Towards Designing a Low-Cost Humanoid Robot with Flex Sensors-Based Movement*

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Abstract— **Humanoid robots have potential applications across diverse sectors, including education, healthcare, and customer service. This paper presents a project on designing and building a low-cost humanoid robot equipped with a flex sensor-based movement mechanism, highlighting its compatibility with Raspberry Pi and microcontrollers such as Arduino Uno and Nano. The project aims to investigate the robot's relevance and effectiveness within educational settings to showcase how a low-cost humanoid robot can potentially support the United Nations' fourth Sustainable Development Goal (UN SDG4) by improving access to quality education through innovative robotics solutions. The robot was tested in a cycle two school (covering Grades 5 to 8 (ages 10 to 13)) in Dubai, United Arab Emirates. It was integrated into math, science, and design technology classes to assess its functionality and efficiency. Surveys conducted among students and teachers showed a high level of acceptance towards the robot, with over 85% of respondents expressing positive attitudes about its presence and interaction in the classroom. However, teachers and students provided feedback concerning the robot's shape, capabilities, and movement mechanism. Teachers also appreciated the robot's alignment with the UN SDG4, stating its capability to support students learning and engagement. The authors highlighted the robot's potential to assist students with sensory challenges, such as hearing and vision impairments, and learning difficulties like dyslexia while emphasizing their commitment to enhancing its accessibility features for a more inclusive learning environment.**

I. INTRODUCTION

A robot that takes its design features and inspiration from the human body is called a humanoid robot [1, 2]. The design may serve functional needs, such as interacting with humans, tools, and environments [3], but it may also fulfil experimental needs, such as researching the robot's simulation for bipedal walking [4] or the effects on stress levels for elderly individuals, as seen with robots like Pepper [5].

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Developing a robust, fully functional robot is among the most challenging yet exciting tasks. Engineers have indicated a significant interest in humanoid robots because of their capability to function in scenarios primarily intended for people, and each humanoid robot is built with a unique set of properties, skills, and equipment during development, which affects its design, cost, and complexity [6].

Robots enable innovative teaching methods [7] and personalized learning and have the potential to increase accessibility and inclusivity in education [8, 9], which aligns with the United Nations Sustainable Development Goal 4 (SDG 4) - Quality Education. By fostering equitable access to education, promoting inclusive learning environments, and addressing global education challenges, humanoid robots play an essential role in advancing the goal of ensuring quality education for all.

In 2021, the United Nations Educational, Scientific and Cultural Organization (UNESCO) published a document titled "AI and Education: Guidance for Policymakers"; this document discussed the integration of artificial intelligence (AI) in education, stressing the potential of humanoid robots in educational settings to enhance learning experiences. It addressed the role of robotics in assisting students with learning impairments or disabilities, emphasizing its potential to support their educational needs and promote inclusion [10]. Additionally, advocating for developing curricula integrating the Universal Design for Learning (UDL) approach. UDL principles ensures equal access to education by employing diverse teaching methods and removing barriers to learning [11] while integrating AI [10] into education based on UDL principles, aligning with SDGs to enhance educational inclusivity, reduce inequalities, and promote well-being through technology-enabled personalized learning [12].

Affordable, low-cost humanoid robots are essential for transforming education by providing interactive and inclusive learning experiences [13]. This paper summarizes our project's work, which aims to explore advancements in humanoid robots and develop a low-cost humanoid robot suitable for educational purposes. The project focuses on testing the robot in educational settings, a critical environment for experimentation and validation.

The robot presents various advanced features designed to enhance user experience and accessibility. Among these features is an interactive touch screen, providing an immersive educational experience. The robot also offers a camera and two-way audio communication featuring speech and visual recognition capabilities for enhanced interaction. Additionally, remote movement control is enabled through a flex-sensor-based glove, ensuring precise and consistent motion in various directions. Detailed technical details are discussed in Section III.

II. RESEARCH BACKGROUND

Robots exhibit a wide range of capabilities across different categories, including humanoid, industrial, service, and social robots. Some industrial robots, for example, are designed to autonomously perform specific tasks within industrial settings, such as welding in automotive plants, commercial vacuum cleaning, and various other applications [14].

Humanoid robots typically feature a torso, a head, two arms, and two legs, while others merely duplicate a portion of the body, such as the upper body [15]. Some robots have heads with mouths and eyes that are exact replicas of human facial characteristics, such as Androids, which are humanoid robots designed to resemble humans visually [16]. Humanoid robots might be only a design of a certain body component or a comprehensive replica of human biomechanics.

By developing humanoid robots, we can create machines that can interact with humans and learn more about how the human body moves [17], making it possible to develop and make more effective prosthetics for injured individuals [18]. With a few intriguing properties, humanoid robots present many challenges to embedded systems architectures. Due to the close interdependence of technological factors, selecting a humanoid robot to create applications or conduct research in a particular area may be challenging [19].

Human-robot interaction (HRI) focuses on designing, understanding, and evaluating robots that interact with humans [20, 21]; this includes considering the social impact of a robot's design, motion, and behavior, especially in fields like manufacturing, space exploration, surgery, and education [22, 23]. By incorporating user perceptions into the design process, errors can be minimized, and the effectiveness of robots can be optimized, saving time and money. Research on HRI has provided valuable insights into how individuals perceive robots [24]. People often use cognitive processes to recognize and respond to robots; similar to how they interact with non-human entities, individuals may assume features and develop emotional responses based on a robot's appearance and actions [25].

Human-computer interaction (HCI) involves designing user-friendly and efficient interactions between people and computers, including tasks ranging from designing and implementing interfaces to refining evaluation techniques and researching novel interactive systems, thereby playing an important role in all aspects of interface development. Integrating (HCI) principles with (HRI) technologies in educational settings allows for the development of more intuitive and engaging interactions between students and humanoid robots, fostering immersive and effective learning experiences [26, 27]. This intersection between HCI and HRI enhances the design and implementation of educational robotic systems, ensuring they are user-friendly and adept at facilitating meaningful human-robot interactions conducive to learning.

Educating both children and the public can enhance robotics' societal image while integrating sustainability into education programs and organizing workshops can boost awareness of SDGs within the robotics community [28]. Socially assistive robots like Nao [29] can enhance inclusivity by offering opportunities for physically impaired, autistic, or vulnerable individuals, improving learning skills and providing reliable companionship and monitoring in public spaces [30, 31], which contributes to promoting sustainable development, inclusion, and well-being.

Students with vision impairments, whether partial or complete blindness, rely on senses other than sight for daily tasks and navigation, presenting challenges in localization and understanding the spatial representations of objects [32, 33]. Similarly, those with hearing impairments face communication obstacles, often mitigated through hearing aids or sign language [34, 35]. Humanoid robots offering multimodal feedback, including spatial sound, lights, and vibration, could potentially benefit these students, enhancing their learning experiences and fostering inclusion and lifelong learning opportunities [36, 37, 38]. Dyslexia, one of the most common learning difficulties, primarily affects reading, phonological skills, and working memory. Consequently, this can lead to challenges with recognizing speech sounds and decoding text, affecting comprehension, spelling, and writing [39, 40]. Robots hold promise in supporting dyslexic students by providing engaging, hands-on learning experiences that cater to their visual-spatial strengths, promoting engagement and ownership through diverse activities and visual aids [41, 42].

The interactive nature of robots allows for iterative learning experiences, enabling students to reinforce concepts through repetition and practice. However, affordability remains a barrier to robots’ adoption in developing countries, though Massive Open Online Courses (MOOCs), remotely accessible robotics labs and open-source tools may help integrate them into educational systems faster [43].

III. METHODOLOGY

Effective development projects follow essential principles such as involving inclusive participation of diverse users, maintaining transparent decision-making procedures, continuously improving through iterative development, and actively fostering community involvement among users, developers, and stakeholders [44]. These principles were demonstrated in the implementation of the robot designing and building stages, as depicted in Fig. 1, where the engineering design process steps were meticulously followed. The sequence of the project's work is briefly outlined in accordance with the engineering design process scheme, arranged as follows:

i. Problem identification and definition.
ii. Designing the robot's virtual 3D model.
iii. Researching and brainstorming.
iv. Classifying the robot's building components.
v. Robot development and testing.

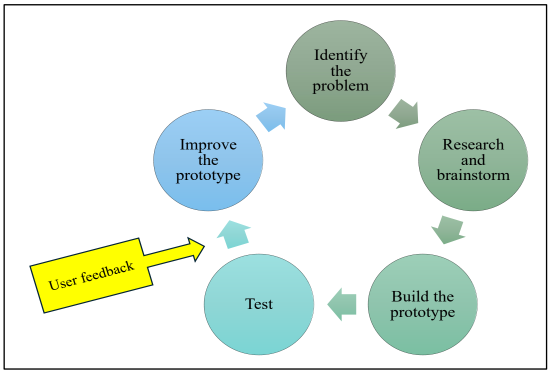

Figure 1. Engineering Design Process

A. Theoretical Analysis and Implementation

1. Identifying and defining the problem

At this stage, it is essential to clearly define the problem and the motivation behind designing a low-cost robot. The initial inspiration stemmed from a demand for an affordable robot capable of various functions. This prompted the development of a humanoid robot that can seamlessly interact with users across different applications. The following questions will help define the project's scope and ensure that the design process effectively addresses the needs and constraints.

- What is the problem?

The problem lies in the need for affordable, versatile robots suited for various applications, such as education and entertainment. However, this project aims to enhance innovation and creativity in planning and designing an affordable robot to be used as an educational tool.

- Who are the target users of the robot?

This robot was designed for educational use and tested in that environment to refine its capabilities. By immersing it in classrooms, both teachers and students can actively engage with the robot and provide valuable feedback. While the integration of robots in education is still a relatively recent development, many experts predict that within the next decade, they will become commonplace in classrooms worldwide. This advancement holds the potential to revolutionize teaching and learning practices, offering innovative ways to enhance the educational experience for students of all ages [45].

- Why is it important to find a solution?

Humans are naturally social beings, relying on interaction and engagement with one another. Despite this, traditional educational systems have moved away from collaborative engagement. However, humanoid robots provide students with a physical, social, and interactive interface to connect so they can actively engage with the robots instead of passively gazing at books or screens, fostering meaningful interaction and intellectual stimulation [46].

Investing in humanoid robots can be costly, particularly within the education sector. The goal is to offer robots that strike a balance between affordability, quality, and functionality. Designing humanoid robots for successful, seamless HRI requires attention to features such as morphology, social presence, and sensing capabilities [47]. Considerations such as safety, dependability, and individual preferences enrich these interactions. Humanoid robots currently available on the market closely resemble the proposed robot for this project. Examples include Nao and Pepper from SoftBank [29]. However, it is essential to note that these robots often come with a relatively high price tag.

Humanoid robots provide a range of sensory options for user engagement, including visual, auditory, and tactile experiences. The choice of a humanoid robot for this project is grounded in the familiarity it offers, mainly in interactions with children. The morphology of humanoid robots simplifies social interactions, making them intuitive and enhancing overall engagement.

Children in the process of developing social skills usually perceive objects as having a strong social presence. Social presence is about how much someone is perceived as a "real person" in mediated communication, and it reflects the level of connection a user feels with another entity's intelligence, intentions, and sensory experiences [48, 49]. Research on children's interactions with robots suggests that perceived social presence positively influences their impressions of robots and reduces anxiety when building relationships with them [50, 51, 52]. To encourage children to use robots more, designers should focus on enhancing robots' perceived social presence, which can lead to more positive attitudes towards robots.

Inclusive education emphasizes equitable access and tailored support for all students, regardless of their diverse needs. Humanoid robots offer a powerful tool for achieving this goal by providing multimodal feedback, allowing personalized content delivery and interactions based on individual preferences and physical abilities. By adapting to different sensory modalities and facilitating social interactions, these robots promote inclusivity in the classroom, ensuring every student can learn and participate fully in the educational experience.

- What design limitations exist, and how can we address them effectively?

The project aims to reduce design costs without compromising the robot's functionality. Market analysis guided our component selection to balance quality and affordability, leading us to make several changes to keep costs down.

Acrylic sheets were used rather than a 3D printed model, proving to be a more cost-effective solution than 3D printing. Keeping the acrylic sheets transparent instead of full coloring or painting saved material expenses and enhanced the educational value of the robot, allowing students or any user to easily observe the internal components and explore the electronics and engineering design.

We prioritized the Raspberry Pi 3B+ for its cost-effectiveness and performance, offering a universal platform for educational projects with extensive community support.

The Arduino microcontrollers provides a cost-efficient, flexible solution catering to educational settings. The 3D model was created using the free application "Autodesk 123D Design," which facilitated the design process and contributed to cost savings, as discussed in point 2. These strategic choices collectively ensure accessibility and affordability without affecting the overall performance.

2. Creating the Robot's 3D Model

Autodesk 123D Design software was used to design the robot's 3D model during this stage. This free web application offers intuitive tools for 3D design, allowing users to design detailed models efficiently. Using solid modelling techniques, the project started by creating the robot's body parts from basic shapes. Fig. 2 illustrates both the 3d model and actual designs, showcasing the project's development. The robot's dimensions were 20.75 inches (Height) × 7 inches (Width) × 13 inches (Base length).

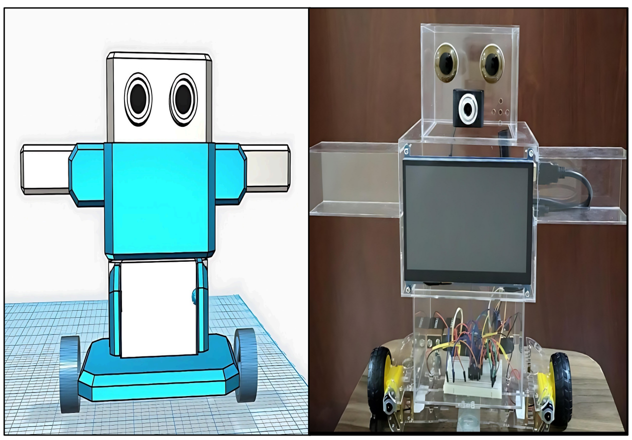

Figure 2. 3D design vs real design

3. Essential Materials for Designing the Robot

To build a humanoid robot, careful consideration was given to selecting the necessary components, designing electrical circuits, and choosing appropriate microcontrollers.

Table 1 provides an overview of the components used, their quantities, and the cost of building both the robot's body and the motion control circuit.

The total cost of the designed humanoid robot was around 230 USD, which is affordable given its capabilities and influence on students and their teachers. Also, purchasing bulk materials and components could further reduce the cost.

Some humanoid robots might be used for stationary tasks or interactions without significant mobility. In this project the humanoid robot integrated with movement capabilities to enhance engagement, accessibility, and collaborative learning, enabling students to participate more actively in learning and fostering teamwork and communication skills through collaborative learning experiences. This inclusive approach ensures that educational opportunities remain accessible to every learner, contributing to the objectives outlined in SDG4 for inclusive quality education.

TABLE 1: THE REQUIRED COMPONENTS TO BULD THE HUMANOID ROBOT ALONG WITH THEIR COST

	Component	Quantity	Cost USD
Motion Mechanism	Flex sensors - 2.2"	x5	47.40
	Arduino Uno	x1	15.00
	Arduino Nano	x1	13.00
	10K Resistor	x5	0.65
	10uF Capacitor	x2	0.50
	Header Pin	x2	2.00
	Power Jack 5.5mm	x1	0.50
	NRF24L01 Transceiver	x2	9.50
	On/Off Switch	x1	0.25
	DC Motors	x2	6.00
	Wheels (including ball caster wheels)	x4	6.25
	L293D motor driver	x1	4.25
	Battery (9v)	x1	4.50
Robot Body	Power supply (10,000mAh)	x1	12.50
	Raspberry Pi Compatible Fan	x1	2.20
	Raspberry Pi (3B+)	x1	43.50
	USB Speaker	x1	4.00
	USB Microphone	x1	5.00
	Raspberry Pi 7-inch screen	x1	32.65
	USB Camera	x1	5.00
	Acrylic sheets	x18	15.00
	TOTAL		**229.65**

The motion mechanism used flex sensors to allow the robot to move. Meanwhile, the flex sensor is a low-cost, easy-to-use variable resistor to measure how far something bends. The sensor's resistance is relatively low when its surface is flat, increases when we bend it gradually and rises at a 90-degree angle. Flex sensors are widely utilized in various applications, including gaming controllers, data gloves, motion trackers, and even biomedical devices for registering static and dynamic postures. Because the sensor's resistance is proportional to the amount of bending, it is a flexible potentiometer. This sensor is often available in 2.2" and 4.5" sizes. When the sensor is straight, it has a resistance of around 10K; when bent, it has a resistance of about 22K [53]. This project uses flexible sensors measuring 2.2" (7.3cm) in length. Fig. 3 shows the remote-control glove.

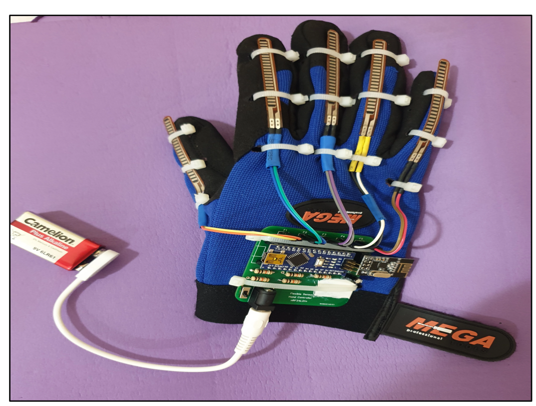

Figure 3. The remote-control glove

4. Building the Robot for User Testing

A humanoid robot with a wheeled base was built during this stage, which encapsulates all preceding steps. The base was engineered to facilitate seamless movement in all directions. Every component of the robot's body, including its sturdy base, was created using acrylic sheets. Additionally, a circuit was integrated into a glove to serve as the interface for controlling the robot's movements.

B. Evaluating Robot Performance

Once all the robot's components were assembled, the testing process commenced, beginning with an assessment of the solidity of the robot's body. Subsequently, a series of rigorous system and user tests were conducted to ensure functionality and performance.

1. System testing:

- Raspberry Pi compatibility:

i. Testing the functionality and readiness of the robot's accessories, including the Raspberry Pi, HDMI screen, USB keyboard/mouse dongle, speaker, and microphone, revealed that all attachments were functioning perfectly.

ii. When powered on, the Raspberry Pi and its attached components can operate continuously for approximately 2 hours and 56 minutes without running any application.

iii. Running a pre-designed application -pedagogical agent- on the Raspberry Pi while powered by a 10,000mAh power bank resulted in a smooth operation for precisely one hour and 19 minutes.

- Motion system and remote-control glove:

The balance system of the robot varies according to the following:

i. Ground surface type:
   - The robot's stability is compromised on smooth surfaces such as ceramic, marble, and glass, leading to potential balance issues.
   - Performs exceptionally well on both rough and rubber surfaces, ensuring reliable performance across various terrains and conditions.

ii. Wheel types (see Fig. 4):
   - Fixed wheel: used as main wheels and produces smooth movement for the robot.
   - Omni wheel: used as main wheels but were not very efficient because the controlling was challenging.
   - Caster wheel (as a supporter-only): to maintain the robot's balance.

Figure 4. Fixed wheels vs. Omni wheels vs. Caster wheel

2. User testing:

At a cycle two school in Dubai, UAE (554 "non-native English speakers" students and 28 teachers), a brief survey was conducted among Grades 5 to 8 students and their teachers. Almost half of the students (294) and (15) teachers (teaching math, science, and design technology) participated. The survey spanned five working days (32 periods/lessons, 45 minutes each). Below are the questions included in the survey:

Q1. What do you want to change in the robot?

-Answers: (Color, Size, Shape/Design, Motion control).

Q2. Where can the robot be used?

-Answers: (Education, Entertainment, Health, Customer service).

Q3. How do you evaluate the motion control of the robot? (1: Low, 5: High)

-Answers: (Reachability, Easy to use, Reliability, Handling).

Q4. What is your opinion about using the robot in the classroom?

-Answers: (Distracting, Excellent, Good, Need improvements).

The Figures 5, 6, and 7 demonstrate the results/answers for the four questions:

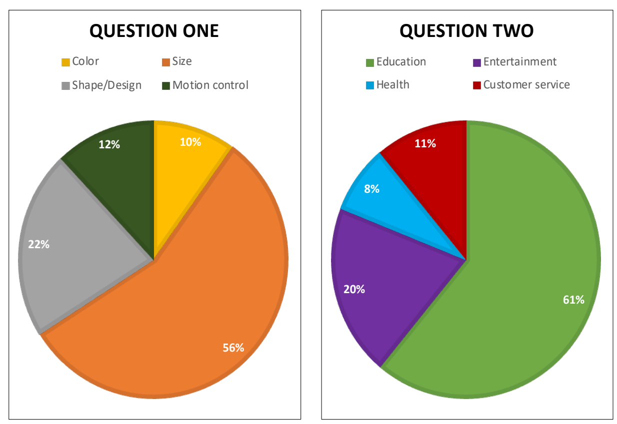

Figure 5. The answers to Q1 and Q2

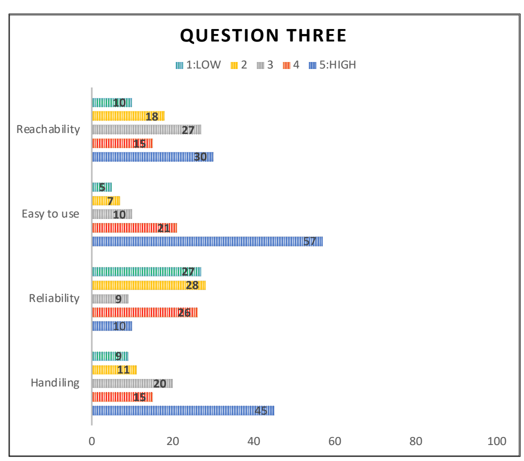

Figure 6. The answers to Q3

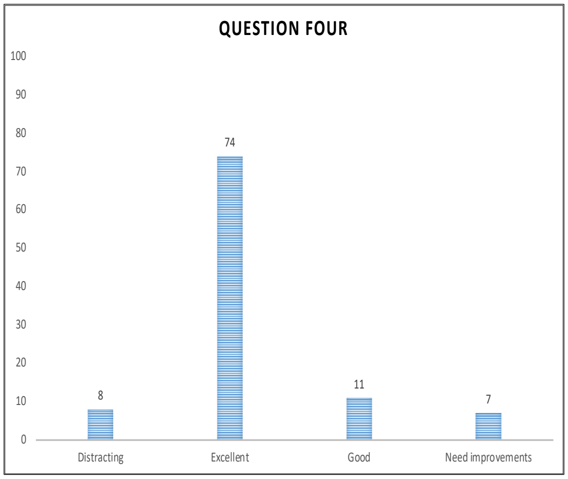

Figure 7. The answers to Q4

IV. RESULTS DISCUSSION

After deciding on an educational environment for testing, the robot was used as an assistive educational tool, enabling interactive multimedia platform features such as displaying videos and open-source quizzes. Alongside this, a predesigned application (pedagogical agent) was used during the testing phase. This application utilizes audio-visual detection and recognition to enhance interactive learning for students (non-native English speakers) to learn the English alphabet and science, technology, engineering, and math (STEM) terms. This promoted a positive learning environment, improved reading skills, and eased comprehension in math, science, and design technology lessons. A survey was distributed to teachers and students following the testing phase.

The students were notably interested in the robot's appearance and its controllability. Most questions from students revolved around understanding the robot's motion mechanism. Fifth and sixth-grade students showed a high level of curiosity, likely due to their age and the robot's alignment with the design technology curriculum.

Students with Attention Deficit Hyperactivity Disorder (ADHD) typically seek attention through disruptive behavior, struggle with following instructions, and may require assistance with tasks such as long division or equation-solving [54]. The teachers' observations of ADHD students indicated an interest in the humanoid robot, translating into increased engagement in class activities, reduced disruptions, and improved adherence to instructions, mainly when delivered by the robot rather than directly from the teacher.

While teachers generally expressed satisfaction with the robot's design, they raised concerns about its size relative to classroom dimensions and student numbers, averaging twenty-five per class. Additionally, complaints centered on the fragility of the robot's materials and screen, suggesting a need for more durable components and screen protection. Nevertheless, teachers praised the performance of the experimental robot, noting its effectiveness in capturing students' attention, especially among lower-achieving and shy students, fostering enthusiasm for learning. Some teachers received positive feedback from parents, who noted that students extended their classroom experiences with the robot to their homes, indicating the impact of the robot beyond school premises.

V. CONCLUSION AND FUTURE WORK

A humanoid robot was developed for potential use across various capacities and environments, including entertainment, customer service, and education. The educational environment was selected as a testing setting. The testing and evaluation focused on integrating the robot into math, science, and design technology lessons, leveraging its capabilities as an interactive multimedia platform using a pre-designed application (pedagogical agent) to enhance students learning.

Feedback from both students and teachers was mostly positive, with recommendations emerging to refine the robot's design, mobility, and potential for incorporating additional humanoid features.

Throughout the final stages of assembly, maintaining balance while in motion and ensuring compatibility with the Raspberry Pi presented significant challenges. Comprehensive detection of input and output components was essential for seamless operation. Despite these problems, the robot successfully completed the testing stage at the designated school.

The designed humanoid robot provides multimodal feedback, including spatial sound and audio-visual detection recognition compatibility. Integrating it with vibration output units within its Raspberry Pi is also feasible. This allows for tailored content delivery, or interactions based on individual learning needs. Holding the potential to support students with sensory disabilities related to vision or hearing.

The future development of the robot will involve various factors and aspects. A key focus will be empowering SDG4 and enhancing accessibility features to ensure all students can fully benefit from the robot's educational applications in STEM subjects regardless of their sensory or learning challenges. The following points outline the anticipated areas of improvement:

1. Design: Enhancing the design for greater adaptability based on the application and incorporating heightened safety settings.
2. Material: Using more robust materials than acrylic for building the robot's body, ensuring durability and longevity.
3. Size: Increasing the robot's size while maintaining balance during movement, providing a more substantial physical presence.
4. Add-ons: Implementing a mechanism to enable the robot's arms movement enhances user interaction across various applications, offering a more intuitive and engaging experience. This design significantly improves the robot's interaction capabilities, allowing it to manipulate objects, perform precise tasks, and engage more naturally in educational environments.

The movable arms increase versatility and enhance the robot's ability to mimic the human body, making it a more relatable and effective tool in teaching. This human-like movement is important in HRI, as it fosters better communication and engagement with students, making the robot a valuable asset in educational settings. Additionally, movable arms improve the robot's dynamic stability and mobility, allowing it to navigate various classroom layouts and maintain balance while interacting with students, expanding its effectiveness in diverse educational scenarios.

5. Movement mechanism: Focusing on refining the movement mechanism to optimize efficiency, incorporating variable speed capabilities during movement, autonomous navigation, and obstacle avoidance system.
6. Simulation: Integrating the Robotics Operating System (ROS) for simulation purposes, enhancing overall functionality and operation.
7. Visual Accessibility: Integrating a built-in accessibility tool featuring high-contrast interfaces, customizable font sizes, and tactile feedback options to enhance accessibility for visually impaired or dyslexic users.
8. Auditory Accessibility: Incorporating built-in text-to-speech and speech-to-text features in the robot will support users with dyslexia by aiding their reading and writing skills while also providing captioning options to ensure equal access to information for those with hearing impairments. These functionalities can help users with dyslexia and hearing impairments improve spelling and the ability to sound out words.
9. Haptic Feedback: Adding haptic feedback mechanisms into the robot's design can offer tactile cues and notifications, allowing users with vision and hearing impairments to receive essential alerts during educational activities. This feature enhances the user experience and facilitates better engagement with STEM learning materials.
10. Gesture-Based Controls: Developing gesture-based controls alongside traditional input methods provides an alternative interaction mode for all users. These controls can be tailored to accommodate varying skill levels, empowering all students to participate in activities the robot stimulates.

By prioritizing these accessibility features in future development, the robot can be a valuable tool for promoting inclusive STEM education, empowering students with diverse abilities to explore, learn, and excel in these critical fields. The use of this robot marks the start of an exciting initiative to create humanoid robots for various uses. It was designed to be affordable, easy to upgrade, and open to anyone interested in educational robotics and HRI.

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