

Design of a hexapod for defence application

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Abstract. Natural hazards such as earthquakes and combat scenarios create challenging conditions including uneven terrain and poor visibility, making rescue operations, medical supply delivery, and area assessment highly dangerous for human responders. These problems limit the traditional methods of delaying support and threaten mission success. A bio-inspired hexapod robot with high-torque servo motors and a smart sensor suite provides an effective solution. It automatically navigates challenging terrain with low power consumption and can also locate individuals in Hidden location or hard-to-reach locations. It can be integrated with the GPS for the location finding and remote monitoring with its adaptive mobility means it can stay stable on the uneven surface. This enables medical supply delivery, threat area observation, and faster, safer, more structured rescue operations.

1 Introduction

Autonomous robotic systems are the forefront of the military's focus will be relate to critical missions in the environment, as their role in circumstances that will require quick response in areas that are out of reach or unsafe for human deployment is important. Most military operations with drones, robotics, and autonomous systems are equipped with some kind of toxic threat, low visibility, and unstable or unpredictable terrain conditions. Human deployed in these scenarios could present even more risk than the threat already on the ground. The ability to deploy remotely operated and autonomous robots capable of working in and around various hazardous environments and conditions would minimize risk for police and military personnel and improve effectiveness and safety on the ground.

Beyond the military and defense space, these emergent and autonomous robotic systems are being advanced by researchers from a variety of fields and can also help in disaster response situations such as a search and rescue operation in an earth quake zone after building collapse and structures coming down, or an industrial accident. In all of these situations wheeled and even tracked robots are often ineffective in rough terrain filled with blockages of human, industrial and/or natural origin. As such, the need for work urgency and moving expediently makes clear the need for legs or a hybrid of wheeled/tracked and legged for deployment and navigation [9].

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2 Literature Review

Zhang et al. [1] addressed the topic dealt with in this paper is that of the classical agricultural robot posed with the problem of uneven terrain, which thereby brings about inefficiency and crop damage. Hence, the authors have opted for the development of a hexapod robot with adaptive gait can maintain the stability and adjustable of the clearance. So, it may cater to different field conditions. The main challenge was to sustain energy-efficient movement on particular surfaces.

Bjelonic et al. [2] focused on enabling stable locomotion in Unstructured terrains were the focus of research since the typical control system cannot maintain stability. An internal proprioception control system for a new hexapod robot, Weaver, was developed with a hierarchy of inclination and impedance control. The main challenge was how to disengage stability from orienting on self-stabilizing locomotion while managing energy-efficient locomotion without external terrain data.

Williamson et al. (2016) – ACRA: Automated Terrain Characterization and Gait Adaptation [3] the problem lies in inefficient locomotion in legged robots caused by terrain variability; the proposed solution is characterizing the terrain in real-time, allowing for adaptive gait control. They developed an implementation of a hexapod robot able to adjust gait via stride length, leg height, using a gait-phase based on a novel method. The main problem is the processing and real-time analysis of sensor feedback with no prior knowledge of the terrain.

Ali Naser & Jihad Hajaj – Smart Hexapod for Search and Rescue [5] in this project main attention is on the problem that exists when the navigation difficult terrain during rescue missions. Their proposed solution is to build a 3D printed hexapod with a Raspberry Pi board and SG90 servo motors, all of which can be printed with an FDA-approved printed plastic. They constructed and programmed a fully functional robot that can autonomously walk using a tripod gait. The main challenge was limited access to resources and, from our current perspective, hardware limitations because of local occupation.

Krishna et al. (2014) - Design and Fabrication of a Hexapod Robot [6] in this Paper the authors research on the concept of difficulties due to uneven terrain areas, the authors had constructed a six-legged hexapod robot that has the capable to walk, turn and rotate easily with stable. The proposed solution which includes mechanical structure and embedded system design and that allows different direction motions. The first challenge was coordination of six limbs each with 3 DOF and a stable locomotion based hexapod robot.

Homberger et al. (2016) – Terrain-Dependent Hexapod Control with Vision [7] the paper presents a solution to the challenge of inefficient gait control and adaptability of hexapods to varied terrains by introducing a stereo vision system that characterizes the terrain. Their solution adapts: (i) Gait stiffness (ii) Stride height using visual features of terrain categorisation [4]. The main challenge in achieving this system is developing a terrain perception system that relies on real-time feedback and then introduces impedance control into the actuation of gait for best results.

Table 1. Comparative summary of hexapod platforms.

Parameter	Naser Hajaj & [5] 2023	Zhang et al. [1] 2024	Bjelonic et al. [2] 2018	Homberger et al. [7] 2016	Proposed
DOF	18 (3/leg)	18 (3/leg)	30 (5/leg)	30 (5/leg)	18 (3/leg)
Actuator	SG90 (~1.8 kg · cm)	Dynamixel MX-106T (8.4 N · m)	Dynamixel (high-torque)	Dynamixel (high-torque)	MG995 (~13 kg · cm)
Frame Material	PLA (3D-printed)	Carbon fibre + Al	Aluminium alloy	Aluminium alloy	Aluminium alloy
Control	RPi Zero W	OpenRB-150 + Jetson Nano	Embedded + PC	Embedded + stereo PC	ESP32 (standalone)
FK/IK model	None published	Non published	Full numerical	Full numerical	Full analytical
Wireless ctrl	Android app	ROS/laptop	Tethered	Tethered	(DH) Wi-Fi HTTP browser
Walking speed	Not reported	Reported	Reported	Reported	8.4 cm/s
Max slope	Not reported	17°	>30°	>30°	12°

3 Objective

- To design and develop a multi-terrain hexapod robotic system equipped and to aid military operations in snow environments. And to improve the safety features of the system so that it protects the robot and the soldiers who depend upon it.
- To transport life-saving supplies like food, medicines, and other materials to the isolated areas or high-risk locations and for emergency and rescue missions, to detect people in locations.
- For future consideration shall be waterproofing and upgraded sensors to boost robot performance and survivability in extreme conditions.

4 Methodology

4.1 Hardware details

The ESP32 microcontroller is at the core of the system and is the brain of the hexapod. The ESP32 microcontroller receives and manages the actual movement commands that are received from many sources (a traditional radio-control receiver, a Wi-Fi link, the onboard GPS module to allow for location aware movement to be achieved, etc.) and turns this input into gait instructions that are handed over to two PCA9685 PWM driver boards to generate the appropriate pulse-width modulation signals required to position all 18 servos (three per leg) about the three degrees of freedom of the robot (coxa yaw, femur pitch, tibia pitch).

Powering the system is a three-series, three-parallel (2S2P) lithium-ion battery pack rated nominally at 7.4 (8.4 V peak) and 8.4 Ah total capacity. This battery pack supplies a dedicated 6–7 V maintaining rail for the PCA9685 drivers to actuate the servos, and regulated 5 V output feeds the ESP32 and (or additional low-voltage electronics). It is important to have the high-current servo supply separated from the logic rail to ensure stable control signals are maintained during actuation when the hexapod is walking dynamically.

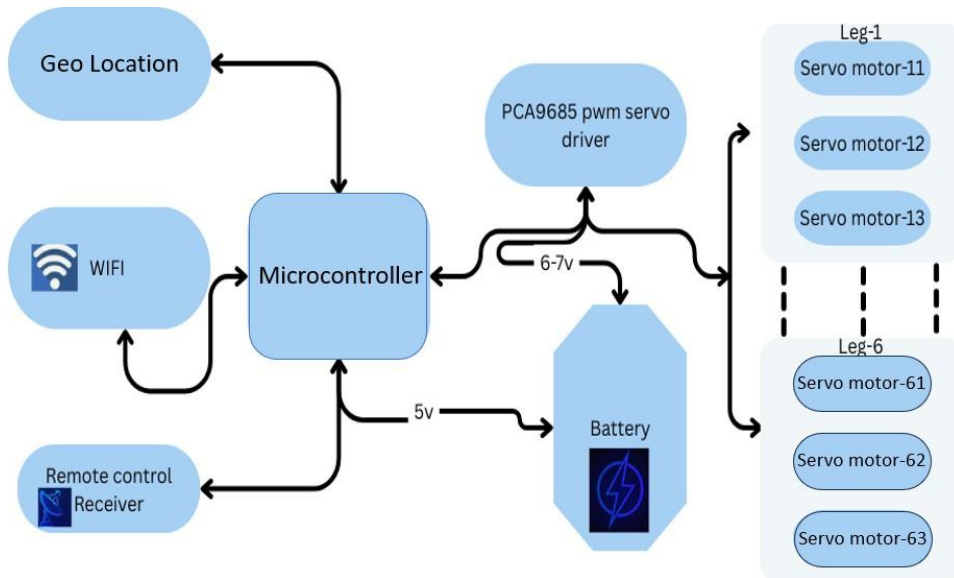


Fig. 1. Hexapod System Architecture

The frame is constructed with the iron plate with strong structure to make internally super thin parts creating a lightweight, and each leg assemble is labeled in the fig 4.1, from “Servo motor-11” to Servo motor-63 and plugs into the PCA9685 -PWM driver via I2C. This hardware design approach receives multiple tripodal gaits, can controlled by the mobile UI web-application.

4.1.1 Software Architecture

The below fig:4.2 flowchart starts with a initialization phase; where the ESP32 microcontroller powers up Serial port (115 200 bps) and checks for I2C bus alive or not with (pins 21 & 22), configures both PCA9685 PWM driver boards at 50 Hz-100Hz, and assign a position of a home-pose align (center-All) to the signal to leg move each of the six coxa, femur, and tibia servos into their neutral angles. Once the mechanics are centered, the system attempts a Wi-Fi association and will print to the Serial Monitor until it joins the network; it then prints its IP address. Next, the HTTP server calls bind four routes / (UI), /action, /test, and /servo, and calls server.begin(), while also sending the HTML control page to the any connecting client. [5] This includes documenting the development of the control system for the hexapod, which primarily involved first setting up the Esp32 and learning how to operate it with its along with a Embedded C programming environment, then researching motion planning algorithms for walking and planning, and then how to integrate sensors. The bug has code was written to drive the hexapod written and tested for performance and tweaked as needed to ensure it functions properly. Lastly, the controller was connected to the hardware of the hexapod, with motors to provide motion and integrate the sensors, to complete functionality of system.

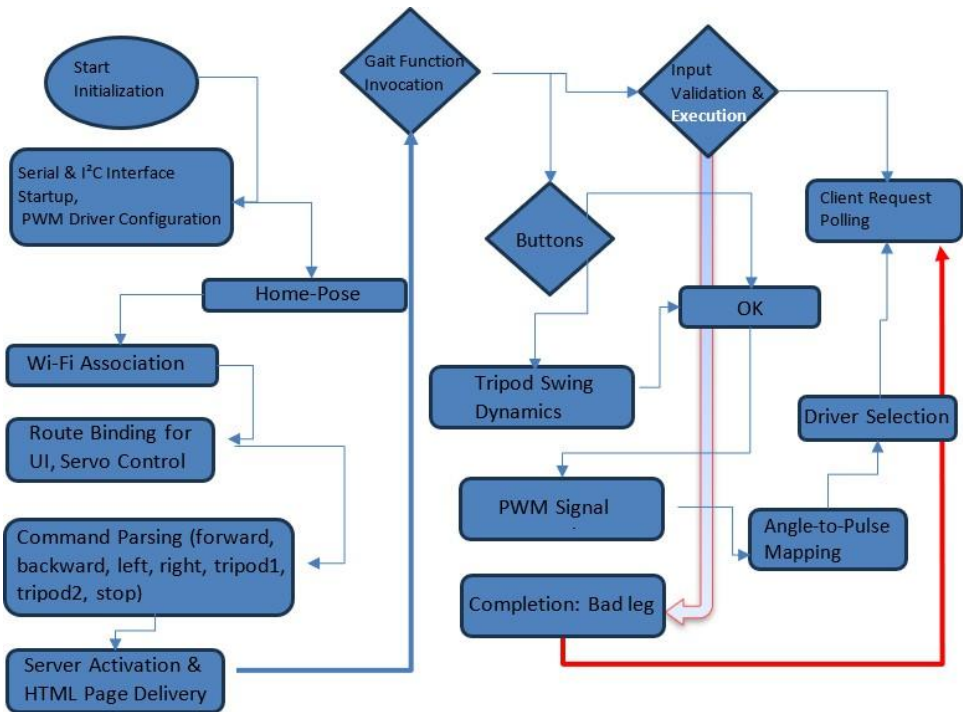


Fig. 2. Flow chart

4.2 Hardware Components

Microcontroller: The Microcontroller is a powerful and versatile for both Wi-fi and Bluetooth module developed by the Expressive system, designed for the IOT, embedded, and robotics application. It integrates a dual-core processor, rich peripherals, and wireless connectivity, making it ideal for advanced microcontroller-based projects like the hexapod robot.

PCA9685 PWM Servo Driver: PCA9685 PWM servo driver generates the PWM signals with the exact mark and space for moving the servo motors of the hexapod. Powered at 6-7V, it drives movements for six legs.

Servo Motors (MG995): Each leg on the hexapod has three for the hip, knee, and ankle joints to move in horizontal and vertical planes. These high-performance servos provide powerful leg movement to negotiate obstacles in agricultural fields.

Lithium Batteries: The hexapod system employs a lithium battery pack arranged in a 2-series and 2-parallel module, providing 7.2 volts at 5 amps, going directly to the PCA9685 servo driver for optimal performance, and then down to a voltage regulator to drop the 7.2 volts down to a safe 5 volts for the microcontroller Therefore, under any other scenario or field exercise, there is reliable musical performance in all elements when powered.

Hexapod Chassis Frame: Made with pre-drilled holes for servo motors, PCA9685 driver boards, batteries, and microcontrollers. Allows clean wiring and layout so that components don't interfere with one another while operating includes dedicated area or arms for legs, with enough space to allow legs to articulate.

Servo Horns and Screws: Servo Horns and Screws are critical accessories used to link the output shaft of servo motors to mechanical connections, arms, or structures. In a hexapod robot these accessories are important steps in passing the rotary motion of the servo motor into the legs of the robot for accurate and stable movement.

4.3 Mechanical Design

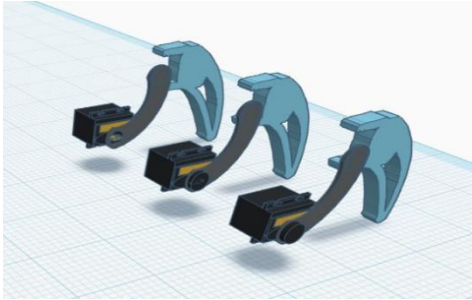


Fig. 3. Hexapod Sit

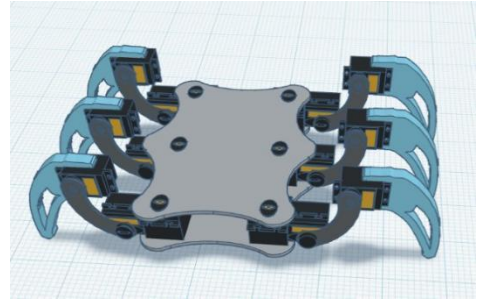


Fig. 4. Individual Legs

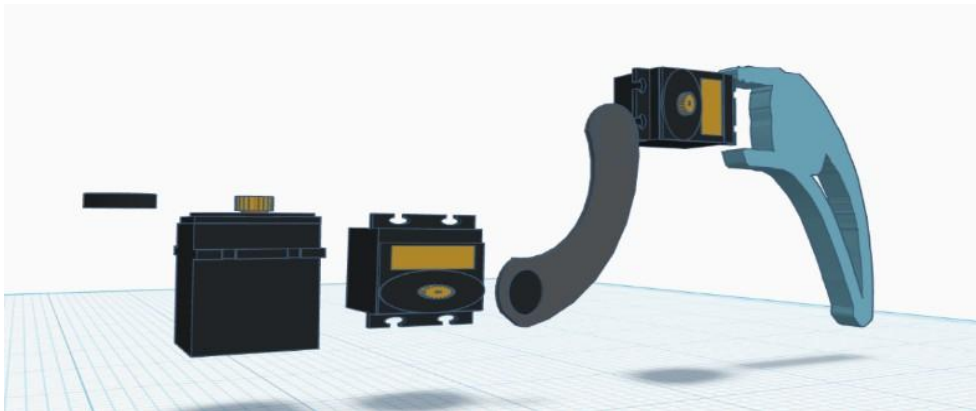


Fig. 5. Leg structure

[1] The motion system of the hexapod has the same specifications provided above, using three MG995 servos per leg to provide the horizontal hip rotation for forward/backward motion, vertical knee and ankle rotation to traverse obstructions like debris, small rocks, or ruts in crop fields. Unlike the 27 cm support rod with a 30° bend and 12V servos with an 8.4 Nm torque of the original design, my MG995 servos will operate at about 7.2V with an estimated 1.67 Nm (17 kg-cm) torque, and keeping all the same construction details with machined aluminum alloy connectors for stressed parts and additive manufactured non-stressed components because this methodology optimizes.

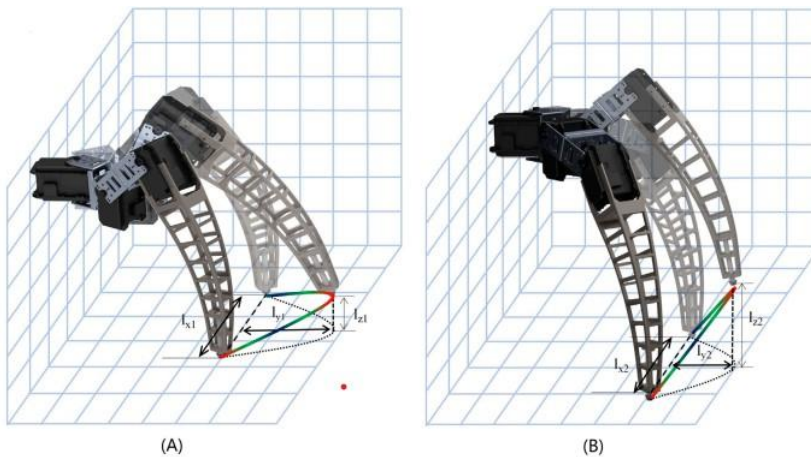


FIGURE 6
3D plot of the foot's trajectory. These figures show the trajectory of the end of the leg as it takes a step, where l_{x1} , l_{y1} , l_{z1} is the furthest distance outward and l_{x2} , l_{y2} , l_{z2} is the height at which the leg is raised. (A). The trajectory of the end of the leg in marching mode. (B). The trajectory of the end of the leg in step-over mode.

Fig. 6. Basic Kinematic Modelling of single leg

4.3.1 Kinematic Modelling

[1] This robot's control system employs an OpenRB-150 motion controller (which is programmed with the Arduino IDE) and a high-performance processor (a lightweight processor which does not sacrifice performance). The lightweight design and powerful processing of the processor allow for the real time processing of complex algorithms and camera image data used in a field application. [5] The tripod gait of hexapod robots, inspired by insects like cockroaches and ants, involves alternating two groups of three legs to achieve stable and continuous movement. Each group consists of the right front leg, right rear leg, and left middle leg, or the left front leg, left rear leg, and right middle leg, with one tripod lifting synchronously while the other remains grounded to support the body [11].

In this Hexapod robot the middle leg of acts as a pivot, with the front pulling leg's tibia and the rear pushing leg's tibia, causing the robot's body to slightly rotate around the middle foot of the hexapod body. This configuration will tell to ensures the center of gravity remains within the supporting of the tripod process, and allowing the robot features to start or stop at any time while following walking forward in a curved path. As shown in Figure 2, legs 2, 4, and 6 lift together initially, while legs of 1, 3, and 5 provide support, maintaining stability through a tripod-like-structure of the hexapod body[8][10].

The hexapod robot works in the half-step increments, works by the metal-gear servos, as the swing legs of (2,4,6) rule to supporting role upon landing, and the another supporting legs of (1,3,5) lift to become swing legs, then continuing this cycle. This tripod movements alternately works with phase S0 and S1, to enables continuous forward motion at a minimal constant speed, where S0 initiates the step and S1 occurs during the movement of equaling the steps of the length S. This hexapod robot is designed to use for stability and adaptable locomotion over a variety of uneven surfaces. This tripod gait mechanism will provides for both stability and the flexibility, which is to mimicking the correct walking style of the hexapod insects.

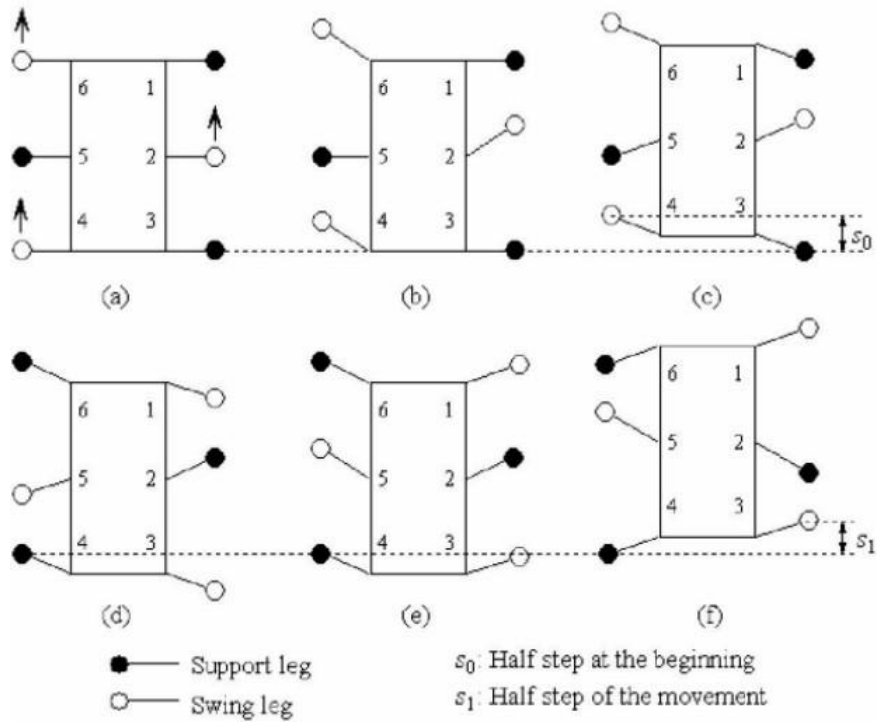


Fig. 7. Tripod gait of hexapod robo0074

4.3.2 Gait Algorithm Implementation

The hexapod gait mechanism has both static and dynamic walking with the gait algorithms to achieve the variety of uneven surface and to ensure the stable and the efficient movement. Coming to the Static gait, such as the tripod gait, rely on the stationary position on the uneven surface, while coming to the dynamic point of view gaits that allow for the consideration of speed on the flat surface, level surfaces, and can be provided the programmed and automated controls to achieve switching between walking patterns in the real time by using the esp32 board which is use to control with the wi-fi based technology after coded with the embedded c language, and also edit the code based on the varying condition.

4.3.2.1 The leg's anatomy and range of motion

The leg consists of three rigid components which include Tibia with a length of 120 mm (L3), Femur with a length of 66 mm (L2), and Coxa with a length of 52 mm (L1). The 3-DOF open kinematic chain structure of each limb exists because the three links in the limb connector through three revolute joints. The joint can serves the following purposes: There are horizontal azimuth swing around the vertical body axis will be represented by θ_1 in J1 (Coxa).

- J2 (Femur): the sagittal plane's angle of elevation θ_2
- J3 (Tibia): the tibia depression angle of the sagittal phase θ_3

4.3.2.2 Denavit-Hartenberg Parameters

The D-H convention will assigns for four parameters as per joint: A link length (a_i), link twist (α_i), joint offset (d_i), and joint angle (θ_i). Shown in the Table 2 lists the complete parameter set.

Table 2. D-H parameters for the 3-DOF hexapod leg.

Joint	a_i (mm)	α_i (deg)	d_i (mm)	θ_i
J1 — Coxa	52	90°	0	θ_1 (free)
J2 — Femur	66	0°	0	θ_2 (free)
J3 — Tibia	120	0°	0	θ_3 (free)

4.3.2.3 Forward Kinematics

Each adjacent frame can have transformation follows that the standard D-H form Here:

$${}^{i-1}T_i = \text{Rot}(z, \theta_i) \cdot \text{Trans}(z, d_i) \cdot \text{Trans}(x, a_i) \cdot \text{Rot}(x, \alpha_i) \quad (1)$$

The Substituting parameters are from each joint and multiplying the three matrices are (${}^0T_3 = {}^0T_1 \cdot {}^1T_2 \cdot {}^2T_3$), and the foot-tip position will be in the base frame as:

$$x = \cos \theta_1 \cdot 52 + 66 \cos \theta_2 + 120 \cos(\theta_2 + \theta_3) \quad [\text{mm}] \quad (2)$$

$$y = \sin \theta_1 \cdot 52 + 66 \cos \theta_2 + 120 \cos(\theta_2 + \theta_3) \quad [\text{mm}] \quad (3)$$

$$z = 66 \sin \theta_2 + 120 \sin(\theta_2 + \theta_3) \quad [\text{mm}] \quad (4)$$

Note: $c_{23} = \cos(\theta_2 + \theta_3)$ and $s_{23} = \sin(\theta_2 + \theta_3)$ throughout.

4.3.2.4 Inverse Kinematics

Given a target for foot position [x_e, y_e, z_e], and the joint angles are found in the closed form by using a four-step typed geometrical approach, computable in $O(1)$ time on the ESP32 within the 20 ms can be a control loop.

Step 1 — Azimuth angle:

$$\theta_1 = \text{atan2}(y_e, x_e) \quad (5)$$

Step 2 — Horizontal reach after Coxa offset:

$$r = \sqrt{x_e^2 + y_e^2} \quad (6)$$

$$r' = r - 52 \quad [\text{mm}] \quad (7)$$

Step 3 — Tibia angle via law of cosines:

$$D = r'^2 + z^2$$

$$\text{Cos } D^2 - 66^2 - 120^2 = D^2 - 18,766 \quad (8)$$

$$\theta_3 = 2 \times 66 \times 120 = 15,840 \quad (9)$$

$$\theta_3 = \text{atan2}(\pm \sqrt{1 - \cos^2 \theta_3}, \cos \theta_3) \quad (10)$$

This positive root gives the elbow-down (preferred) configuration for the maximum ground clearance in the equation.

Step 4 — Femur angle:

$$\theta_2 = \text{atan2}(z_e, r') - \text{atan2}(120 \sin \theta_3, 66 + 120 \cos \theta_3) \quad (11)$$

4.3.2.5 Joint Limit Constraints

The MG995 servo can operate over 0°–180° mechanical range. Firmware enforces the following operational limits here:

$$\theta_1 \in [-45^\circ, +45^\circ] \text{ (Coxa: lateral swing)} \quad (12)$$

$$\theta_2 \in [-60^\circ, +60^\circ] \text{ (Femur: elevation)} \quad (13)$$

$$\theta_3 \in [-90^\circ, +20^\circ] \text{ (Tibia: flexion)} \quad (14)$$

A target that poses is kinematically reachable only when $|\cos \theta_3| \leq 1$, which requires:

$$|D^2 - 18,756| \leq 15,840 \implies D \in [47.2 \text{ mm}, 190.8 \text{ mm}] \quad (15)$$

Any request outside this range will be rejected by the trajectory planner and interpolated to the nearest valid pose and it is to prevent servo stall. This feasibility check runs into under

0.1 ms on the ESP32 microcontroller.

4.3.2.6 Reachable Workspace

The Sampling $\theta_1 \in [-45^\circ, +45^\circ]$, $\theta_2 \in [-60^\circ, +60^\circ]$, and $\theta_3 \in [-90^\circ, +20^\circ]$ in 1° are the steps and applying the FK equations in yields for the partial-toroidal reachable to the volume with the following characteristics are here:

Horizontal state reach: $r_{\min} = 52 \text{ mm} \rightarrow r_{\max} = 238 \text{ mm}$

Vertical state range: -136 mm (below body) to $+100 \text{ mm}$ (above body) Workspace volume: $\approx 0.18 \text{ m}^3$

Ground clearance at the maximum reach can be approximately by 30 mm, exceeding the 25 mm obstacle can threshold set of the test protocol can be done. The workspace comfortably with supports in 80 mm stride length with in a 50% safety margin on the horizontal reach.

4.3.2.7 Joint Torque and Power

The Worst-case in quasi-static torque at the Femur joint (J2) then during swing phase with the leg fully extended:

$$\tau_{2_swing} = \frac{m_{leg}}{2} \times g \times \frac{L_2}{2} + L_3 = 0.0425 \times 9.81 \times (0.033 + 0.120) = 0.064 \text{ N}\cdot\text{m} \quad (16)$$

(5.9% of MG995 rated stall torque)

In Stance-phase the body support torque, The shared across three legs at a nominal 100 mm foot offset:

$$\tau_{stance} = \frac{M_{total} \times g \times r}{3} = \frac{2.0 \times 9.81}{3} \times 0.100 = 0.654 \text{ Nm} \text{ (60.6% of stall torque)} \quad (17)$$

These values can be confirmed the MG995 is a well-suited for the current mass budget. The most impactful route can be reducing the power consumption is lowering the effective foot offset r' during stance by adjusting body height can be via IK-guided posture control.

4.4 Actuation and Control System

The hexapod robot is used control system to employs an esp32 wroom module to drive motion controller (which is programmed with the Arduino IDE) and a high-performance metal-gear servos with the low voltage battery power. The lightweight design and powerful processing of the microcontroller that allow for the real time processing of complex algorithms and data used in a field application.

4.5 Power Management (Testing and Validation)

Average Over Five Cycles:

No Load Measurements:

Table 3. Average No Load Measurements

<u>Angle</u>	<u>Current (A)</u>	<u>Voltage (V)</u>
0	0.0327	6.376
90	0.0633	6.352
180	0.0987	6.330

With Load Measurements:

Table 4 Average With Load Measurements

<u>Angle</u>	<u>Current (A)</u>	<u>Voltage (V)</u>
0	0.1535	6.294
90	0.1323	6.308
180	0.0973	6.372

Power Consumption Comparison:

Table 5. Average Power Consumption Comparison

<u>Angle</u>	<u>No-Load Power (W)</u>	<u>With-Load Power (W)</u>	<u>Current Diff (A)</u>	<u>Voltage Diff (V)</u>	<u>Power Diff (W)</u>
0	0.210	1.020	0.1210	-0.084	0.810
90	0.428	0.864	0.0690	-0.054	0.436
180	0.648	0.650	-0.0013	0.040	0.004

Estimated Power for 18-Servos:

Table 6. Average Estimated Power for 18-Servos

Angle	No-Load Current (A)	No-Load Power (W)	With-Load Current (A)	With-Load Power (W)
0	0.588	3.768	2.766	18.342
90	1.140	7.706	2.382	15.532
180	1.776	11.662	1.754	11.714

4.5.1 Output Graph

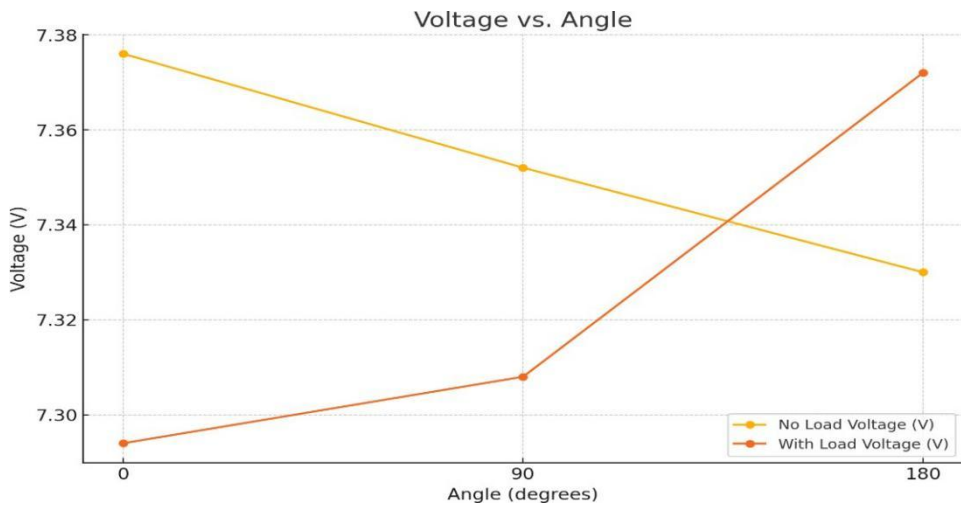


Fig. 8. Supply Voltage Variation Across Servo Angles

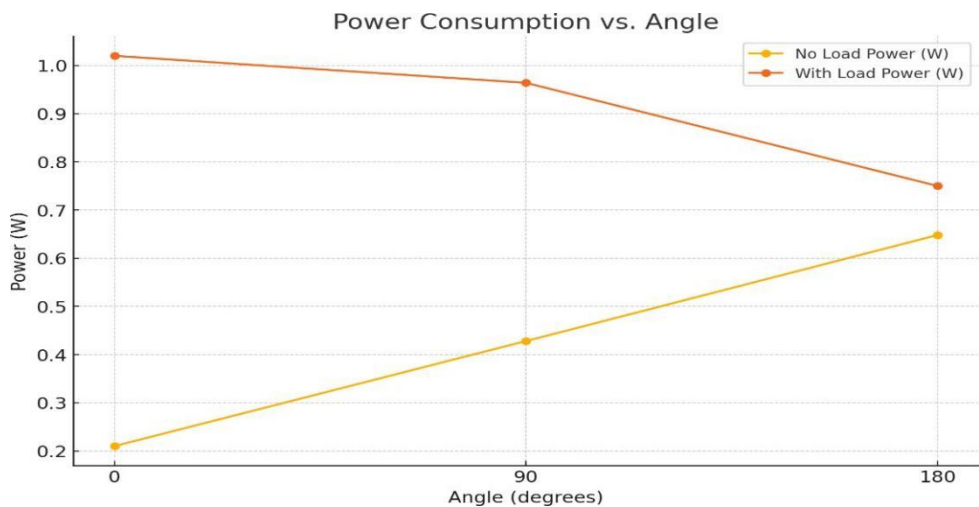


Fig. 9. Servo Power Draw Across Angular Positions

Conclusion

The bio-inspired hexapod robot will give an effective and innovative solution for the combat and rescue operations in uneven terrain. It has the ability to work with the Ui web application to control it by using the high-torque metal gear servo motors with the lightweight metal body. It has inbuilt GPS tracking on it used to locate the present area and it combined with advanced sensing capabilities, By enhancing the speed, safety, and efficient low power management to survive in the long way, This robot reduce the ricks faced by the human responder and it will improves the changes for saving lives during the critical situation. The hexapod robot has a terrain sensitivity mechanism which enables it to detect both ground contact and obstacles that include rocks and uneven surfaces. A limit switch sensor detects contact when the leg makes contact with an object before it reaches its original walking height and this contact stops the step function within the servo control system. The robot uses this mechanism to identify obstacles while its leg height automatically changes based on the surface it detects. The system functions through servo loop control logic which enables the robot to walk on uneven ground. The current state of this function exists at testing stage while future development will enhance its ability to detect terrain types and achieve stable movement.

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