Modeling and Design for a Wireless Bipedal Robot

Ojasvi Tak1, a), Yogesh Giri1, b), Sindhu Hak Gupta1, c), Ashwani Kumar Dubey1, d), Tse-Kian Neo2, 3, e) and Angela Amphawan4, f)

1Department of Electronics And Communication Engineering, Amity School Of Engineering And Technology, Noida, Uttar Pradesh, India

2 Faculty of Creative Multimedia, Multimedia University, Persiaran Multimedia, 63100, Cyberjaya, Selangor, Malaysia.

3 Centre for Innovative and Immersive Technology, CoE for Immersive Experience, Multimedia University, Persiaran Multimedia, 63100, Cyberjaya, Selangor, Malaysia.

*4 Smart Photonics Research Laboratory, School of Engineering and Technology, Sunway University, 47500 Petaling Jaya, Selangor, Malaysia.*

*e)Corresponding author: tkneo@mmu.edu.my*

*a)ojasvi.tak@s.amity.edu*

*b)yogesh.giri@s.amity.edu*

*c)shak@amity.edu*

*d)dubey1ak@gmail.com*

*f)angelaa@sunway.edu.my*

**Abstract.** This paper highlights the design of POCO (Point Contact), a bipedal robot that utilizes a combination of serial and parallel leg mechanisms i.e. hybrid mechanism. The design includes three degrees of freedom (DOF) in each leg and a round foot with point contact using Autodesk Fusion 360 software. A four-bar parallel link mechanism is employed to enhance the movement of the lower leg and provide higher stability as compared to a three-bar linkage mechanism. Based on CAD modeling and mechanical design assumptions, the robot is expected to maintain posture stability during stepping on uneven terrain. Bearings are installed in the hip and femur joints for smooth and enhanced movement increasing its durability over time. Key features include magnetic suspension designed in the four-bar linkage for shock absorption, specifically in uneven terrain or for sudden impacts, limit switches in the foot for foot contact detection. Bearings provide smooth movement to the servo-controlled 3-D printed legs and increase their efficiency for long-term use. This work focuses on the common challenges faced by bipedal robot instability and is a cost-effective approach for real-world applications by using CAD tools in robotic design.

# introduction

The design of leg mechanisms for bipedal robots or a two-legged robot has been a major focus in robotics research, to achieve stable, efficient, and adaptable locomotion keeping in mind cost-effectiveness. Over the years, various leg designs have been proposed, each addressing unique challenges and contributing to the advancements of bipedal robots. In this paper an innovative design approach of a bipedal robot named “POCO” (Point Contact) featuring a 3 DoF (Degree of freedom), round foot for point contact, 3D CAD model with a magnetic suspension in a 4-bar linkage mechanism for absorbing shocks while walking on rough terrains and bearings installed in the hip and femur joints for smooth movements reducing wear and tear seen in belt mechanism. The four-bar linkage mechanism with magnetic suspension in the support link is visible through the front and back orthographic view in Figure 1. An organized framework for leg design, as outlined in [1], guides the systematic development of mechanical and dynamic features to increase performance. Designing a 3 DoF leg in POCO is an initial step in building the legs making it easier to design, for simplicity and ease in controlling further. A notable trend in [2], such as the 3-D printed, 3 DoF leg with a round foot and a pulley system for lower leg movement, which is a great inspiration for our work. Different linkage mechanisms have been used till now which help in the movement of legs with 3-D printed parts or maybe with other materials like carbon fibers incorporated into a 5-bar hybrid linkage mechanism in [3] which emphasizes the role of lightweight yet robust materials in increasing leg efficiency. Despite the great usage and advancements of 3-D printed parts in robotic industries, there are issues faced by it for e.g in designing the lead screw mechanism in [4] due to limitations of 3D printed components, they shifted the design to a 4-bar linkage mechanism with bearings mounted at the hip joints. A slider-crank mechanism integrated with belts for lower leg movement in [5] represents an efficient approach whereas a lightweight parallel linkage mechanism is used in [6] to decrease the weight of the robot maintaining its structural coherence overall. Our research focuses on the leg design of a bird whose legs are bent backward contrary to humans. A great effort on mimicking the human leg design has been seen in [7] which is a design on a humanoid robot presenting 12 DoF and lead screw mechanisms powered by DC motors. For actuating legs with great stability, flexibility, and smooth movement, various actuators are used for control.

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |

**FIGURE 1.** Designed bipedal robot POCO (a) front view (b) back view

Some of these approaches comprise electro-pneumatic actuators along with the design of a series elastic actuator in the hip joint as seen in [8], focus on flexibility and smooth control. BLDC motors and AC motors are generally seen as actuation in advanced projects for high precision and control. Linear actuators with DC motors are seen in ADDAM [9], a very highly advanced humanoid robot. Furthermore, the use of AC motors for upper leg movement and a variable hydraulic damper at the knee joint is seen in [10] for reducing impact forces. But here we are using a high-torque servo motor with precision control and a cost-effective approach. Servo motors, if used with bearings, provide smoother movement to the legs which increases its efficiency whereas some of the work has been seen in the integration of bearings with a pulley system instead of a linkage mechanism as seen in the hyper leg mechanism developed by Japan in [11], there are bearings and pulleys at the hip and knee joints to move without mechanical stress. However, the pulley system may cause wear and tear and might not be feasible for the long term. So here we prefer the linkage mechanism over the pulley system. Many of these mechanisms are applying the D-H rule for kinematic behavior modeling, as explained in [12]. Autodesk Fusion 360 is a reliable, easy-to-use software that helped design the biped precisely by limiting motions in joints. For shock absorption, magnetic suspension has been used in our design that is built up in the parallel link itself for improving efficiency while the robot is walking. There is no high heat dissipation in our bipedal robot, so it is safe to use magnetic suspension here. Some of the alternatives like torsion springs have been observed in the femur pulley system in [13] and as a support link in the four-bar linkage mechanism in [14] for improving efficiency and shock absorptions. Compared to existing studies, this paper addresses several critical gaps in bipedal robot design, particularly emphasizing cost-effectiveness, robustness, and efficient shock absorption. Unlike conventional designs relying on pulley mechanisms, heavy actuators, or expensive force sensors in feet, our approach introduces a lightweight four-bar linkage mechanism with integrated magnetic suspension, precision servo motors, and an implementation of limit switches to reliably detect foot-ground contact. Additionally, Autodesk Fusion 360 is uniquely utilized for precise joint control and optimization, significantly advancing practical applications. The paper is divided into 5 sections starting with Section II which includes Robot design and specifications, section III includes Methodology, section IV Results, and Section V as Conclusions and Future Works.

# ROBOT DESIGN AND SPECIFICATIONS

## Poco Geometry

The design approach for POCO emphasizes modularity, lightweight construction, ease of manufacturing, and the ability for quick repairs and reproduction. The robot's structure consists of a central body module (core) and two identical legs, each with three degrees of freedom (see Table 1). The 3-D printed components of POCO weigh approximately 1.37 kg, and the robot stands 0.337 meters tall from the ground to the top of its torso (see Table 2). The estimated weight of components calculated here is derived from Ultimaker Cura. This is a user-friendly software that slices a 3D model uploaded in .stl format. Slicing means converting a 3-D model (.STL or .OBJ files) into thin layers that a 3-D printer can print at a time. This slicing is done through G-code instructions generated by the software automatically without human intervention and given to 3-D printers for printing 3-D models.

The length of the components of the legs is taken in such a way because of the following calculations (all the weights here are estimated from Ultimaker Cura software). The torque rating of the selected Pro range servo motor is 20 kg-cm, meaning it can exert a force equivalent to 20 kg at a 1 cm distance.

|  |  |  |
| --- | --- | --- |
| **TABLE 1.** Physical parameters | | |
| **Parameters** | **Value** | **Units** |
| Mass (only 3D printed parts) | 1371 | g |
| Body Heights | 33.7 | cm |
| Body width | 17.6 | cm |
| Upper leg length | 19.1 | cm |
| Lower leg length | 23.27 | cm |
| Servo attachment length | 5.54 | cm |
| Connecting rod length | 14.5 | cm |
| Outer Diameter of suspension | 2.3 | cm |
| Inner Diameter of suspension | 1.4 | cm |

|  |  |  |
| --- | --- | --- |
| **TABLE 2.** Weight of components | | |
| **S. No.** | **Component** | **Weight** |
| 1. | Upper Leg W₁ | 70g |
| 2. | Lower Leg W₂ | 83g |
| 3. | Other attached parts W₃ | 79g |
| 4. | Servos W₄ | 70g x 2 = 140g |
|  | Total (W) = W₁ + W₂ + W₃ + W₄ | 372g |

*Torque* (1)

Hence, (2)

The torque analysis indicated that Servo motors comfortably meet operational requirements. Specifically, the torque capability assessment revealed that the selected servos adequately support their intended loads: Servo 1 effectively supports 372g, Servo 2 sufficiently manages 253g, and Servo 3 reliably handles calculated loads demonstrating safe operational conditions within the defined mechanical constraints and design specifications ). From the above calculations (see Equations (1) and (2)) servo motor will be able to handle the weight of the robot and the length of the robot’s legs and other components will not create a barrier to it. With this length and weight robot will be able to walk with ease after assembly.

## Center of Mass Calculation

The center of mass (CoM) of an object is the point at which the entire mass of the body can be considered concentrated, serving as the average position of all the mass within the object. In physics and engineering, understanding the center of mass is crucial, as it determines stability, balance, and motion behavior. Objects supported or pivoted below their CoM remain stable, while incorrect positioning can cause imbalance or failure, making accurate CoM calculations essential in mechanical design, robotics, automotive engineering, and structural analysis. The coordinates of the Center of Mass (CoM) are calculated using:

(3)

(4)

(5)

Where:

• mi is the mass of each component

• xi, yi, and zi are the respective coordinates of CoM of each component.

Using Equations (3), (4) and (5):

*X-coordinate of CoM:* -474.72/1549 = -3.065 cm

*Y-coordinate of CoM:* 6053.41/1549 = 3.91 cm

*Z-coordinate of CoM:* 6262.15/1549 = 4.04 cm

*Final Center of Mass (CoM):* (Xcom, Ycom, Zcom) = (-3.07, 3.91, 4.04)

## Leg Design

Each leg has three DoF thanks to the leg design's four-bar linkage mechanism, which is divided into five separate sections: the thigh, lower leg, hip flexion, hip abduction, and connecting rod with integrated magnetic suspension. Three Pro Range servo motors of torque 20 kg-cm are positioned at the hip abduction, hip flexion, and thigh segments to power the leg's movement. As shown in Figure 2, the servo motor is housed in a support structure that connects the upper leg, or thigh, to the hip flexion section. With the help of a bearing, which reduces friction and permits fluid motion at the joint, this construction is made to enable smooth movement, improving movement efficiency overall. Another servo motor is mounted directly to the hip at the hip flexion component, which incorporates a bearing to allow for side-to-side movement. This motor provides a vital component of stability during intricate movements like walking or turning. To connect it to the connecting rod that runs to one end of the lower leg, a third servo motor is also placed inside the thigh. The exact control of the robot's leg motions, which allows it to execute intricate tasks with great precision, depends on the placement and integration of these motors.

|  |
| --- |
| Inserting image... |
| **FIGURE 2.** Bearings and servo motors (orange) covered through components |

In Figure 3, the four links are visible as mentioned. The thigh part of the leg which houses the servo motor is considered Link-1. The servo motor placed in link-1 has a servo attachment which helps to convert the rotational force of the motor into motion attached to it which is labelled as Link-2. The attachment is further connected to the connecting rod in which magnetic suspension is present that is helpful for stability and flexibility to the movement of legs, this is labeled as Link-3. The last link of the leg is the lower leg with a round foot for point contact which is labeled as Link-4. This 4-bar linkage mechanism increases power efficiency as the motor load is divided into the links and shocks are reduced due to bearings and magnetic suspension. Since screws hold these links together, there is a hole provided in that section where a screw may be inserted. When these parts are 3-D printed, screws are going to be placed wherever necessary for the assembly of the robot. The connecting rod is equipped with a magnetic suspension system as seen in Figure 4 where the rod has three parts. The upper and lower parts of the connecting rod have magnets placed in it with the same pole and a shield to cover these two parts. The shield serves to securely cover both components, ensuring they remain in place and reducing the risk of misalignment. Magnetic suspension is a key feature that significantly enhances the robot’s performance. This magnetic suspension reduces disruptions during movement by cushioning shocks and jerks, enhancing stability and lessening wear on mechanical parts. It also guarantees more fluid functioning, particularly when the robot is traversing uneven ground or is struck suddenly. The robot's overall performance and stability are improved.

|  |  |
| --- | --- |
|  |  |
| (a) | (b) |
| **FIGURE 3.** Four Bar Linkage Mechanism (a) Normal view and (b) Exploded view | |

## Torso Design

The torso or upper body is designed as such that the robot can balance and stand stable.

1. *Design and dimensions:* The torso of the bipedal robot is crucial for storing critical components such as a Raspberry Pi, vision cameras, and a lithium-ion battery. All necessary subsystems are efficiently arranged and secured within the torso's small, rectangular shape. Its dimensions are 11.765 cm in height, 13.83 cm in breadth, and 16 cm in length. Both the back and the sides of the torso include ventilation holes to promote passive airflow and heat dissipation from the Raspberry Pi and other heat-sensitive components. The passive cooling system maintains the interior temperature within acceptable ranges even during prolonged work.
2. *Impact of CoM on Stability:* The robot may attain a more stable position and lessen the chance of tipping while moving by optimizing the CoM. Smooth and steady movement is made possible by a well-balanced torso with a low and centrally positioned CoM, which guarantees that the robot's legs carry a constant load.

# METHODOLOGY

## Design of the Bipedal Robot

The first step was to design the general construction of the robot. To increase gait efficiency, a hybrid leg shape that combines parallel and serial mechanisms was chosen. The upper leg and lower leg were the two major pieces that made up the leg design. The design process is shown in Figure 4.

The bipedal robot's intricate 3D CAD model was made with Autodesk Fusion 360. Separate components were modelled, including the torso, upper and lower legs, joints, and foot pads. The thigh part of the leg or femur and hip joints were equipped with bearings to guarantee durability and smooth rotation while in use.

*Incorporating Mechanical Elements:* For the legs to absorb shocks while moving, a four-bar linkage mechanism with magnetic suspension was created. To guarantee smooth and controlled shank movements, the linkage system was carefully aligned before the magnetic suspension was installed at the knee joint.

*Choosing Materials And 3D Printing:* For future 3D printing prototypes, PLA filament is recommended due to its ease of availability. Every part was made to be 3D printed in a modular way so that the actual prototype could be assembled and tested with ease.

A diagram of a process

AI-generated content may be incorrect.

**FIGURE 4.** Methodology for design

*Estimating Mass And Distributing Weight:* To provide realistic simulations, a mass value was calculated through Ultimaker Cura software for each component of the robot and mentioned in Table 2.

The expected payloads including all electronic components is approx. 500g (including batteries, buck converters, raspberry pi)*.*

# RESULTS

The calculated coordinates for the Center of Mass (CoM) of the designed bipedal robot POCO are presented below:

X-coordinate: Xcom = -3.065 cm

Y-coordinate: Ycom = 3.91 cm

Z-coordinate: Zcom = 4.04 cm

Thus, the final calculated Center of Mass for the bipedal robot is: Xcom, Ycom, Zcom = (-3.07, 3.91, 4.04).

* The determined position of the CoM significantly contributes to the stability and balance of the robot, which is especially important during locomotion and interactions with varying terrains. The low and centralized placement of the CoM ensures minimal risk of tipping, enhances gait stability, and provides efficient weight distribution across the robot’s structural components. These results are validated through simulations conducted using MATLAB software (see Figures 5 (a) and (b)), where the positioning of the CoM aligns closely with theoretical predictions, ensuring confidence in the design’s performance in real-world applications. Hardware implementation is shown in Figure 5(c).

|  |  |
| --- | --- |
| (a) | (b) |
|  | \\ |
| (c)  **FIGURE 5.** 3D model showing CoM on bipedal robot on MATLAB software and hardware implementation | |

# COnclusion

This work offers a thorough design of a bipedal robot, highlighting its unique characteristics including three degrees of freedom in each leg, a 4-bar linkage mechanism, a point-contact foot, limit switch in foot for contact detection, and an integrated magnetic suspension system for improved stability and shock absorption according to CAD modelling and mechanical constraints assumptions. The modular design demonstrates a strong approach to robotic engineering by enabling easy installation and maintenance in addition to efficient mobility. The complete 3D CAD model was developed using Autodesk Fusion 360 with estimated physical parameters and center of mass calculations, demonstrating the robot’s feasibility and readiness for future simulation and prototyping. These outcomes provide a concrete foundation for hardware realization and control integration. In the future, concentration will be on simulating the design in software like MuJoCo or MATLAB, hardware construction of the robot by 3D printing the design created in this paper through a 3D printer, assembling its components with electronic components like microcontrollers, camera modules, etc. and applying reinforcement learning algorithms to enhance its autonomous capabilities. By using the knowledge gathered from this design, the robot's capacity to adapt to different terrains and dynamic surroundings will be improved. The practical application for this project focuses on domains including industrial automation, personal support, and search and rescue in disastrous places.

# ACKNOWLEDGEMENT AND FUNDING

We would like to acknowledge the support of TM R&D Grant (RDTC/231106; MMUE/230053) from TM R&D Sdn. Bhd., MMU and thank the members for their contribution and collaboration towards this research publication.

# References

1. S. Rezazadeh, A. Abate, R.L. Hatton, and J.W. Hurst, “Robot Leg Design: A Constructive Framework,” IEEE Access **6**, 54369–54387 (2018).
2. G. Mothish, K. Rajgopal, R. Kola, M. Tayal, and S. Kolathaya, “Stoch BiRo: Design and Control of a Low-Cost Bipedal Robot,” in *2024 10th International Conference on Control, Automation and Robotics (ICCAR)*, (IEEE, Orchard District, Singapore, 2024), pp. 135–140.
3. K.G. Gim, J. Kim, and K. Yamane, “Design and Fabrication of a Bipedal Robot Using Serial-Parallel Hybrid Leg Mechanism,” in *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, (IEEE, Madrid, 2018), pp. 5095–5100.
4. M. Haywood and F. Sahin, "A novel 3D printed leg design for a biped robot," in Proc. IEEE Conf. Electr. Microelectron. Eng., Rochester, NY, USA, (2024).
5. C. Fisher, and N. Weiss, “A Simulation Based Approach to Designing a Bipedal Robot,” in *2023 21st International Conference on Advanced Robotics (ICAR)*, (IEEE, Abu Dhabi, United Arab Emirates, 2023), pp. 199–205.
6. Y. Tazaki, “Parallel Link-based Light-Weight Leg Design for Bipedal Robots,” in *2019 IEEE-RAS 19th International Conference on Humanoid Robots (Humanoids)*, (IEEE, Toronto, ON, Canada, 2019), pp. 565–571.
7. F. Sun, H. Ju, and P. Cui, "A new 12 DOF biped robot's mechanical design," in Proc. IEEERAS Int. Conf. Humanoid Robots (Humanoids), Toronto, Canada, Oct. (2019).
8. Y. Liu, X. Zang, Z. Lin, and J. Zhao, “Concept and design of a lightweight biped robot for walking on rough terrain,” in *2017 IEEE International Conference on Robotics and Biomimetics (ROBIO)*, (IEEE, Macau, 2017), pp. 1240–1245.
9. Y. Lee, "A biomimetic biped robot with a coupled link mechanism and endoskeleton framework," in Proc. IEEE Int. Symp. Robot Human Interact. Commun., Gyeongju, Korea, (Aug. 2013).
10. D. Huang, W. Fan, Y. Liu, and T. Liu, “Design of a Humanoid Bipedal Robot Based on Kinematics and Dynamics Analysis of Human Lower Limbs,” in *2020 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, (IEEE, Boston, MA, USA, 2020), pp. 759–764.
11. D.-Y. Kim, S.-H. Yun, J.-K. Lee, J. Yoon, D. Nam, C.-Y. Maeng, and Y.-J. Kim, “HyperLeg: Biomechanics-Inspired High-DOF Leg and Toe Mechanism for Highly Dynamic Motions,” in *2024 IEEE International Conference on Robotics and Automation (ICRA)*, (IEEE, Yokohama, Japan, 2024), pp. 2456–2462.
12. W. Shujian, G. Zhiwei, C. Qiang, Q. Lei, S. Fengyi, and S. Zhehui, “Design of an Autonomous Biped Robot Based on Modularization,” in *2022 International Conference on Mechanical and Electronics Engineering (ICMEE)*, (IEEE, Xi’an, China, 2022), pp. 139–143.
13. A. Ming, S. Nozawa, R. Sato, Z. Yu, and M. Shimojo, "Development of leg mechanism using a knee joint with variable reduction ratio adaptive to load," in Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO), Shenzhen, China, (Dec. 2013).
14. S. Hiasa, R. Sato, A. Ming, F. Meng, H. Liu, X. Fan, X. Chen, Z. Yu, and Q. Huang, "Development of a bipedal robot with biarticular muscle-tendon complex between hip and knee joint," in *2018 IEEE International Conference on Cyborg and Bionic Systems (CBS)*, (IEEE, Shenzhen, 2018), pp. 391–396.