Design of Hexapod Robot Using Inverse Kinematics for Educational Purpose

Kinley Penjor[1], Karma Tenzin[2], Tashi Namgyel Ghalley[3], Dechen Lhamo[4*]

Electronic and Communication Engineering Department, College of Science and Technology, Royal University of Bhutan,

E-mail: 02200246.cst@rub.edu.bt[1], 02200243.cst@rub.edu.bt[2], 02200260.cst@rub.edu.bt[3], dechenlhamo.cst@rub.edu.bt[4*]

Abstract

Hexapod robots are modern tools to support STEM education, enabling to determine movement trajectories by inverse kinematics and overcoming various obstacles with equal ease. Some are as simple as Quadrupeds, while others are as complex as Octopods, the latter being more intricate due to having more joints and limbs. They promote robotics and engineering, and evidence shows that they enhance learning when adopted as STEM instructional tools. However, the educational transformation in Bhutan does not offer opportunities for practicum, such as robot programming which aligns with His Majesty the King's vision and current strategies to enhance STEM education. Thus, the aim of this work is to construct a hexapod robot that allows students to study the design, inverse kinematics method, and several types of trajectory algorithms and mathematics. The assembly manual, as well as the code, will also be made available online for free on GitHub. For this reason, hexapod robots are crucial in STEM learning as it brings theory into practice.

Keywords: *Hexapod robot, Educational tool, Robotics, STEM education, Interactive learning.*

1. INTRODUCTION

For many years, researchers have studied multi-legged walking robots that mimic the limb anatomy and motion control of insects and other arthropod animals. Multi-legged robots offer advantages over wheeled motors when traversing uneven terrains, as they do not require continuous ground contact (Collins, 2016). The hexapod robot is one of the most common types of multi-legged robots. It has an advantage over a quadruped robot in that it can move across unstructured terrain with ease and maintain a static balance (Duan et al., 2009). This characteristic enables them to navigate through challenging environments more effectively, adapting to various surfaces and obstacles.

However, controlling those six legs becomes a challenging task due to many factors to monitor. An essential component of controlling a walking machine is gait. The robot's kinematics model and well-known walking laws from insect locomotion may serve as the foundation for gait synthesis (Duan et al., 2009). A significant amount of research has been conducted on hexapod robot control, including kinematics control and gait planning. Many researchers have implemented forward and inverse kinematics to control the movement and position of the Hexapod legs, allowing the robot to navigate efficiently.

Researchers have explored many approaches to solve the forward kinematics problem. Denavit and Hartenberg proposed a new method that included four parameters deemed necessary for the transformation procedure occured between two joints (Sharkawy and Khairullah, 2023). According to the required Cartesian route or trajectory, inverse kinematics (IK) generates the joint movements (Schmidt et al., 2014; Zang & Nelson, 2011, as cited in Rokbani et al., n.d.). Several methods for solving IK were examined for this type of application, as analytical solutions are often difficult, especially when the system has a large number of degrees of freedom. The design and development of such robots require extensive knowledge of science and mathematics that can be implemented in the educational system to provide a practical approach to learning.

Educators must recognize that stimulating children's attention during their early school years is essential for improving learning and cognitive processes. To this end, open-science strategies must be developed to ensure that educational achievements among the school-age population improve. The goal of the field of educational robotics is to design, build, and operate robotic prototypes. The NAO robot, the Phantom X Hexapod, and the LEGO® robotic kit are some of the robotic platforms that are currently implemented.

Hexapod robots can serve as educational tools that foster interest in robotics and engineering among students. One of the studies showed an enhancement of student learning and engagement in STEM festivals through the use of hexapods. Exhibiting the hexapods at STEM festivals can boost interest and learning opportunities about robots. The hexapod robot will employ inverse kinematics to control its movements. By utilising this technique, inverse kinematics allows accurate determination of the joint angles required for the desired endpoint positions. This approach ensures precise trajectory planning and execution, vital for tasks such as generating the angular movements in the implemented swivel gait.

Another advantage of the hexapod robotic system is its capability to serve as a research tool in addition to practical utilization, considering its pedagogy-related aspect. Applying hexapod mechanics to imitate biological organisms' movement can facilitate a deeper understanding of the movement flexibility of animals and their nervous systems. Chen et al. (2019) used hexapods to analyse the intricate patterns of multi-leg locomotion and drew some valuable insights into how bio-creatures can operate stably and efficiently using six or more limbs.

This work proposes the use of different gaits such as tripod gait, wave gait, quad gait, and bit gait for hexapod leg coordination in forward, backward, left, right and turning movements. To enable the robot to move more freely, inverse kinematics calculations are completed before the control method is applied to the robot. The traditional inverse kinematics methodology, where the computation is directly applied to the robot as part of the control algorithm, performs better in terms of time than this straightforward method. The work also aims to develop a user-friendly remote control that will communicate with the robot using the RF module to control the robot's motion and various other parameters, such as speed and distance from the ground.

The structure of this document is as follows. The hardware of the constructed hexapod utilized in this investigation is described in the next section, along with the locations of the servos in each leg and their measurements and motions. Section 3 then discusses the suggested strategy, such as how to coordinate the legs of a hexapod utilizing a tripod gait and a straightforward geometric method. The steps for the suggested tripod gait motions are explained in this section. Section 4 explains the inverse kinematics computations, while Section 5 elaborates on the experimental findings and discusses how the suggested technique was performed. The study's conclusions are presented in Section 6.

2. DESIGN

Fig. 4 below shows the final elliptical hexagonal design for the Hexapod body modelled using SolidWorks. According to Takahashi et al., (2000) they found that hexagonal robots can rotate and move in any direction simultaneously, better than rectangular ones, by comparing the stability margin and stroke in wave gait.

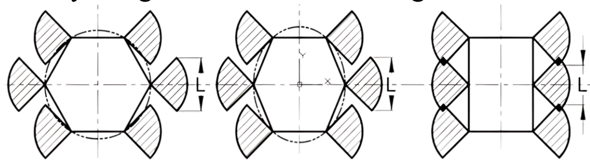

Fig.1: *Schematic Layout of Fuselage Layout.*

As per Manoonpong et al. (2021), most insects have a leg-length ratio of l:2:4 for the coxa, femur and tibia. This ratio is commonly found in the animal kingdom, shaping the legs of several insects such as ants, spiders, and flies. The long tibia enables the leg to reach the end effector position without much trouble, while the short coxa and femur make the leg stronger, more stable and efficient.

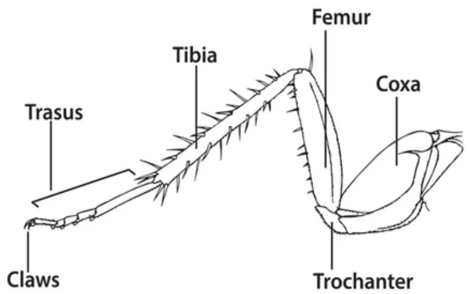

Fig.2: *Actual Insect Legs Labelling.*

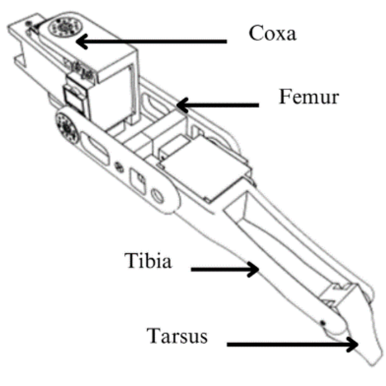

Fig.3: *SolidWorks Design and Labelling of Single Hexapod Leg.*

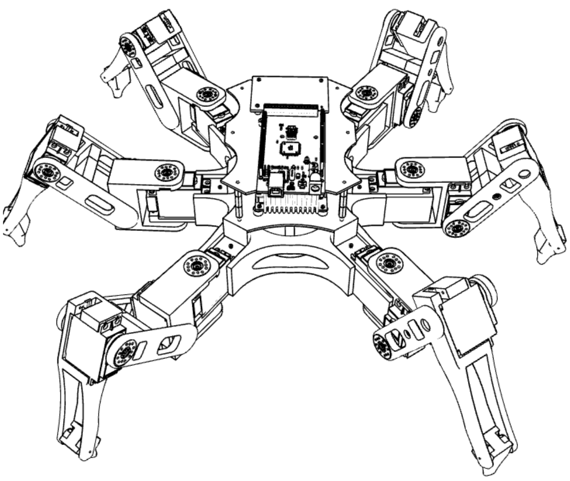

Fig.4: *Hexapod Robot Assembly in SolidWorks.*

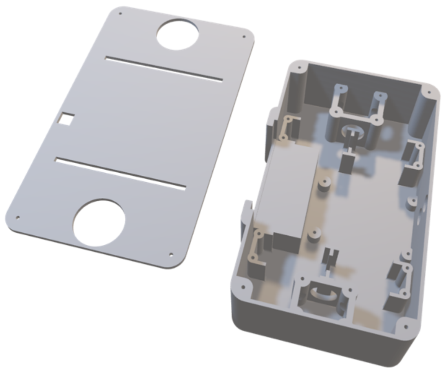

Fig.5: *Controller's Design for Hexapod.*

3. METHODOLOGY

Robot kinematics may be divided into two categories: forward and inverse kinematics. The forward kinematics problem is straightforward, and obtaining the equations is not hard. This means that the forward kinematics solution of a manipulator is always achievable. Inverse kinematics, on the other hand, presents a significantly greater challenge. The problem of inverse kinematics is computationally complicated and usually takes an extended period of time to solve, particularly when it comes to real-time robot control.

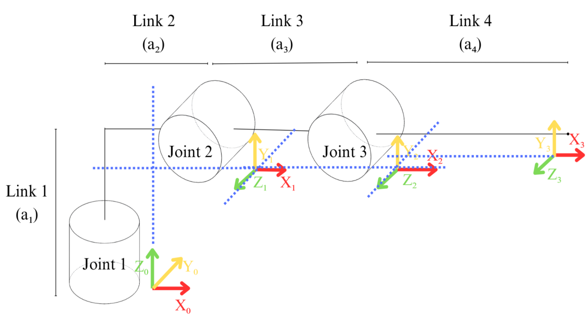

Fig.6: *Joint Allocation of Single Hexapod Leg.*

3.1 Denavit Hartenberg Method

Denavit-Hartenberg is one of the methods for determining the forward kinematics of any robot. The ability to operate a robotic movement is enabled by equations derived from Denavit-Hartenberg (D-H) frames. Fig. 6 shows the joint diagram of a single leg of the Hexapod.
Table 1 specifies the Denavit Hertenberg parameter for the hexapod robot. This parameter can be used to determine the end effector position of the robot's leg in the 3D coordinate system using the Homogeneous transformation matrix. It is deduced using the above diagram.

Table 1: *DH Parameters for Hexapod Leg.*

Joint i	θ	α	r	d
1	0	90	0	4
2	0	0	8	0
3	0	0	15	0

After specifying every necessary column in a suitable D-H parameter table for the robotic arm, the homogeneous transformation matrices need to be determined. The equation below shows the equation for calculating the coordinate transformation frame of the n^{th} frame.

$$H_n = \begin{pmatrix} \cos\theta_n & -\sin\theta_n \cos\alpha_n & \sin\theta_n \sin\alpha_n & r_n \cos\theta_n \\ \cos\theta_n & \cos\theta_n \cos\alpha_n & -\cos\theta_n \sin\alpha_n & r_n \sin\theta_n \\ 0 & \sin\alpha_n & \cos\alpha_n & d_n \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$H_{01} = \begin{pmatrix} \cos\theta_1 & -\sin\theta_1 \cos\alpha_1 & \sin\theta_1 \sin\alpha_1 & r_1 \cos\theta_1 \\ \cos\theta_1 & \cos\theta_1 \cos\alpha_1 & -\cos\theta_1 \sin\alpha_1 & r_1 \sin\theta_1 \\ 0 & \sin\alpha_1 & \cos\alpha_1 & d_1 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$H_{12} = \begin{pmatrix} \cos\theta_2 & -\sin\theta_2 \cos\alpha_2 & \sin\theta_2 \sin\alpha_2 & r_2 \cos\theta_2 \\ \cos\theta_1 & \cos\theta_2 \cos\alpha_2 & -\cos\theta_2 \sin\alpha_2 & r_2 \sin\theta_2 \\ 0 & \sin\alpha_2 & \cos\alpha_2 & d_2 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$H_{23} = \begin{pmatrix} \cos\theta_3 & -\sin\theta_3 \cos\alpha_3 & \sin\theta_3 \sin\alpha_3 & r_3 \cos\theta_3 \\ \cos\theta_3 & \cos\theta_3 \cos\alpha_3 & -\cos\theta_3 \sin\alpha_3 & r_3 \sin\theta_3 \\ 0 & \sin\alpha_3 & \cos\alpha_3 & d_3 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

All of the above transformation matrices are multiplied together to get the homogeneous transformation matrix from the base frame (frame 0) to the end-effector frame (frame 3) using the equation below.

$$T_0{}^3 = T_{01} \,.\, T_{12} \,.\, T_{23} \qquad (1a)$$

3.2 Inverse Kinematics

An analytical technique for converting Cartesian space to a joint space is called inverse kinematics. The link between the notions of a joint space geometry in a robot and the notion of coordinates, which are frequently employed to establish the location of an item, may be determined using the kinematics equation.

There are two different methods of obtaining the inverse kinematics (IK) in the robotic system. The first one is the analytical method which involves solving the IK algebraically to find a closed-form solution. The other one is the geometrical method, which involves the use of geometric relationships and visualization.

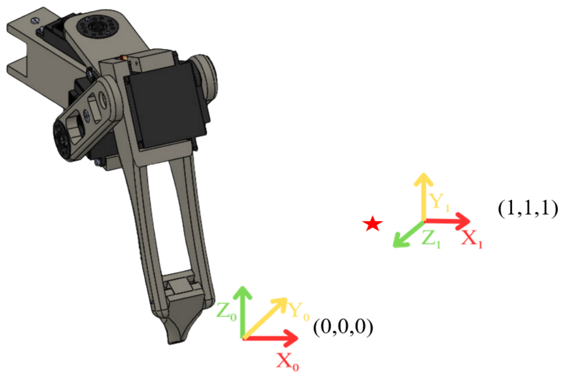

Fig.7: *Inverse Kinematics of Single Leg.*

In order for the leg of the robot to move from the initial position of (0,0,0) to the final position of (1,1,1) the required joint angles of the robot are calculated using the inverse kinematics which will be obtained through the geometrical method of calculation.

To calculate the IK of the hexapod's leg, a single leg was considered, and a line drawing was obtained, as shown in the Fig. 8. The geometrical approach was applied to derive the joint angles of the coxa, femur and tibia joint which are θ_1, θ_2, θ_3.

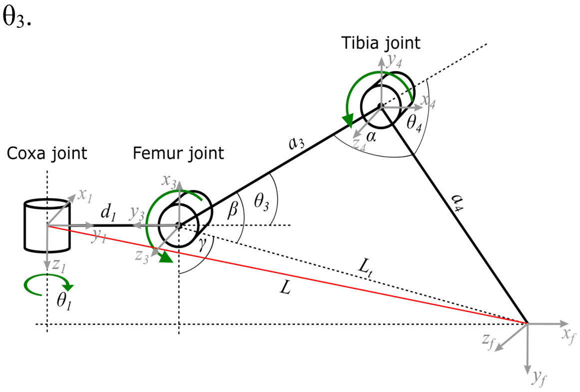

Fig.8: *Kinematics Diagram for Single Leg.*

To obtain the θ_1 along the x and y coordinate.

$$\theta_1 = tan^{-1} + \alpha_1 \qquad (2a)$$

$$l_1 = \sqrt{x^2 + y^2} \qquad (2b)$$

$$l_1 = l - \alpha_1 \qquad (2c)$$

To obtain the θ_2 along the x and z coordinate is being considered

$$h = \sqrt{{l_1}^2 + z^2} \qquad (2d)$$

$$\phi_1 = cos^{-1}(\frac{h^2 + \alpha_2^2 - \alpha_3^2}{2h\,\alpha_2}) \qquad (2e)$$

$$\phi_2 = tan^{-1}(\frac{x}{l_1}) \qquad (2f)$$

$$\theta_2 = \phi_1 + \phi_2 + \alpha_2 \qquad (2g)$$

Calculating the θ_3,

$$\phi_3 = cos^{-1}(\frac{\alpha_2^2 + \alpha_3^2 + h^2}{2h\,\alpha_2}) \qquad (2h)$$

$$\theta_3 = \phi_3 - 180 + \alpha_3 \qquad (2i)$$

3.3 Bézier Curve

In graphic design and related disciplines, a Bézier curve is a parameterized curve used to describe smooth curves. Four control points are the 4 Ps in the curve. The curve always begins at P0 and ends at P3. The black curve generated in the Fig. 10 represents the Bézier curve generated with the help of four control points.

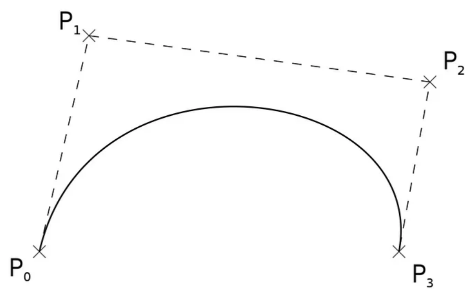

Fig.9: *Bezier Curve Trajectory.*

Fig. 10 shows the Bezier Curve Trajectory of one of the hexapod's legs which is self-explanatory as it depicts the movements of the legs concerning the terrain it traverses. The leg drops along the red curves obtained by applying the Bézier curve formula.

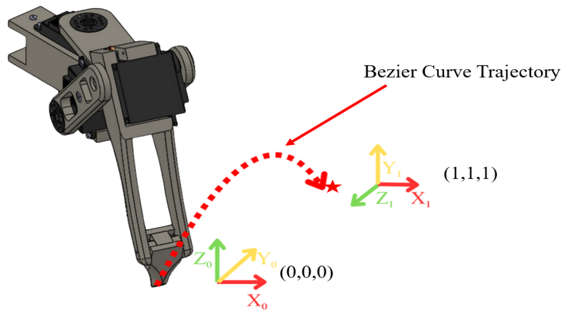

Fig.10: *Image Showing Bézier Curve Trajectory.*

The sum of Bernstein basis polynomials multiplied by a Bernstein coefficient yields a Bernstein polynomial of degree n. The formula below is used to calculate the curve using the control points P0, P1, P2, and P3.

$$P(t) = \sum_{i=0}^{n} B_i^n (t) P(i) \quad (3a)$$

$$B_i^n(t) = \binom{n}{i} t^i (1-t)^{n-i} \quad (3b)$$

$$\binom{i}{n} = \frac{n!}{i!(n-i)!} \quad (3c)$$

$$(a+b)^n = \sum_{k=0}^{n} (i_n^k)\, a^k B^{n-k} \quad (3d)$$

4. GAITS

Gait is a cyclic motion pattern that produces locomotion through a sequence of foot contacts with the ground (Haynes, 2006). Gait describes the manner or set of series through which the legs of the robot are used to make movements toward achieving the goal of locomotion.
The gait is classified into five major groups namely:

1. Tripod Gait
2. Quadruped Gait
3. Wave Gait
4. Ripple Gait
5. Bi Gait

There are two important terms associated with gaits: stance and swing. Stance defines the period in which the leg is in contact with the ground and generates the robot's movement. Flight (swing) is the period during which the leg is not in contact with the ground, that is, the period in which the leg returns to the stance period (Leonor et al., 2022).

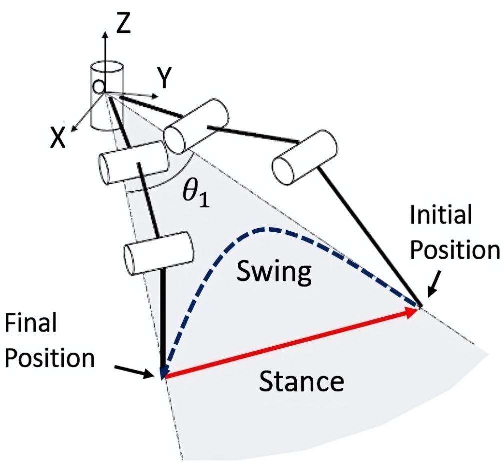

Fig.11: *Stance and Swing Phase of Robot Leg.*

Fig. 12 to Fig. 16 depict various gait patterns. Black represents the stance phase and grey represents the swing phase showing the leg cycle over six consecutive cycles.

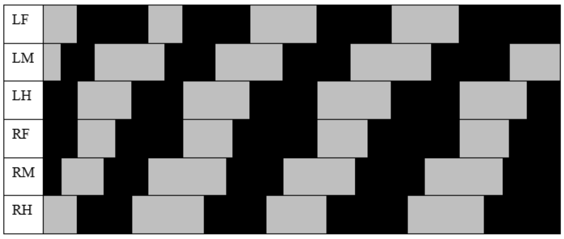

Fig.12: *Ripple Gait.*

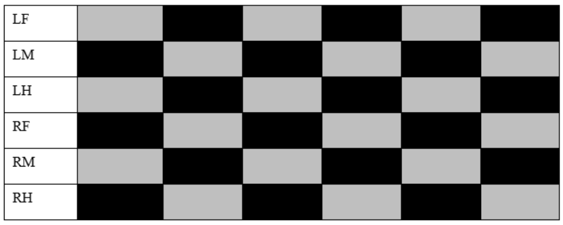

Fig.13: *Tripod Gait.*

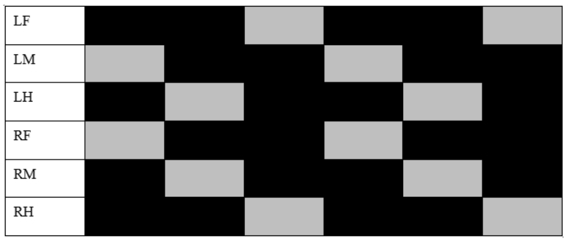

Fig.14: *Bi Gait.*

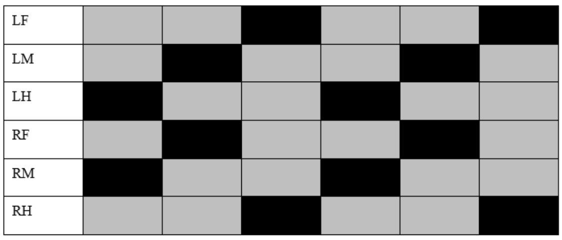

Fig.15: *Quad Gait.*

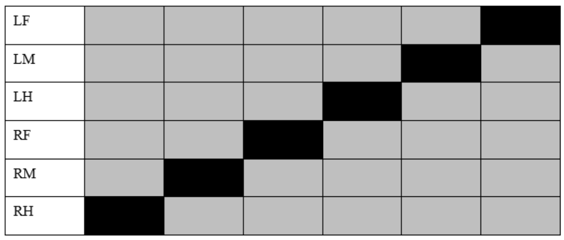

Fig.16: *Wave Gait.*

5. ALGORITHM

The robots start to move upon receiving the command signal from the remote control. If there is no command, they are set to a stand-alone position. The two linear potentiometers can be used to set the height and speed of the robot.
Movement is accomplished with the help of the forward kinematics (FK), IK and Bezier trajectory calculation. It also includes vector analysis for plotting out the next point in the 3D

space and logic for synchronizing the walk cycle of various gaits.

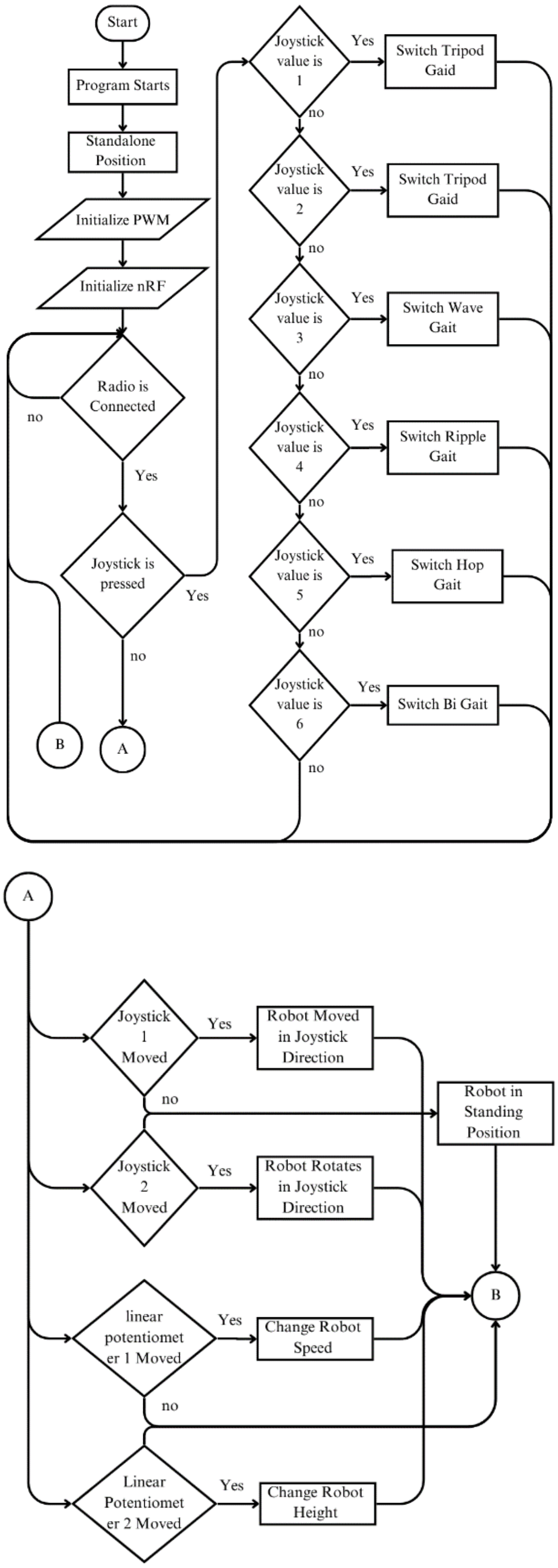

Fig.17: *Logic Diagram for Hexapod Robot.*

6. TESTING AND ANALYSIS

Fig. 18 shows the complete assembly of the Hexapod robot and the remote control which will be used for testing.

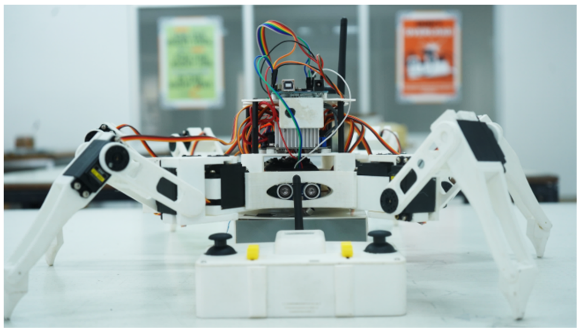

Fig.18: *Complete Hexapod and Controller Assembly.*

6.1 Testing of Algorithm and Trajectory

The testing of the algorithm and trajectory planning of the robot was simulated using the Python NumPy and SciPy libraries. The graph below shows the testing of the robot's leg algorithm and its ability to draw a circle with 10 samples. This was to test the inverse and forward kinematics of the robot and to estimate the workspace of individual robot's leg.

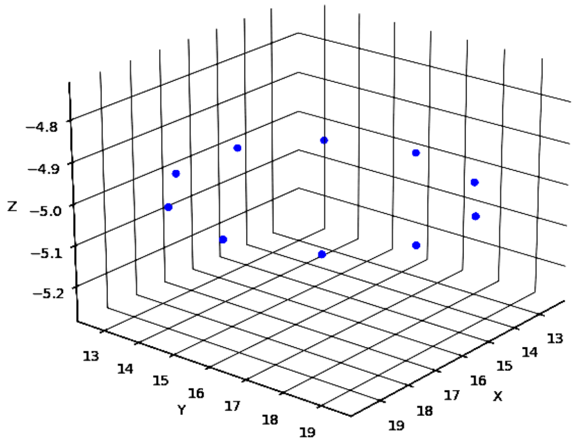

Fig.19: *Testing the Trajectory.*

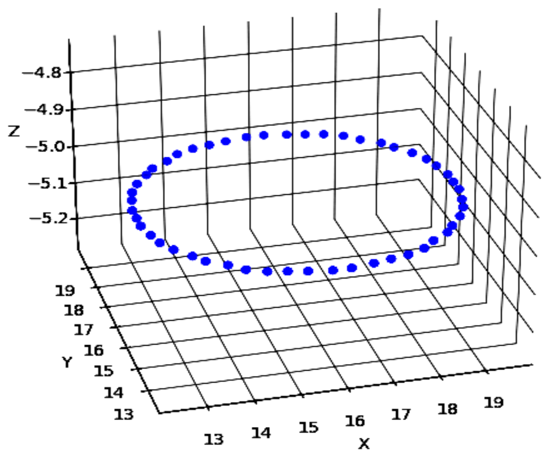

Fig.20: *Testing Trajectory.*

Fig. 20 shows a graph depicting the output using 100 samples. The inverse kinematics of robot's leg resulted in a smooth curve, although there was a minor calculation error at the coordinate (15, 18, -5). However, implementing it in real time did not impact in walk cycle.

Fig.21: *Real-Time Implementation.*

Fig. 22 shows the output of the Bezier curve trajectory algorithm implemented together with the inverse kinematics algorithm. The same pattern curve will be implemented in actual locomotion of the Robot's legs.

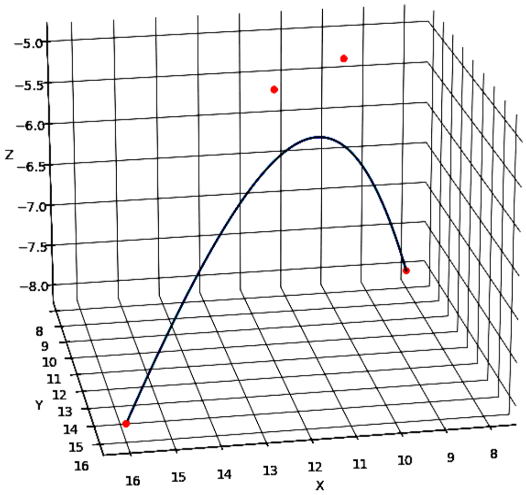

Fig.22: *Testing the Bezier Curve.*

6.2 Testing of Various Gait

The hexapod robot has six gait algorithms implemented for locomotion, namely the tripod gait, wave gait, ripple gait and the tetrapod gait, bi gait and hop. Due to the low cost of the servo motors located in joints of the leg, the bi gait and hop gait were not implemented, as they required more force and quick actions. The other four gaits were implemented, and following parameters were maintained for the test of these four gaits:

1. Speed of Robot: 30% of its maximum speed
2. Robot Height: 0.05m from the base
3. Distance Traveled: 1.30m
4. Distance Between Remote Controller and Robot: 2m

For each gait four number of trials were carried out to measure the time taken by the hexapod robot to cover the distance of 1.30m and the offset from the end point as shown in Fig. 23 and Fig. 24.

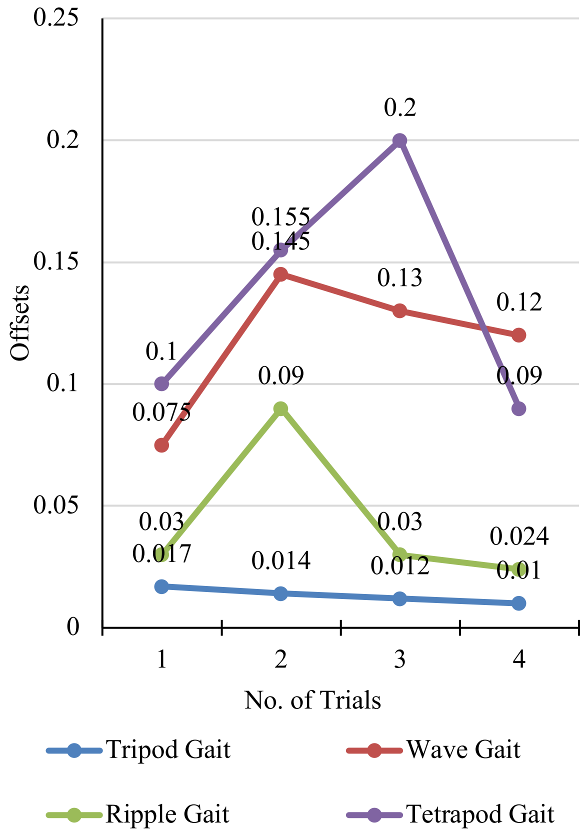

Fig.23: *Comparing Based on End Offsets.*

From the above two graphs (Fig. 22 and Fig. 23), it is notable that tripod gait is preferable. The linear projection of the tripod gait demonstrates a degrading effect in terms of offsets and time taken as the number of trials increases. The tripod gait and quad gait have the fastest speed, taking approximately 20 seconds to traverse a distance of 1.30 meters. It was also observed that the tripod gait was more stable, maintaining the centre of gravity throughout the run.

Although the wave gait took the longest to reach the destination, it was more stable and can be used for traversing uneven terrain due to its stability gained from having five feet on the ground while only one is in the air.

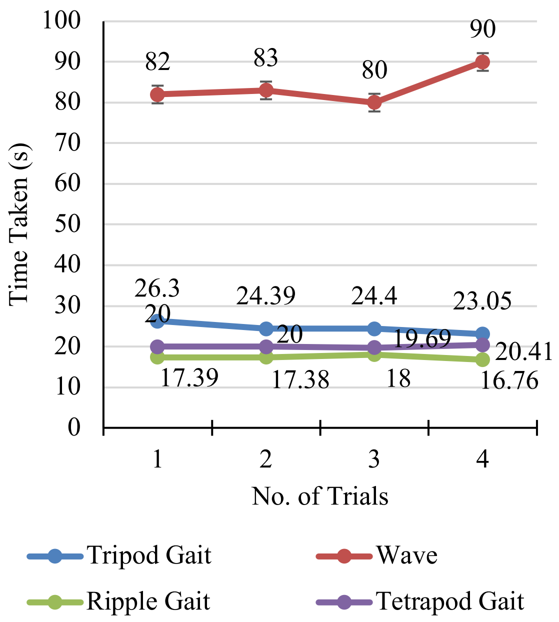

Fig.24: *Comparing various Gaits Based on Time Taken*

6.3 Torque Calculation

The torque on each joint of the hexapod is as follows:

- Servo motor (MG996R) Torque = 1.08 Nm
- Torque at Tibia Joint (T1) = 0.173 Nm
- Torque at Femur Joint (T2) = 0.197 Nm

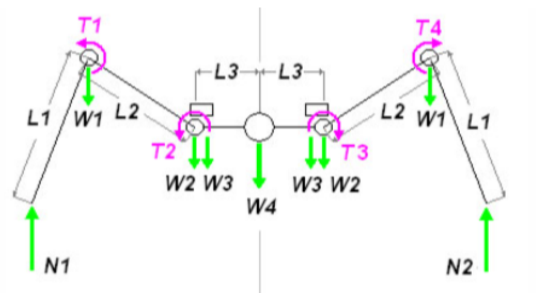

Fig.25: *Torque Calculation for Hexapod.*

6.4 Cost Calculation and Comparison

The total cost of the project is Nu. 25,924/-, which is significantly lower than the price range. Similar products are available in the market, priced between Nu. 41,499 and Nu. 1,08,316. For instance, the Xiao Geek Hexapod Robot Kit available on Amazon costs Nu. 41,500. The lower cost enhances accessibility, ensuring that quality STEM education is within reach for enthusiastic learners participating in the STEM Olympiad.

The affordability of this device compared to market alternatives broadens its potential user base, enabling a diverse range of users to benefit from its features. It is designed to promote and empower students in STEM learning by providing hands-on experience in assembling and coding, thereby demonstrating the practical application of the STEM principles. A distinctive feature of this project is its affordability coupled with the availability of open-source code and assembly manuals, further enhancing its educational value and accessibility.

7. CONCLUSION

Showcasing hexapods during STEM festivals has the potential to ignite students' interest in robotics and engineering. In alignment with the Royal Decree advocating for educational reforms to strengthen STEM subjects as integral components of students' learning experiences, this project seeks to incorporate STEM education into students' lives. It does so by employing hexapod robots that implement inverse kinematics and offering the project as an open-source initiative. The project successfully developed a modular hexapod robot, complete with an algorithm for locomotion based on inverse kinematics and a user-friendly remote-control interface. These features are specifically designed to promote STEM education by providing practical, hands-on learning experiences. The hexapod features six legs with a total of 18 degrees of freedom (DoF), with 3 DoF per leg. The movement of the legs is controlled by high-torque servo motors, which are operated via a microcontroller in conjunction with a servo driver. During traversal, the servo angles are calculated using inverse kinematics and Denavit-Hartenberg (DH) parameters. The integration of inverse kinematics and a gait algorithm ensures flexible and precise movement based on joystick commands from the remote controller. The hexapod incorporates six distinct gaits for traversal, each with unique advantages and limitations. For navigating rough terrain, the Wave Gait is optimal due to its stability, whereas the Tripod and Bi Gaits provide faster movement, making them suitable for smoother surfaces. Moreover, the hexapod can be adapted and customized for various applications, such as search-and-rescue operations. This adaptability opens avenues for further development, such as integrating additional sensors like gyroscopes and utilizing a faster, more robust microcontroller to enhance program efficiency and expand its functionality.

REFERENCES

Angliss, C., & Parker, G. (2023). Coevolving hexapod legs to generate Tripod gaits. Proceedings of the *14th International Conference on Agents and Artificial Intelligence,* 1063–1071. https://doi.org/10.5220/0011896200003393

Bartsch, S., & Planthaber, S. (2009). Scarabaeus: A walking robot applicable to sample return missions. *Communications in Computer and Information Science,* 128-133. https://doi.org/10.1007/978-3-642-03558-6_12

GAINA, M. (2019). The hexapod robot for aircraft fuel tank and the use of calculation in the analysis of the effectiveness of radio interference. *INCAS BULLETIN,* 11(3), 67-76. https://doi.org/10.13111/2066-8201.2019.11.3.6

García-López, M., E.Gorrostieta-Hurtado, Vargas-Soto, E., Ramos-Arreguín, J., Sotomayor-Olmedo, A., & Morales, J. M. (2012). Kinematic analysis for trajectory generation in one leg of a hexapod robot. *Procedia Technology*, 3, 342-350. https://doi.org/10.1016/j.protcy.2012.03.037

Ji, W., & Cho, B. (2018). Development of a walking algorithm on the uneven terrain for a hexapod robot little Crabster200. *Advances in Mechanical Engineering,* 10(7), 168781401878481. https://doi.org/10.1177/1687814018784818

Muslimin, S., & Istardi, D. (2018). Inverse kinematics analysis for motion prediction of a hexapod robot. 2018 *International Conference on Applied Engineering* (ICAE). https://doi.org/10.1109/incae.2018.8579402

Nonami, K., Barai, R. K., Irawan, A., & Daud, M. R. (2013). Kinematics, navigation, and path planning of hexapod robot. *Intelligent Systems, Control and Automation: Science and Engineering*, 85-104. https://doi.org/10.1007/978-4-431-54349-7_4

Reverse kinematic analysis problem statement. (1998). *Kinematic Analysis of Robot Manipulator*s, 44-52. https://doi.org/10.1017/cbo9780511530159.006

Rokbani, N., Casals, A., & Alimi, A. M. (2014). IK-FA, a new heuristic inverse kinematics solver using firefly algorithm. *Studies in Computational Intelligence,* 369-395. https://doi.org/10.1007/978-3-319-11017-2_15

Suprihono, H., & Mashoedah. (2021). Development of inverse kinematics learning media using hexapod robot for robotics course. *Journal of Physics: Conference Series*, 1737(1), 012035. https://doi.org/10.1088/1742-6596/1737/1/012035

Ulum, M., Khoirut, M., Haryanto, H., Alfita, R., Rahmawati, D., Wibisono, K. A., & Ibadillah, A. F. (2018). Designing and implementing trajectory planning and inverse kinematics algorithms using hexapod robot platform. *Proceedings of the International Conference on Science and Technology (ICST 2018).* https://doi.org/10.2991/icst-18.2018.164

Use of robotic platforms as a tool to support STEM and physical education in developed countries: A descriptive analysis. (2022, January 28). MDPI. https://www.mdpi.com/1424-8220/22/3/1037

Zhang, G. E. (2016). Inverse kinematics of multi-joint robot based on improved firefly algorithm. *International Journal of Simulation: Systems, Science & Technology*. https://doi.org/10.5013/ijssst.a.17.02.07

Zhou, X., Wei, W., Gao, Y., Li, K., & Chen, R. (2019). Research on terrain recognition for gait selection of hexapod robot. *IOP Conference Series: Materials Science and Engineering*, 611(1), 012072. https://doi.org/10.1088/1757-899x/611/1/012072