Towards Affordable and Lightweight Humanoid Robots: A Task-Specific Design Approach

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***Abstract*—The core concept of the fifth industrial revolution is the harmonization of humans and machines, emphasizing a human-centric approach where humanoid robots are designed to interact with humans or work and collaborate with humans in human-centric environments. However, full-size humanoid robots are highly expensive, which diminishes their suitability for application-specific activities such as teaching in classroom environment. Researchers in numerous studies have been found facing challenges regarding the development costs and complexity while designing the mechatronics. This article addresses the gap by proposing a cost-effective design for a humanoid robot (Dbot) capable of performing specific functions such as talking, moving, shaking hands, and communicating with humans, which can be utilized in activities aiming classroom teaching. With 31 Degrees of Freedom (DOF), Dbot demonstrated human-like motion relying on a lightweight and rigid mechanical structure made of aluminium followed by a building process utilizing low-cost hardware sourced from local and commercially available sources. The design with its multistage development went through rigorous testing and optimizations. A functional Dbot was tested with students of specific age group at Daffodil International School and College, and its performance as a classroom teacher or instructor was evaluated based on response, accuracy, command recognition and other criteria. These tests and overall analysis resulted that Dbot with its lightweight and low-cost design can successfully perform with students in classroom, with a 95% accuracy in voice recognition along with appropriate gesture and interaction representing significant potentials for the advancements in task specific application of humanoid robots.**

***Keywords*—humanoid robot, human-robot interaction, lightweight design, educational robot, cost effective robot**

I. Introduction

Over the last decade, robotics has grown at an unparalleled rate. Robots are rapidly being used in a variety of sectors, which include robots and microrobots in assistance, caring, and healthcare systems [1], robots in consultation and service, cultural activities, industrial development and assembly, security and defense etcetera. Numerous recent robots have been seen providing task-oriented services like delivering food and groceries under collaborative management, and recent studies have presented design and development of such robots with detailed elaborations [2]. However, among these robots, humanoids possess a significant potential as they can be customized to individual demands, for instance home assistance, manufacturing operations, and interpersonal relationships where human-like appearance is required or convenient [3]. Among these improvements, humanoids have the true potential to be used for teaching by enabling interactive learning experiences and stimulating research in Artificial Intelligence (AI) and Machine Learning (ML) [4]. Furthermore, they can help with studies on human-robot interaction, give insight into social behaviors, and improve their incorporation into ordinary human activities for day-to-day life.

Recent research emphasizes the use of humanoid robots in Science, Technology, Engineering and Mathematics (STEM) education and teaching, highlighting their contribution to enhance student interest and cultivating critical thinking skills, which might support development of the group projects the learners involve with [5]. Compared to conventional teaching techniques, research indicates that the use of humanoid robots for educational purposes enhances students' motivation in scientific and engineering domains of study [6]. However, due to their high cost, instructional humanoid robots like NAO and Pepper may not be able to be used at a global scale in academic institutions with limited funding [6]. Moreover, a lot of these high-end robots may consume comparatively higher energy, which makes them unsuitable for long-term and consistent classroom integrations.

Designing humanoid robots involves many constraints that need to be addressed during the design and development. It includes kinematic and dynamic parameters that ensure physical consistency, such as the robot's center of mass, height, link geometry, and density [7, 8]. Humanoid robots must navigate and

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manipulate objects in environments designed for a human being. Robustness to perturbations and collisions is essential, necessitating sophisticated modeling approaches to maintain balance and dynamic stability [9]. The robot's motion must be adjusted in real-time based on sensory data, and the sensitivity must also be adjusted so that the motion looks as natural as a human. This involves overcoming challenges related to the computational complexity of kinematics and the need for rapid adaptation to changing environments. The design parameters of humanoid robots are closely linked to their control systems, which affect their capabilities. This coupling makes the design process iterative as well as complex, especially for bipedal robots with nonlinear and hybrid dynamics [10]. The selection and optimization of actuators are critical, particularly for upper-body movements. The lower body part and joints must be rigid enough to withstand the load on top. Actuator specifications are determined based on regional load, data from human motion, and optimization indices are used to evaluate configurations for speed, acceleration, and torque [11].

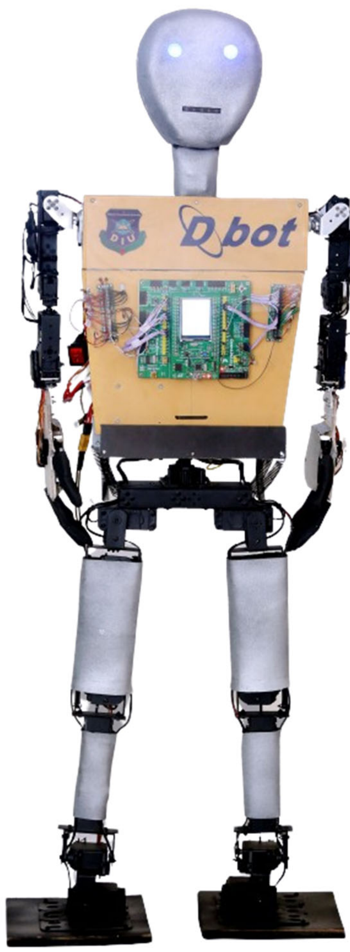

Fig. 1. Dbot: A cost-effective lightweight humanoid robot.

Since a full-size humanoid robot is expensive and not suitable for classroom teaching purposes in many cases, it is necessary to have a low-cost humanoid with minimum functionality while ensuring performance for classroom learning activities by robot. In this article, a cost-effective and lightweight humanoid design has been proposed (shown in Fig. 1) to serve classroom teaching purposes, aiming to provide interactive primary education in schools or institutions for elementary or secondary education. The design also ensures low power consumption for long-term service. This research was conducted along with the following research objectives:

- Design a cost-effective humanoid robot for task-specific applications.
- To design low-power hardware for a humanoid robot to serve consistently for a long-time.
- To design a lightweight humanoid robot mechanical body that can mimic human movements.

II. Literature Review

This section elaborates the relevant works exploring the evolution of humanoid robots, applications and constraints for development, and recent research trends in industry and academia. The exploration of humanoid robots began in the late 1960s, with significant contributions from Waseda University in Japan. They developed a series of bipedal walking robots, including Waseda Automatic Pedipulator (WAP), Waseda Legged (WL), WAseda BIpedal humANoid (WABIAN), and WAseda roBOT (WABOT), which successfully accomplished fundamental walking functionalities [12] (Fig. 2).

The second stage marked significant advancements with the introduction of highly integrated systems [13–15]. Honda's humanoid robots, particularly ASIMO2000 [16], unveiled in 2000, were notable for their ability to anticipate future movements and adjust their center of gravity, allowing for seamless walking during turns. Other mentionable robots from this era include Sony's "QRIO," the first humanoid robot capable of running [17], and "BIP2000" from France, Sony's "SDR" series, and South Korea's "HUBO," which exhibited capabilities such as standing, navigating stairs, running, and engaging in physical exercises [12] like a human being does (Fig. 2).

The third stage (Fig. 2) showcases breakthrough progress in the development of humanoid robot, with companies like Boston Dynamics and Tesla leading the way. These robots have achieved highly dynamic motion and advanced cognitive capabilities, enabling them to perform intricate movements independently and with stability. Boston Dynamics' ATLAS [18] robot demonstrates human-like perception, judgment, and decision-making skills, while Tesla's "Optimus prime" is anticipated to revolutionize mass production and contribute to industrial progress [19].

As far as the research in humanoid robots linking education is concerned, Chalmers *et al.* [20] suggested that Educational Robotics (ER) can play a crucial role in preparing students by acting as pedagogical agents to facilitate and evaluate learning, particularly in STEM subjects. The paper noted that humanoid robots have been used in educational settings, primarily focusing on technological capabilities for language acquisition and STEM education. However, there is a lack of understanding regarding their efficacy in School Learning Environments (SLEs).

Schwatz *et al*. [21] in their research aims to design a humanoid legged robot that integrates aesthetics with practical research goals, focusing on human-like and compliant motion through torque-controlled joints. The design process involves multi-axis CNC machining to create an integrated frame, reducing parts and complexity for easy maintenance [22]. The research presents a unique integration of design and functionality, achieving aesthetic appeal and practical usability without the need for additional casings. The weight of the simulated robot was a total of 71.295 kg, in which 40.245 kg was for the lower body and 30.05 kg was for the upper body making the robot comparatively heavy one.

Omoush *et al*. [23] discussed designing and constructing a low-cost humanoid robot utilizing a movement mechanism based on flex sensor. It emphasizes compatibility with affordable platforms like Raspberry Pi and microcontrollers such as Arduino Uno and Nano. The robot was tested in a Dubai school for Grades 5 to 8, and integrated into various subjects such as math, science, and design technology. Surveys indicated a strong acceptance from students and teachers, with over 85% expressing positive attitudes towards the robot. Feedback from teachers and students indicated limitations regarding the robot's shape, capabilities, and movement mechanism, suggesting that improvements are needed to enhance its overall functionality and user experience in the classroom setting.

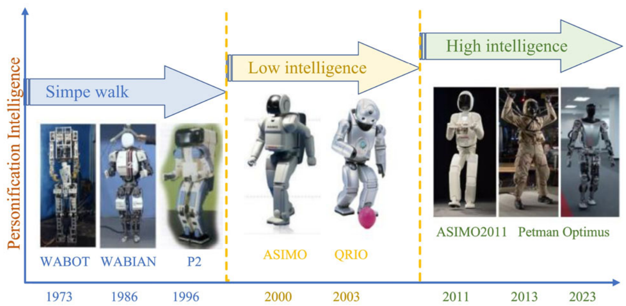

Fig. 2. Evolution of humanoid robots in the past decades.

In another study, Elsayed *et al*. [24] developed a lightweight and cost-effective humanoid robotic arm aimed at assisting elderly and vulnerable populations, utilizing 3D printing technology to achieve significant weight reduction and employing low-torque servos for enhanced functionality and cost efficiency. Their robotic arm achieved a weight reduction of over 60% through the use of 3D printing technology with 40% infill, and it demonstrated high accuracy in joint fit percentages ranging from 87.5% to 97.07%, indicating effective system identification and precise control of the arm's movements. However, it does not address the long-term durability and maintenance of the 3D-printed components, particularly under varying environmental conditions and usage scenarios. The rigidity under certain load has not been validated by the study as well.

Yousefi-Koma *et al*. [25] presented the SURENA IV humanoid robotics platform, which features 43 degrees of freedom, a height of 170 cm, and a mass of 68 kg, designed to mimic the morphological and mass properties of an average adult human, aiming for cost-effectiveness in real-world applications. This design aims to make humanoid robotis more accessible for real-world applications, demonstrating capabilities such as grasping various objects and performing tasks like drilling and writing. The SURENA IV humanoid robot experiences a foot position error of 7 cm due to the accumulative error of links and deflection in connections, which can affect its walking accuracy and stability on uneven surfaces.

Designing a cost-effective humanoid robot thus involves a multifaceted approach that balances affordability with performance, functionality, and efficiency. Carbon Fiber Reinforced Plastic (CFRP) is widely recognized for its high strength to weight ratio and is used in various robotic applications. For instance, the SHERPA biped robot employs a lightweight carbon fiber skeleton, mimicking human anatomy to achieve efficient walking motion illustrated in their study by Olaru *et al.* [26]. Similarly, Elsayed *et al.* [24] employed CERP in their robotic arm to reduce weight while maintaining structural integrity. However, CERP is comparatively expensive, which leads to the higher development cost of such humanoids.

Folgheraiter *et al*. [27] highlights the use of in-house-developed servomotors, achieving a power-to-weight ratio of 160 W/kg. This high efficiency enables the robot NU-Biped-4.5 to perform dynamic tasks with minimal energy consumption. The total cost for their prototyping was under USD 5000. It features a lightweight design, standing 1.1 m tall and weighing 15 kg (excluding the battery), and incorporates off-the-shelf components. On the other side, Gouaillier *et al*. [28] described the mechatronic design of the NAO humanoid robot developed by Aldebaran-Robotics. The design aims to make a high-performance biped robot accessible to a wider audience, with a target price of approximately 10,000 euros for academic uses. NAO robots have 25 degrees of freedom with a compact design, but a height of only 0.57 m, and a weight of approximately 4.5 kg. The approximate production costs of some popular humanoid robots like Poppy $4500, Nao $5000, Unitree G1 $8000, Tesla Optimus $15,000, Walker $35,000, Figure 01 $75,000, and HRP-4C $100,000 [29–32].

From the reviewed literature, it is quite clear that the production cost of such high-end humanoid robots may range between USD 5000 to USD 100,000 and it might even add additional cost in the consumer level, making these robots non-suitable for the classroom teaching activities which this study aimed for. The high cost of maintenance may exert added burden to the educational institutions of low to medium income or underdeveloped countries. Addressing this cost while developing a humanoid robot with certain nominal features, therefore, been considered as a gap that needs further contributions under the domain.

III. Materials and Methods

A. Designing Cost-Effective Hardware Architecture for Dbot

In this section, a modular and cost-effective hardware architecture of a humanoid robot has been discussed. The hardware architecture of the humanoid robot, as depicted in the diagram (Fig. 3), is centered around the STM32F4 Discovery Board, which acts as the core control unit. This microcontroller board manages the integration and communication between multiple subsystems, enabling synchronized operation. It interfaces directly with two primary finger controllers, the Right finger controller (A3) and the Left finger controller (A2), which manage the servos for the right and left hands of the robot, respectively. Each hand consists of five servo motors (R1–R5 for the right hand and L1–L5 for the left hand), facilitating intricate finger movements for tasks requiring fine motor skills.

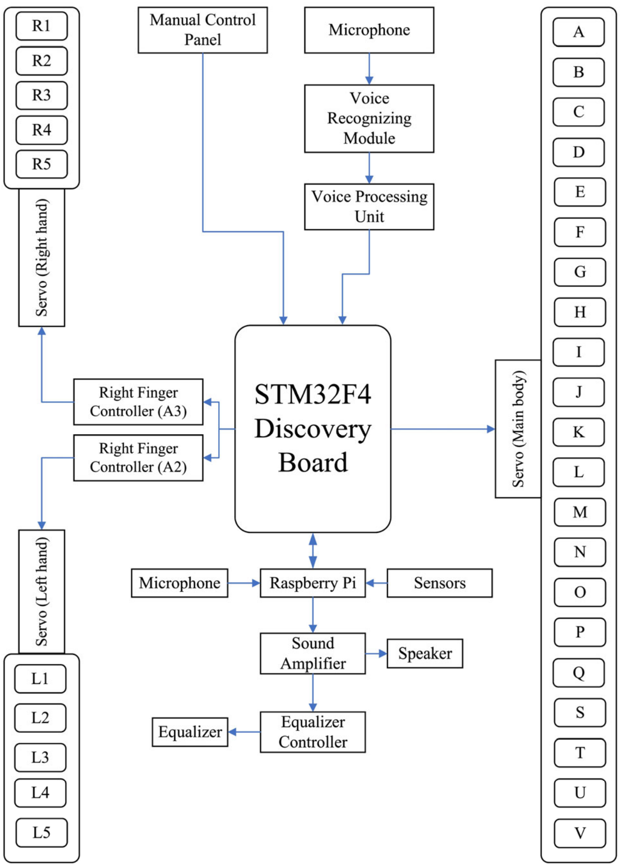

Fig. 3. Hardware architecture of Dbot with all components.

This dedicated servo arrangement enhances dexterity and precision in manipulating objects, an essential trait for humanoid robots. A critical feature of this architecture is its dual control input: a Manual Control Panel and a Voice Recognition Module. The Manual Control Panel offers direct, human-mediated command input, allowing for precise manual operation when needed. In parallel, the Voice Recognizing Module, integrated with a Voice Processing Unit, enables voice-command control. The microphone captures audio inputs, which the voice processing unit interprets into actionable commands. This hybrid control approach enhances flexibility, allowing the robot to operate autonomously in voice-controlled environments while retaining the option for manual overrides during complex or sensitive tasks.

The robot's locomotion and physical articulation are managed through a separate servo system dedicated to the main body that is responsible for controlling key segments labeled A through V (Fig. 3). These servos facilitate complex bodily movements, enabling humanoids to replicate human-like gestures and mobility. The segmentation of the body servos allows for a wide range of motions, from simple limb movements to more dynamic postures, supporting tasks that demand balance, flexibility, and coordinated body mechanics. The connection to the STM32F4 ensures real-time synchronization of these movements with hand and sensory inputs, vital for maintaining overall stability and control.

The architecture integrates sensory perception and sound output through the Raspberry Pi module, which functions as an auxiliary processing unit. The Raspberry Pi collects data from multiple sensors and an additional microphone, broadening the robot's environmental awareness. This setup is crucial for tasks involving object detection, obstacle avoidance, and sound localization. The Raspberry Pi also manages audio outputs via a sound amplifier and speaker system, allowing the robot to communicate verbally or emit alerts. An equalizer and an Equalizer Controller further refine audio quality, ensuring clear sound transmission, which is particularly beneficial for interactive applications with real human beings.

Overall, this humanoid robot's architecture emphasizes a modular design, where distinct subsystems are dedicated to specific functionalities; however, they are centrally coordinated through the STM32F4 Discovery Board. This modularity allows for easier upgrades and maintenance while promoting system reliability. The combination of advanced voice recognition, manual control, complex motor coordination, and rich sensory input creates a highly adaptable platform capable of performing a diverse range of tasks in dynamic environments. However, the system's complexity also necessitates robust programming and precise calibration to ensure harmonious operation across all components.

B. Lightweight Mechanical Design of Dbot

The mechanical component for the design of this Dbot is crucial. Many Degrees of Freedom (DOF) and valuable joint mechanisms are required to accomplish mobility and flexibility similar to that of the human body. More degrees of freedom will allow for more flexible movement, however, will add complexity to the design. The major considerations are weight, size, and energy consumption. However, this varies depending on the nature of the job. Robots designed for industrial usage or other heavy-duty tasks will be heavier and require more energy than general-purpose humanoids such as social or educational robots.

Brushless DC motors, servo motors, gears, joints, links, springs, and other essential elements (Table I) are used to create the mechanical body of the Dbot [33, 34]. Brushless motors are utilized in the body of the iCub [35] robot, which is an open-source humanoid development platform. The Nino [36] instructional robot, produced by Sirena Technologies, is another example. Servo motors are used to move the joints of the entire body (Fig. 4). The main advantage of employing servos in robot designs is that they are modular and simple to repair.

TABLE I. MECHANICAL MAJOR COMPONENTS USED IN DBOT WITH SPECIFICATIONS

Components	Specification
S1 servo motor	Torque: 30 kg/cm (7.2 V), Speed: 0.18 s/60° (7.2 V)
S2 servo motor	Torque: 15 kg/cm (4.8 V), Speed: 0.14 s/60° (4.8 V)
S3 servo motor	Torque: 1.4 kg/cm (4.8 V), Speed: 0.12 s/60° (4.8 V)
STM32F429	32-bit, 180 MHz, Cortex M4 core
Raspberry Pi 3B+	1.4 GHz 64-bit quad-core processor
Voice recognition module v3	Supports 80 voice commands
Microphone	Frequency range: 100 to 10,000 Hz
Accelerometer & Gyro sensor	MPU-6050

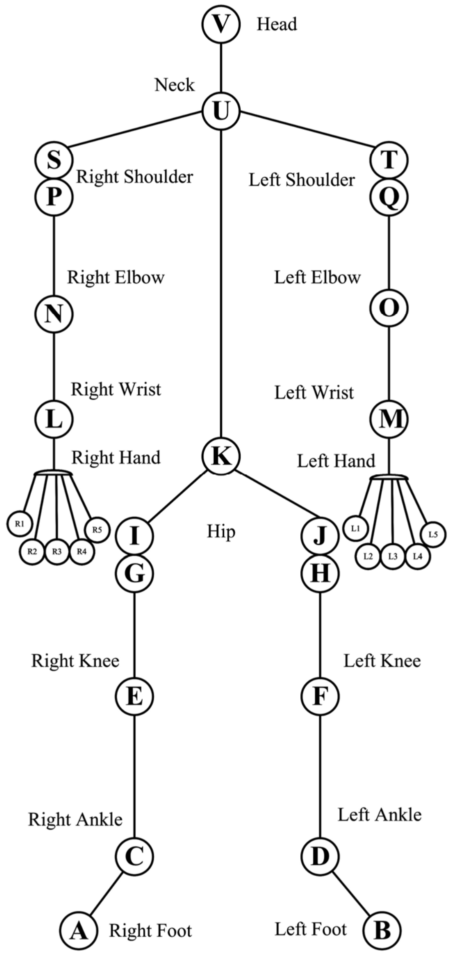

Fig. 4. Mechanical joint configuration of Dbot.

The full scale Dbot is about 145 cm tall weighing 17 kg, similar in height and weight of teenagers. This size will pay attention to both kids and younger children. Dbot is not designed to do any heavy lifting, therefore it was designed to be light. This design allows for mobility in any situation. Throughout the body, three types of servos are used depending on the load. Because servo motors already have internal gear systems for performing low-speed, high-torque tasks, this design eliminates the need for any extra gear mechanisms, making it simpler and versatile.

1) Head

The head consists of two joints with two degrees of freedom. S2 type servo is used in both joints U and V as shown in Fig. 4. The horizontal and vertical movable ranges of the Dbot head are 20° to 150° and 90° to 160°, respectively, as referred to in Table II. Inside the head, other components such as microphone, voice recognition module, and sound adjuster are integrated. The main materials of the head are aluminum and soft foam for a synthetic human look.

2) Arm and hand

Humans do most of their physical work with their arms and hands. It is preferable to use humanoid arms, similar to human arms, to interact with humans and execute human-centric applications. Dbot arms consist of four joints with four DOF. Fig. 4, illustrates each joint of both arms. Each shoulder has two joints made of servo motors, in which S2 type is used for S and T, S2 type servo is used for P and Q. S and T are responsible for the Pitch motion, whereas P and Q are responsible for the Yaw motion. Right elbow(N) and left elbow(M) are also made of S2 type servo to produce arm pitch motion. Right wrist (L) and left wrist (M) both provide roll motion, and they are made of S2 type servo.

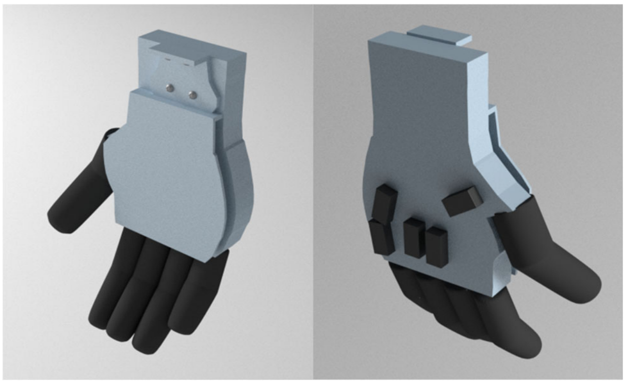

Fig. 5. 3D design of Dbot hand with five fingers.

The number of fingers used in robot hands depends on the nature of the task performed by the robots. For instance, ASIMO, HUBO, iCub, and TORO all have five fingers in their hands to help them function better for multidimensional jobs. NAO only has three fingers. In contrast, Atlas has no fingers. Both hands of Dbot consist of five fingers having 5 DOF each. R1, R2, R3, R4, and R5 servos (S3 type) are used in the right hand, while L1, L2, L3, L4, and L5 servos (S3 type) are used in the left hand. Each finger is equipped with a spring mechanism and is protected by a soft fiber screen. When servos release tension, the fingers straighten due to a spring mechanism as shown in Fig. 5.

TABLE II. MECHANICAL DESIGN SPECIFICATION OF EACH PART OF DBOT

Body Parts	Actuator Type	Joint	Movable Range in Degree
Head	S2	U, V	U (0–150), V (0–90)
Left Arm	S1, S2	M, O, Q, T	M (90–0), O (90–0), Q (180–0), T (180–0)
Right Arm	S1, S2	L, N, P, S	L (0–90), N (0–90), S (0–180), P (0–180)
Hip	S1	G, H, I, J, K	G (0–90), H (180–90), I (0–90), J (180–90), K (0–20)
Knee	S1	E, F	F (180–100), E (0–80)
Ankle	S1	A, B, C, D	A (0–40), B (180–140), C (0–45), D (180–135)
Left Hand	S3	L1, L2, L3, L4, L5	L1–L4 (0–90), L5 (0–45)
Right Hand	S3	R1, R2, R3, R4, R5	R1–R4 (0–90), R5 (0–45)

3) *Hip joint*

The hip joint plays a crucial role for the robot since it connects the upper body with the lower body of the robot. The Dbot hip joint was made of a specialized pinion mechanism as shown in Fig. 6. The pinion mechanism amplifies the servo (S1 type) torque to balance joint force. A 50 mm diameter ring gear with a bearing attached to the bottom portion of the body, and a 20 mm diameter metal shaft with a 4 mm thin solid plate attached to the top part of the body. To drive motion, a 22 mm pinion gear is directly coupled to the servo K, as shown in Fig. 4. This joint allows the body of the robot to roll from left to right.

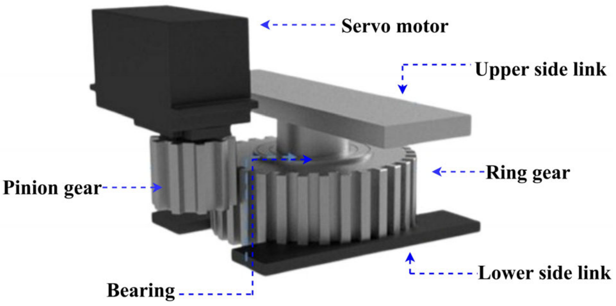

Fig. 6. 3D design of Dbot hip joint.

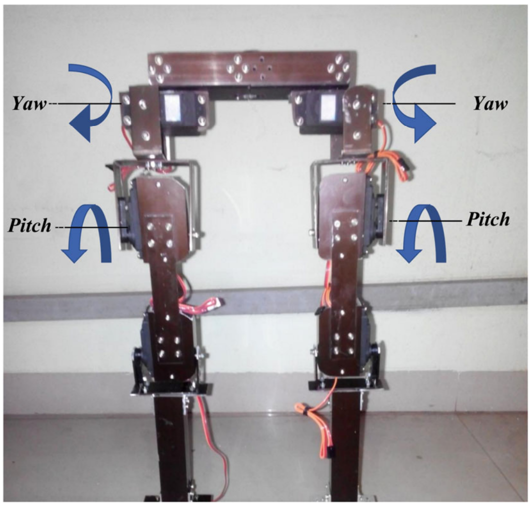

Fig. 7. Yaw and pitch motion of Dbot legs.

4) *Leg*

Each leg of Dbot has five degrees of freedom. Design mechanism of the leg is considered important as it carries load and maintains optimum balance. This is the most crucial aspect as far as a biped robot is concerned. Although Dbot's primary design was not for walking, however, it is designed to stand and balance on its own using its legs. Hip, knee, and ankle are the three primary components. Joint I, G, E, C, and A together produce pitch and yaw motion of right leg and joint J, H, F, D, and B produce pitch and yaw motion of left leg. Fig. 7 illustrates pitch and yaw motion of the Dbot's legs.

Fig. 8, on the other hand, shows the ankle and knee joint, which is also made of S1 type servos. For pitch motion, the knee has just one DOF.

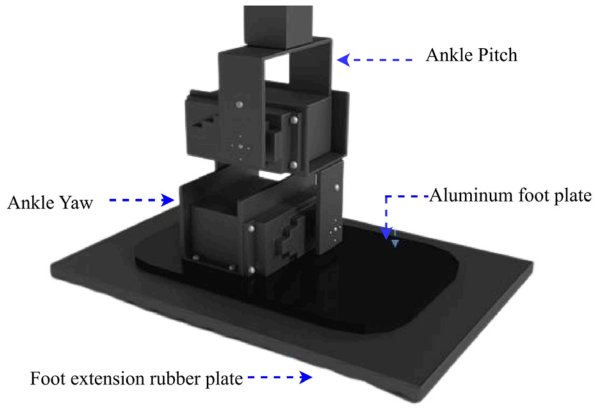

Fig. 8. 3D model of Dbot's ankle and foot.

For Yew and Pitch, each ankle has two degrees of freedom. In the ankle joint, servos A, B, C, and D are employed. In order to achieve more grip, a rubber pad has been installed on the bottom of each foot of Dbot.

IV. RESULT AND DISCUSSION

A. *Full Body Weight Optimization*

Optimization of robot weight is a major area of difficulty for the researchers of humanoid robots. More weight requires more energy to operate and makes it more difficult to maintain balance when moving due to the excessive consumption of energy. The Dbot's body is mostly made of aluminum, with some iron and wood thrown in for good measure. Without an auxiliary power pack, the Dbot weighs 17 kg. Dbot operates with a direct power source (220V AC) when the application is stationary or in the case where waling is less to not required. An auxiliary portable DC power source weighing roughly 5 kg can also be used when it is necessary for long-distance movement or movement withing the interaction zone

The comparison of various humanoid robots, highlighting their DOF, weight, height, and mobility has been illustrated in Table III. Among these, Dbot stands out as a lightweight, moderately flexible bipedal robot designed for specific task-oriented environment. With 31 degrees of freedom, it finds a balance between flexibility and mechanical simplicity that is ideal for indoor interactive tasks. Weighing 17 kg and standing at 1.3 meters, Dbot is lighter than most counterparts like REEM-C (70 kg) or Valkyrie (44 kg), enhancing its safety and energy efficiency in educational settings.

TABLE III. COMPARISON OF DBOT WITH OTHER HUMANOID ROBOTS BASED ON DOF, WEIGHT, HEIGHT AND MOBILITY

Robot	Research Institute	DOF	Weight (kg)	Height (m)	Mobility
ATLAS [18]	Boston Dynamics, USA	28	82	1.65	Biped
NAO [28]	Aldebaran, France	25	4.5	0.57	Biped
Poppy [29]	INRIA, France	25	3.5	0.83	Biped
ROMEO [30]	Aldebaran, France	37	44	1.4	Biped
Pepper [31]	Aldebaran, France	20	28	1.28	Wheeled
REEM-C [32]	Pal Robotics, Spain	68	70	1.6	Biped
Optimus Prime	Tesla, USA	40	56	1.73	Biped
iCub [35]	IIT, Italy	53	25	1.04	Biped
HRP-4C [37]	AIST, Japan	42	43	1.58	Biped
Valkyrie [38]	NASA, USA	44	44	1.9	Biped
Albert-HUBO [39]	KAIST South Korea	66	57	1.37	Biped
Dbot	Daffodil Robotics Lab	31	17	1.3	Biped

Compared to small robots such as NAO (0.57 m, 4.5 kg) and Poppy (0.83 m, 3.5 kg), Dbot has a more humanoid presence that offers better interaction with learners. Notably, robots like ASIMO [40] and ATLAS have more degrees of freedom for complicated movement, whereas Dbot favors stability and task-specific interactions, which aligns with its teaching function. Unlike Pepper, which uses wheeled mobility, Dbot's bipedal design allows it to navigate varied classroom layouts more naturally. Overall, Dbot's design provides the best combination of usefulness, safety, and interaction possibilities, making it an excellent assistant or facilitator for the teaching and learning environment

The back-drivability and compliant motion are demonstrated by the experiment of gravity compensation conducted in the Daffodil Robotics Lab. For this experiment, the robot stood on its right foot and then a person manually moves the left foot of the robot to a specific position for 2 seconds and returns it to its original location in about 8 seconds. Fig. 9, shows the experimental data, where the x, y, and z values represent the position of the left foot, and the measured forces in the Cartesian coordinate system are denoted by Fx, Fy, and Fz, respectively. The directions correspond to the Ventral (x), Lateral (y), and Cranial (z) axes of the robot. It is important to note that the force sensors were solely used to monitor the applied forces during the movement and were not utilized for force control.

The data reveals that the force required to initiate and sustain the foot's movement ranged from approximately 10 N to 30 N. These force levels primarily reflect the static friction within the robot's joints. Upon initiating the movement, the joints become backdrivable, enabling smooth and compliant motion as the foot was guided along the intended path. The absence of abrupt force fluctuations during the holding phase highlights the system's ability to maintain position without resisting user-applied forces, demonstrating the effectiveness of the gravity compensation mechanism.

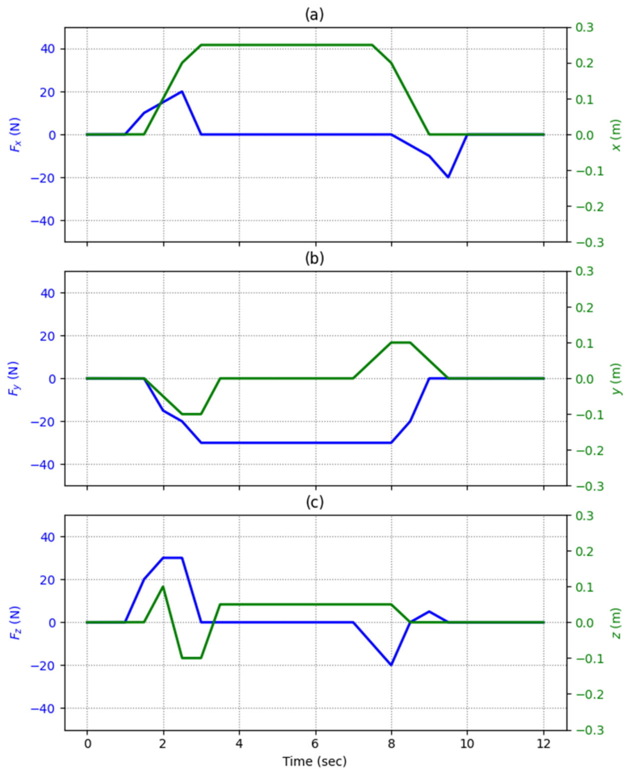

Fig. 9. Experimental data presenting the force exerted and the foot position of the motors during gravity compensation.

This experiment successfully validates the compliant behavior of the lightweight humanoid robot during gravity compensation, achieved without relying on joint torque sensors. The consistent and stable force profiles, coupled with the robot's ability to smoothly follow external inputs, showcase the robustness of the control strategy. The system's capability to facilitate natural and intuitive human-robot interaction further underscores its potential for applications requiring adaptive and responsive robot behavior.

B. Overall Cost Minimization

The cost minimization of a humanoid robot is another major challenge that requires propser attention. Cost minimization involves the cost of many parts and components of the robot, including hardware, mechanical, software, and operation. The simplified mechanical structure in this case plays a vital role in reducing weight. A lightweight robot body requires less power compared to a heavyweight body. For the Dbot aluminum is used to build the main structure since aluminum is lightweight and cost-effective. To reduce design complexity and cost, high-performance compact servos have been used in each join of the Dbot. Without using high-end mechanical joint and force sensors, Dbot uses servo feedback to calculate joint torque and motion.

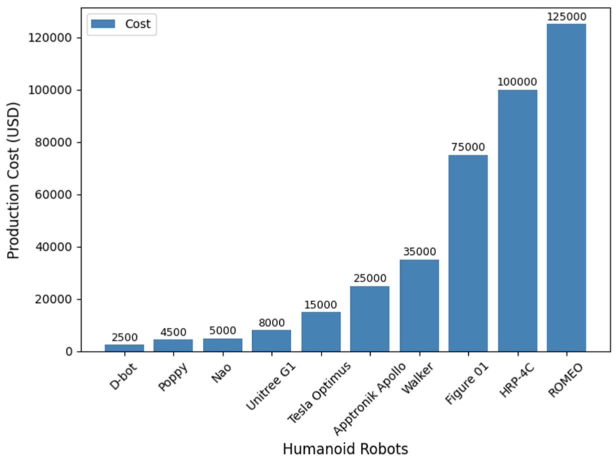

Fig. 10. Comparison of production cost with other humanoid robots.

Fig. 10 illustrates the production cost (in USD) of various humanoid robots, showcasing a wide range of pricing. In this case, the production cost is calculated with the following Eq. (1):

$$Cp = \mathrm{Cm} / 2 \tag{1}$$

where *Cp* represents the approximate production cost, and *Cm* represents the approximate market cost. Among them, Dbot is the most cost-effective at $2500, making it highly affordable compared to other humanoid robots. Poppy ($4500) and Nao ($5000) are also relatively low-cost, suggesting that they are designed for research and educational purposes rather than high-end industrial or commercial applications.

C. Test Case and Performance Evaluation

Dbot has been tested with students from Daffodil International School and College (DISC). The audience and participants for the test case and testing environment have been carefully chosen from the students' group with the age range 10–12 years (standard VI). The reason for choosing this specific age group remains within the capacity of the participant to have strong oral or verbal communication and the promptness to interact (physical and gesture) with a human size robot. Primary school students may be too shy to respond and secondary school or above students may not be easy to manage for a longer-term interaction with patience. Junior students seemed a better choice for this test therefore two sections of standard VI students (15 students in each section) were chosen. The test lasted for approximately a month; however, the first 2 weeks were for inspection regarding the selection of the participants and suitability of the test environment including the source of power and safety of the test environment. Dbot's performance was tested in the last two weeks with the participants mentioned. Three courses (Physics, English and Geography) were chosen considering the teaching contents as per the syllabus and curriculum. Dbots training on the courses mentioned was conducted in the first two weeks as well. Each class was designed to be 45 min long, like the regular classes. As per the test case, the first 30 min were allocated for Dbot to perform a class lecture based on a pre-selected content of the specific course. It performs this part with gesture and voice commands, with reasonable movement of the upper body and a very little movement of the lower limbs to avoid structural deformity as already it was tested that the loads were extreme on the lower joints on feet and toes. Table IV represents the specification of the test case along with its environment in a tabular format.

TABLE IV. SPECIFICATION OF THE TEST CASE AND ENVIRONMENT

Test Case Components	Specifications	Remarks
Age group	10–12 Years	Participants are students of standard VI of DISC
Total participants	30	2 sections of students 15 each
Total course or subjects	3	Physics, English and Geography
Duration of test	1 month (4 weeks)	First 2 weeks for test environment inspection and training, last 2 weeks for performance evaluation
Duration of each class	45 min	30 min for lecture, 15 min for question answer and interactions
Performance evaluation criteria	response time, accuracy, speech recognition, and physical interaction	Comprehensibility is tested on overall performance

The last 15 min were for questions and answers for the robot. It was expected that the participants would ask questions based on the topics covered in the first 30 min, however, Dbot's response was not made limited to the specific contents only, that means while answering it could access its entire domain of knowledge to mimic the classroom practice similar to what a teacher or instructor does in such environment.

Performance of Dbot was evaluated based on the following criteria and metrics: response time, information accuracy, speech recognition, comprehensibility, and physical interaction. Among these evaluation criteria, voice and speech recognition from the audience was the most important one. Other criteria were secondary to it, as the accuracy of the information spoken by Dbot was depended on the question recognized by Dbot from the audience. Two other secondary criteria, such as the response time and physical interaction with the audience were depended on the performance of the audience as well. The more active the audience was (in terms of bold and accurate pronunciation and active interaction while conversation), the less response time with higher physical interaction such as handshaking and greetings were observed while testing (Fig. 11(b), (d)). The overall results showed that Dbot can successfully interact with the students through voice conversation with around 95% accuracy and share relevant information with students through voice and gestures. Fig. 11 illustrates four different gestures during its operation. Depending on the voice command, Dbot responds with voice along with a physical gesture that makes it perform interactive actions in the test environment. Note that the gesture expression of Dbot in this test scenario was tightly coupled with the voice command, that means the gesture actions are preset or pre-scripted with the contents of the voice command and all Dbot needed to perform was based on its detection and recognition of the voice command from the audiences. Therefore, 95% accuracy in recognition of voice command had 100% accuracy in gesture expression as per the contents in the voice commands (shown in Fig. 11).

(a) (b) (c) (d)

Fig. 11. Different gestures of Dbot during its operation: (a) expression with both arms and head, (b) expression with only one arm and head, (c) expressions with both arms and fingers, (d) performing interactive expression, such as a handshake with a human.

TABLE V. COMPARISON OF DBOT WITH OTHER EDUCATIONAL ROBOTS: SCOPE, FEATURE AND PRICE

Robot Name	Robot Photo	Application/Scope	Features	Price (USD)	Citation
LEGO Mindstorms EV3		Robotics, STEM (Ages 9–15)	Programmable brick; sensors, Programming: Drag and drop, Python/C; Height: ~16 cm (assembled); Payload: Light objects only.	~$490	Kalaitzidou and Pachidis [41]
NAO Robot		Humanoid robotics, AI, HCI	25 DoF humanoid robot; Voice/speech/vision recognition; Height: 58 cm; Payload: ~300–500 g	~$11,000	Gouaillier *et al.* [42]
Thymio II		Primary–Secondary STEM	20+ sensors, LEDs; Programming: Scratch, Blockly, Python; Height: 5 cm; Payload: ~100–200 g.	~$160	Kalaitzidou and Pachidis [41]
Bee-Bot		Pre-K programming & sequencing	Direction buttons; No screen needed; Height: 7 cm; Payload: None	~$110	Kanaki *et al.* [43]
Pepper		Social robot, emotion-based interaction	20 DoF, Facial/emotion recognition; humanoid shape, Tablet interface; Height: 120 cm; Payload: ~1–2 kg	~$50,000	SoftBank Robotics [44]
RealAnt		Reinforcement learning, quadruped research	Quadruped walking robot; Open source, lightweight; Height: ~10 cm; Payload: ~200 g	~$410	Boney *et al.* [45]
SMARTmBOT		ROS2 education, mobile robotics	ROS2 based, swarm support; Open-source, modular; Height: ~8 cm; Payload: ~500 g	~$210	Jo *et al.* [46]
iCub		Embodied cognition, advanced robotics	53 DoF, humanoid shape; Full sensory suite; Height: 104 cm; Payload: ~2–3 kg (arms)	~$270,000	Robots Guide [47]
Scribbler		Intro to CS/programming	Line/sound sensors; GUI or Python control; Height: ~7 cm; Payload: Minimal (light objects)	~$100	Miller and Robila *et al.* [48]
Wakamaru		Elder care, social communication	Speech recognition, internet access- Human interaction roles; Height: 100 cm; Payload: ~1 kg	~$15,000	Mitsubishi Heavy Industries [49]
Dbot		Classroom Teaching, social communication	31 DoF, humanoid shape, speech recognition, workspace: classroom, Height: 130 cm, Weight: 17 KG; Biped; Payload: ~500 g (arms).	~$5000	This study

D. Comparison with Other Educational Robots

There are two main purposes of using robots in the classroom: learning and teaching. Learning purpose robots are used to teach students how robots work and how to program those robots. On the other hand, the robots for classroom teaching are robots that are used as a teacher or instructor or as a facilitator to assist with teaching in the classroom environment. Teaching robots should be able to share and discuss classroom content and interact with students. If a humanoid robot wants to perform like a classroom teacher, the shape and size should be as close as possible to a human being in terms of size and appearance. Most importantly, it should not be beyond the buying capacity of schools or the institutions aiming to use them in the classroom.

While the comparison includes a variety of educational robots, Table V emphasizes humanoid robots used in educational contexts. Among the ten robots listed in the table, NAO, Pepper, and iCub stand out as humanoid platforms designed for advanced learning, human-robot interaction, and cognitive research.

NAO, widely adopted in schools and research labs, offers speech, facial recognition, and multi-language support, making it suitable for teaching programming, AI, and social interaction. Pepper extrends these capabilities with emotion recognition and a built-in tablet, often used in social robotics, therapy, and inclusive education. iCub, the most advanced in the list, is primarily used in research on embodied cognition, developmental learning, and neuroscience due to its full-body sensory and motor systems.

These humanoid robots are more expensive (ranging from ~$11,000 to ~$270,000) but offer rich, multimodal interaction experiences that go beyond basic coding, fostering deeper engagement in subjects like psychology, robotics, and linguistics. Their human-like form and behavior also make them powerful tools for inclusive and emotional learning environments. In contrast, entry-level robots like Bee-Bot and Thymio II, LEGO Mindstorms EV3 are affordable, compact, and ideal for introducing basic programming concepts through visual or tactile interfaces. Open-source mobile robots like SMARTmBOT and RealAnt support ROS2 and reinforcement learning, making them ideal for undergraduate robotics and AI experimentation. However, despite being loaded with numerous features, these low-cost educational robots can't be used for classroom teaching because of their size, shape, and scope. Because NAO has only 66 cm height with 25 DOF, Pepper is a semi-humanoid robot with 17 DOF is suitable for classroom teaching purposes, but the cost is so high ($50K), other low-cost educational robots like Bee-Bot, Thymio II, SMARTmBOT, and RealAnt don't have a human-like shape and height, and also their scope is different. These robots are only for learning programming in robotics and learning the robotics technology in classroom or lab, however, cannot be used for the purpose of classroom teaching. Dbot, on the other hand, is designed to be used for the purpose of classroom teaching since it has a 31 DOF humanoid body that ensures human-like gestures. A speech recognition system allows interaction with the students. Since a human-sized high-end humanoid robot from industry is highly expensive, it may be difficult to afford and deploy such robots in classroom teaching activities. Dbot, in this context, presents an affordable solution for classroom instruction.

V. Conclusion

Full-size humanoid robots are expensive as they are aimed at mimicking natural human activities developed through high-end sensors, mechanical structures, and delicate hardware. This article presented a detailed design and approach for a lightweight humanoid robot featuring a low-cost or cost-effective development. It provides a detailed description of the electro-mechanical design highlighting the stages of development. At the end a comparison is conducted to validate the performance, and the robot is deployed in a real-life test environment to observe the outcome. Analysis of the data and results suggest that the proposed design can perform basic human activities with limited motions that are sufficient for the classroom teaching environment and suitable for relevant applications involving social interactions. This development has been proved to be a cost-effective solution for low income or underdeveloped countries where the cost might matter. However, this article presents some areas of improvement for the future. Mechanical and hardware development have been highlighted in this article; the control and software have scopes of improvement in terms of smoother performance and further adoptability in motion. Furthermore, future AI based pretrained transformers deployed in Dbot with smoother physical humanoid appearance can address the integration of intelligence and human-like activities in teaching-learning environments.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

MHI conducted the experiment and drafted the original article; TB analyzed the data and reviewed the article; KS drafted the original article and conducted multiple revisions; IM performed the validation of methodology and proofreading of the article; all authors had approved the final version.

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