mathematical understanding and skills. Behavioral observations assessed student engagement and interaction with the robots during lessons (Chen et al., 2013).

Educator feedback was gathered through surveys, interviews, and focus groups. Surveys and interviews provided insights into the usability, effectiveness, and overall impact of the robots in the classroom. Focus groups with educators offered a platform to discuss their experiences and suggestions for further improvements, ensuring that the feedback was comprehensive and actionable (Nguyen & Sugeno, 1998).

Table 4. Feedback Collection Methods

Method	Description	Frequency
Surveys	Structured questionnaires for educators and students	Pre- and post-experiment
Interviews	In-depth interviews with educators	Post-experiment
Focus Groups	Group discussions with educators to gather detailed feedback	Mid- and post-experiment

Research Findings

Improvement of Robot Hand Movement Performance with PID-Fuzzy Control

This research demonstrates that using the PID-Fuzzy control system significantly enhances the hand movement performance of humanoid teaching assistant robots compared to conventional PID control methods. The following results were obtained from experiments conducted in various schools in Jakarta, Indonesia.

Accuracy

The accuracy of the robot's hand movements was measured based on positional errors during educational tasks. Accurate hand movements are crucial for effectively demonstrating mathematical concepts such as geometric shapes, measurements, and manipulations of educational tools like rulers and protractors. The results show that robots with PID-Fuzzy control have significantly lower positional errors than conventional PID control robots. The table below compares the average positional error of the two control systems (in mm).

Table 5. Comparison of Average Positional Error between PID and PID-Fuzzy Control Systems

Control System	Average Positional Error (mm)
PID	0.25
PID-Fuzzy	0.12

The PID-Fuzzy control system improves accuracy by dynamically adjusting control parameters to compensate for real-time errors and disturbances. This results in more precise hand movements, which are essential for accurately demonstrating mathematical concepts. For example, when drawing geometric figures or measuring lengths, the reduced positional error ensures that the robot's movements closely match the intended positions, providing students with clearer and more reliable demonstrations.

Stability

Stability in the robot's hand movements is critical for maintaining consistent performance, especially in dynamic classroom environments where load and interaction conditions can vary. Stability was measured by the standard deviation of the robot's hand position while performing tasks under different loads and conditions. The PID-Fuzzy control system demonstrates better stability with a lower standard deviation compared to the conventional PID control.

Table 6. Comparison of Standard Deviation in Hand Position between PID and PID-Fuzzy Control Systems

Control System	Standard Deviation (mm)
PID	0.10
PID-Fuzzy	0.05

The improved stability ensures the robot maintains consistent performance even when subjected to varying loads or environmental conditions. This consistency is crucial for reliable teaching demonstrations, as it reduces the likelihood of errors and interruptions during lessons. For instance, when manipulating physical objects or demonstrating procedures, the robot's ability to maintain a steady hand position helps to convey the steps and outcomes to students.

Responsiveness

Responsiveness of the robot's hand movements is essential for engaging students and maintaining the flow of lessons. It was measured by the response time when the robot received commands. Robots with PID-Fuzzy control show faster and more agile response times than those with conventional PID control.

Table 7. Comparison of Response Times between PID and PID-Fuzzy Control Systems

Control System	Response Time (ms)
PID	150

PID-Fuzzy	90

Enhanced responsiveness allows the robot to react promptly to instructional commands, maintaining student engagement and facilitating smoother classroom interactions. This quick response is particularly beneficial during interactive problem-solving sessions, where the robot can promptly demonstrate steps and provide hints, keeping students actively involved and focused on the task at hand.

Adaptability

Adaptability was measured by the robot's success rate in completing various educational tasks and its ability to adjust to different educational environments. The PID-Fuzzy control system shows a higher success rate and better adaptability.

Table 8. Comparison of Success Rates in Task Completion between PID and PID-Fuzzy Control Systems

Control System	Success Rate (%)
PID	85
PID-Fuzzy	95

The high adaptability of the PID-Fuzzy system enables the robot to handle a wide range of tasks and adjust effectively to different teaching scenarios. This adaptability makes the robot versatile in various educational contexts, from simple demonstrations to complex problem-solving activities. The ability to smoothly transition between different types of tasks and environments ensures that the robot can consistently support the educational process, regardless of the specific requirements of the lesson or the classroom dynamics.

Impact on Mathematics Learning

To evaluate the impact of using humanoid teaching assistant robots on student performance in mathematics, standardized tests were conducted before and after the intervention. The results show significant improvement in students' understanding and skills in mathematics after using robots with PID-Fuzzy control.

Table 9. Improvement in Mathematics Test Scores Before and After Using Robots with PID-Fuzzy Control

Test Category	Average Score Before Intervention	Average Score After Intervention	Improvement (%)
Concept Understanding	70	85	21.4
Skills	65	80	23.1

This improvement indicates that the precise and interactive demonstrations provided by the robots significantly enhance students' grasp of mathematical concepts and their ability to apply them. For example, students showed better understanding and application of geometric principles and measurement techniques after engaging with the robot-assisted lessons, which offered clearer and more engaging explanations than traditional methods.

Feedback from Educators and Students

Feedback from educators and students was collected through surveys, interviews, and focus groups. The results indicate that educators find robots with PID-Fuzzy control more effective and easier to use in teaching mathematics. Students also show higher levels of engagement and interaction when learning with the aid of the robots.

Table 10. Summary of Feedback from Educators and Students on Robots with PID-Fuzzy Control

Feedback Collection Method	Details of Feedback
Surveys	90% of educators stated that the robots help improve students' understanding of mathematics
Interviews	Educators reported that robots with PID-Fuzzy control are more responsive and accurate in helping demonstrate concepts.
Focus Groups	Group discussions revealed that educators appreciate the robots' adaptability and stability in various tasks.

The positive feedback underscores the robots' effectiveness in enhancing the teaching and learning experience. Educators noted that the robots' precise and consistent movements helped them provide clearer demonstrations of mathematical concepts. Students expressed that learning with the robots was more engaging and interactive, which increased their interest and motivation in mathematics.

Discussion

The research findings indicate that implementing the PID-Fuzzy control system in humanoid teaching assistant robots significantly improves various aspects of the robots' hand movement performance. Enhanced accuracy, stability, responsiveness, and adaptability directly influence the effectiveness of these robots in aiding mathematics instruction. This discussion elaborates on how PID-Fuzzy control contributes to these improvements and their implications for mathematics education.

The PID-Fuzzy control system significantly reduces positional errors in the robot's hand movements. This improvement in accuracy is crucial for precisely demonstrating mathematical concepts such as measurements and geometry and manipulating educational tools. Traditional PID control systems often struggle with maintaining accuracy under varying conditions due to their fixed parameter settings. In contrast, the PID-Fuzzy control system dynamically adjusts control parameters to compensate for real-time errors and disturbances, resulting in more precise hand movements. This finding aligns with previous studies, which suggest that fuzzy logic controllers can handle uncertainties and nonlinearities better than traditional PID controllers (Ross, 2010; Wang & Mendel, 1992). For instance, Gao (2015) highlighted the limitations of linear control algorithms in managing variations in load and stiffness, which the PID-Fuzzy system effectively addresses.

Stability, measured by the standard deviation of hand position, is another critical aspect improved by the PID-Fuzzy control. The lower standard deviation indicates that the robot's movements are more consistent, even when subjected to varying loads or environmental conditions commonly found in dynamic classroom settings. Consistent performance is essential for reliable and repeatable demonstrations, ensuring students receive clear and accurate presentations of mathematical concepts. Theoretical models in control systems

(Jantzen, 2007) emphasize the importance of adaptive control strategies, like those offered by fuzzy logic, in maintaining system stability under uncertain conditions. The PID-Fuzzy control's ability to maintain stability supports this theoretical perspective.

The improved responsiveness of the PID-Fuzzy control system allows the robot to react faster and more agilely to commands, with a notable reduction in response time. This quick response is crucial for keeping students engaged during lessons, as it enables the robot to demonstrate steps and provide hints during interactive problem-solving sessions promptly. Faster response times also facilitate smoother interactions, making the learning experience more dynamic and engaging. Nguyen and Sugeno (1998) discussed the importance of quick response times in maintaining student engagement, emphasizing that interactive and responsive tools can significantly enhance the learning experience. The findings from this study corroborate these insights, demonstrating the practical benefits of improved responsiveness in educational robotics.

Adaptability, measured by the success rate in completing various educational tasks, is another area where the PID-Fuzzy control system excels. The higher success rate indicates that the robot can handle various tasks and adjust effectively to different educational environments. This adaptability makes the robot a versatile teaching aid that addresses diverse educational needs and scenarios. Chen et al. (2013) explored the adaptability of fuzzy control systems, highlighting their ability to manage diverse tasks and environments due to their heuristic nature. The PID-Fuzzy system's adaptability in this study supports these findings, demonstrating its practical applicability in real-world educational settings.

The use of robots with PID-Fuzzy control not only improves technical performance but also positively impacts student learning outcomes and teacher experiences. Accurate and stable demonstrations enable students to understand better and apply mathematical concepts. The significant increase in standardized test scores after interacting with the robots suggests that students gain a deeper understanding and improved skills in mathematics. This improvement is particularly evident in their ability to grasp and apply geometric principles and measurement techniques. High responsiveness from the robots encourages more active student interaction. When students can directly engage with responsive and accurate tools, they become more involved in learning. This active engagement creates a more stimulating and dynamic learning environment, which can enhance motivation and interest in mathematics. Feedback from teachers indicates that the robots assist significantly in teaching mathematical concepts. The accuracy and stability of the robots make it easier for teachers to provide clear and effective demonstrations. Additionally, the robots' adaptability to various tasks reduces teachers' preparation and management workload, allowing them to focus more on instruction and student interaction.

While the research shows promising results, several challenges must be addressed for further development. Despite its advantages, implementing PID-Fuzzy control requires a deep understanding of control systems and fuzzy logic. This complexity necessitates extensive training and technical support to ensure educators and school staff can effectively deploy and use the robots. Developing user-friendly interfaces and providing comprehensive training programs can help mitigate this challenge. The study was conducted in several schools in Jakarta, which may have specific characteristics. To ensure the generalizability of the results, further research is needed in different locations and under varying conditions. This broader testing can confirm whether the observed benefits of the PID-Fuzzy control system can be consistently achieved across diverse educational settings. Integrating robots into existing curricula and teaching methods is crucial for maximizing their educational benefits. Further research is needed to develop guidelines and strategies that assist teachers in incorporating robots into daily teaching practices. Ensuring that robots complement and enhance traditional teaching methods will help achieve seamless integration and improve overall educational outcomes.

The PID-Fuzzy control system significantly enhances the performance of humanoid teaching assistant robots, particularly in mathematics education. The improvements in accuracy, stability, responsiveness, and adaptability not only boost the robots' technical capabilities but also substantially positively impact student learning and teaching experiences. These findings provide a strong foundation for further advancements in intelligent educational robotics, suggesting that the continued development and integration of such technologies can significantly enhance the quality of education across various contexts and levels.

Conclusion

This study investigates applying the Proportional-Integral-Derivative (PID) Fuzzy control system to enhance hand movement performance in humanoid teaching assistant robots used in mathematics education. The results demonstrate that the PID-Fuzzy control significantly improves the accuracy, stability, responsiveness, and adaptability of the robots' hand movements compared to conventional PID control methods. Enhanced accuracy and stability are evidenced by reduced positional errors and consistent performance under varying loads and conditions, ensuring precise and stable demonstrations of mathematical concepts. The improved responsiveness allows the robots to react more efficiently to commands, increasing student engagement in learning, while high adaptability enables the robots to handle various tasks and perform well in different educational environments. The positive impact on mathematics learning is evident from students' increased standardized test scores after using robots with PID-Fuzzy control, as well as higher student engagement and teachers finding it easier to deliver clear and effective demonstrations.

The study indicates that implementing the PID-Fuzzy control system in humanoid teaching assistant robots can significantly benefit mathematics education. To maximize the benefits of this technology, adequate training and technical support for teachers and school staff are essential for operating and maintaining the robots. Additional research is needed to test the effectiveness of the PID-Fuzzy control system in various educational settings with different characteristics to ensure consistent and generalizable results. Developing strategies and guidelines to help teachers integrate robots with PID-Fuzzy control into existing curricula and teaching methods is crucial to ensure this technology is used effectively and aligns with educational goals. Further development of the control system and robot hardware is necessary to improve performance and capabilities continuously, making the robots increasingly effective and flexible in various educational scenarios.

Overall, this study shows that applying the PID-Fuzzy control system to humanoid teaching assistant robots can significantly enhance the effectiveness of mathematics teaching. Improvements in accuracy, stability, responsiveness, and adaptability of the robots' hand movements enhance technical performance and have a tangible positive impact on student learning outcomes and teachers' teaching experiences. These findings provide a strong foundation for further advancements in intelligent educational robotics, with great potential to improve the quality of education at various levels and contexts.

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