Design and Development of Multileg Locomotive Robot for Life Threaten Areas

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Abstract

The world of technology is the workbook of crises waiting to be solved, where robotics is the top-most essential technology, which is utilized for surveillance purposes to detect catastrophic events, such as detecting poisonous and explosive gases in mines, monitoring nuclear sites for contaminations and crops to determine the existence of biological threats, and inspecting buildings for gas leaks to protect human lives. The multi-legged robot has numerous capabilities, such as carrying heavy payloads, executing long-duration missions, and interacting with the environment. However, their bizarre mobility to reach everywhere in any complex territory makes them phenomenal. On the contrary, due to variation in its limb structure, the motion has several possibilities, which complicates its overall movement. For this reason, this research presents the precise locomotion of the multileg robot on any terrain. This work initially concentrates on the peculiar gaits planning, and later the kinematics analysis is carried out for the three jointed legs of a Multileg robot's locomotion on bumpy grounds. Besides, an attempt has also been made to achieve forward kinematic analysis on the design for validation. Moreover, this paper also exhibits the model simulation through the simulation software to examine the theoretical and practical conclusive results. The motion simulation was implemented, and the results are satisfactory.

Keywords—Multileg Robot, Surveillance robot, Lifesaving robot, Forward and Kinematic Analysis, Gait Stability

1 Introduction

In today's age, there are numerous circumstances where humans are powerless to fulfill undeniable tasks for their survival, such as military reconnaissance, aerospace exploration, mine disasters, underground detection, and many more [1]. Therefore, mobile robots are highly in demand to overcome these challenging situations. Nevertheless, the significant hurdle is determining whether to utilize wheeled or legged robots. In comparison to wheeled and tracked robots, multi-legged robots can walk across both continuous and discontinuous ground [2]. As a result, in conditions where those robots cannot travel, multi-legged robots can support humans in executing special tasks [3]. This superiority has tempted researchers to focus on legged robots, especially spider robots, because of their high flexibility and adaptability during walking over irregular surfaces [4-5]. In addition, the flexible motion of this robot relies upon its leg's structural design because while walking, the mechanical legs alternate between swinging and supporting phases, which assesses the performance of its motion [6]–[11]. This mechanical leg can also act as a robotic manipulator [12], and its mechanism can control the movement of the end-effector gripper, like, for proper griping with balanced air pressure [13-14]. Hence, various applications have been applied to ensure their motion flexibility and preciseness, especially in the industrial field, such as repetitive motion planning, the influence of body shape on transient movement, and optimized jumping on a quadruped robot [15]–[19].
All over the end of the 20th century, the modeling and development of a spider-like robot began with the purpose of climbing vertical ducts or pipes and 2D horizontal tunnels [20-21]. The prevailing notion of insects, including a spider, and the architecture of horizontal tunnels were scrutinized [20-21]. Subsequently, in the 21st century, the conclusion was made

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that slippery surfaces of ducts and tunnels complicate locomotion due to the unstructured congested environments and complex geometry. In addition, from the observation of motion behaviors recorded by a 3D-locomotion observation system, the legs walking behavior, center of mass movement, and joint-rotation angle on horizontal surfaces were acquired, and the spider prototype was also acquainted with detecting anti-personnel landmines along with the tracking system [22-23]. After perceiving the consistent progress, the researchers also worked on obstacle avoidance by utilizing many sensors by operating different bumping and ultrasonic sensors. Afterward, walking patterns were offered, and based on that proposition algorithm was created to conquer various deficiencies in legged robots placed in an uncertain field [24]. Years later, spider robots became prevalent, and researchers ventured to work on introducing advanced features in the prototype. Later, to enhance its load capacity and operate it in the environment via wireless communication, the number of actuators was reduced, and several alternative theories for unconventional spider models were examined, respectively [25]–[27]. Sequentially, the requisite configuration issues, limitations that impact the technical feasibility, and operation performance became the significant concentration. Eventually, a strategy comprised of the mechanical structure, along with the actuating methods, drive mechanisms, payload, and motion conditions, was reported for the walking robots, specifically the hexapod, to provide a convenient tool in terms of the systematic design [28]. In order to alter the multi-legged robot's behavior, parameters like torque and joints' speed were lowered and experimented on the mammalian-inspired robot [29]. Besides, a mathematical model and algorithm for the position, velocity, and non-contact leg were developed and verified by the simulation [30].

With time, the availability of the spider robot's leg structure expanded, which ultimately increased the possibilities of its locomotion, thus causing the movement problematic. However, to solve this perplexing problem of humanity, kinematic modeling came hugely in hand despite the number of spider legs [31]–[33]. Since the legged design requires several parameters, such as limb composition, stability, leg joints, and actuators [33], the main parameters are the suitable designing of its leg kinematics and CAD modeling to develop the appropriate dimensions for the actual design in order to work smoothly on rough terrains by adjusting the speed parameter at the same time [34], and stability can be achieved with the fastest movement of two legs contacting the ground at half the walking cycle [35]. For this purpose, our research aim is to focus on the peculiar gaits outlining and kinematic modeling of the four-legged spider prototype's locomotion on irregular terrain. Moreover, this paper also exhibits the CAD model and its simulation through the RoboAnalyzer software to analyze the conceptual and experimental summarized outcomes.

2 Walking Theory

A gait is the series of leg movements to drive a robot's body in the desired direction, and the periodic gait indicates the similar states of the identical leg during successive strokes that occur at the same interval for all the legs. The general periodic movement of the legs of the four-legged robot is presented below in Fig. 1.

The leg motion of a four-legged spider robot depends upon the utilization of one or two legs concurrently in a phase. The two basic gait types are illustrated below in detail.

2.1 Types of Gaits

2.1.1 Creep/Crawl/Statically Stable Gait

In this mechanism, only one limb is uplifted from the ground, while the remaining three try to build a triangular structure (tripod) to stabilize the whole body simultaneously [34]. This gait gives slow but steady motion on level ground and is shown in Fig. 2.

The ground legs try to sustain a geometry in a certain respect that the center mass of the quadruped resides inside the triangle formed by the other limbs. When the suspended leg takes a forward step, tripod limbs shift the body forward synchronously, and when it comes down, another stable tripod is composed, providing a smooth movement.

2.1.2 Trot/Amble/Dynamically Stable Gait

In this mechanism, two diagonally connected limbs are uplifted from the ground simultaneously while the remaining two try to sustain the whole body and move backward. The motion of this gait is fast twice as the creep gait, and the body stability is concerned with the legs' frequency. Fig. 3 shows the leg positions during the trot gait.

3 Multi-leg Model Design

The four-legged spider robot comprises one body and four legs, and each limb includes three parts, coxa, femur, and tibia, and three joints, base, hip, and knee [35]. The coxa link is bound to the body with a base joint, which could revolve around the body from the axis plumb to the long and wide side. The femur link is

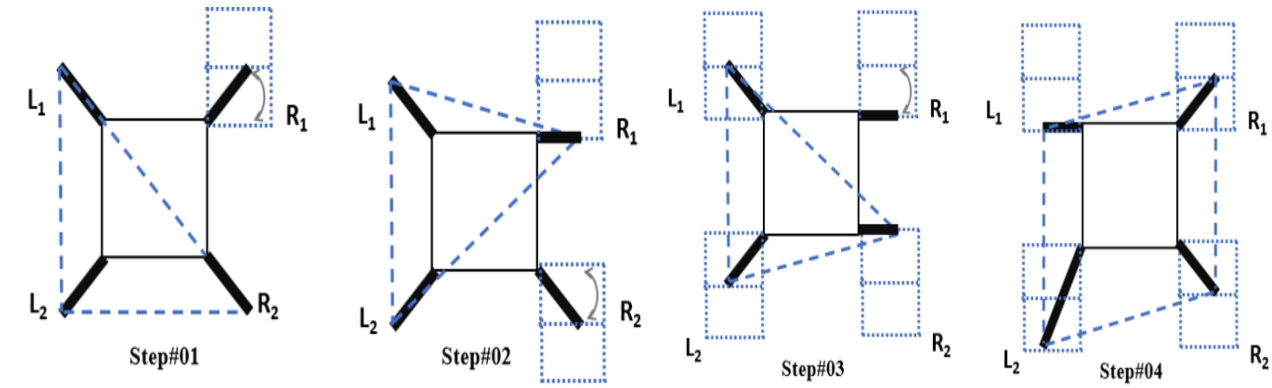

Fig. 1: Periodic Movement of the Legs of the Four-legged Spider Robot

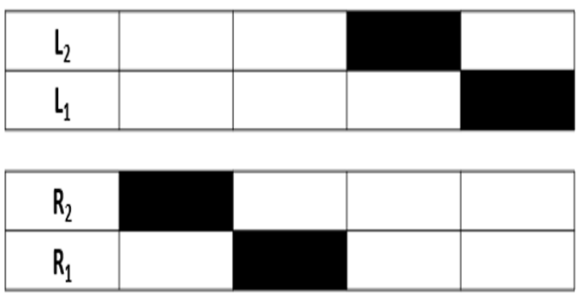

Fig. 2: Movement of the Legs using Creep Gait

Fig. 3: Movement of the Legs using Trot Gait

TABLE 1: Physical Parameters of the designed spider robot

Body Part	**Length (mm)**	**Height (mm)**	**Width (mm)**
Lower body	172.75	29.10	131.11
Upper body	138.81	26.85	92.38
Coxa	38.10	38.10	43.35
Femur	29.27	19.83	53.25
Tibia	77.16	23.83	38.26
Shield	83.8	16.22	35.34

TABLE 2: DH-Parameters of the Robot Leg

Link i	$a_i(mm)$	$\alpha_i(deg)$	$d_i(mm)$	$\theta_i(deg)$
1	$a_1 = \mathbf{87}$	90	40	θ_1
2	$a_2 = \mathbf{106.5}$	0	0	θ_2
3	$a_3 = \mathbf{154.32}$	0	0	θ_3

connected to the coxa by the hip joint, which plumbs to the coxa and base joint. Finally, the tibia link is attached to the femur link by the knee joint, and a shield is affixed to the tibia to protect it from the load. The entire design of the robot is built on SolidWorks software, and its mechanical parts were created from a 3D printer using PLA Pro material. The spider model and the dimensions of its components are shown in Fig. 4 and Table 1, respectively.

4 Motion Analysis through Kinematics

Direct kinematics uses the kinematic equations of a robot to estimate the position of the end-effector from designated values for the joint parameters, whereas inverse kinematics is the reverse process of direct kinematics. [33]

4.1 Denvait-Hartenberg (DH) Representation of the Model

It is an unfussy method of interpreting the links and joints of the robot leg to solve the kinematics. The parameters that construct the table are link length (a_i), twist angle (α_i), joint offset (d_i), and joint angle (θ_i). A manipulator having 3 revolute joints and 3-DOF, consisting of 4 frames and 4 links, is utilized, and all the arrangements for the 3-DOF leg are shown in Fig. 5 and Table 2.

4.2 Kinematics Analysis

4.3 Direct Kinematics Analysis

The link transformation matrices are as follows:

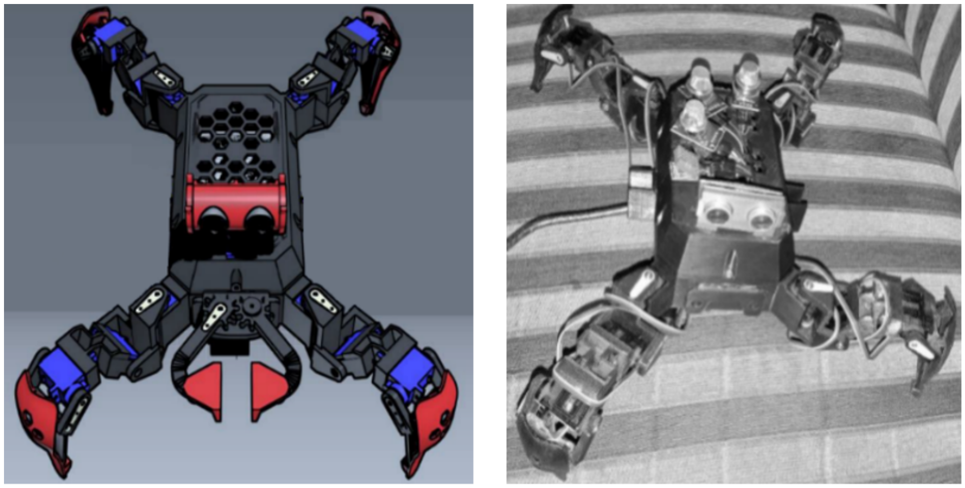

Fig. 4: The Assembled Four-Legged Robot

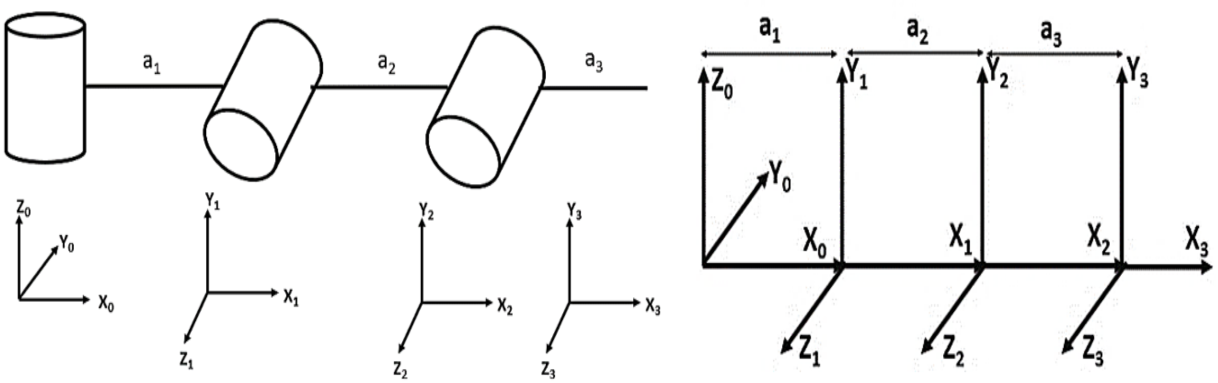

Fig. 5: Arrangement of 3-DOF actuators and leg's assigned frames

$$^{0}T_1 = \begin{bmatrix} C_1 & 0 & S_1 & a_1 \times C_1 \\ S_1 & 0 & -C_1 & a_1 \times S_1 \\ 0 & 0 & 1 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where $C_1 = Cos\theta_1$ and $S_1 = Sin\theta_1$

$$^{1}T_2 = \begin{bmatrix} C_2 & -S_2 & 0 & a_2 \times C_2 \\ S_2 & C_2 & 0 & a_2 \times S_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

where $C_2 = Cos\theta_2$ and $S_2 = Sin\theta_2$

$$^{2}T_3 = \begin{bmatrix} C_3 & -S_3 & 0 & a_3 \times C_3 \\ S_3 & C_3 & 0 & a_3 \times S_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where $C_3 = Cos\theta_3$ and $S_3 = Sin\theta_3$. Now the final matix will be:

$$^{0}T_3 = \begin{bmatrix} C_1C_{23} & -C_1S_{23} & S_1 & a_1C_1 + a_2C_1C_2 + a3C_1C_{23} \\ S_2C_{23} & -S_1S_{23} & -C_1 & a_1S_1 + a_2S_1C_2 + a3S_1C_{23} \\ S_{23} & C_23 & 0 & a_2S_2 + a_3S_{23} + d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

where $C_{23} = Cos(\theta_2 + \theta_3)$ and $S_{23} = Sin(\theta_2 + \theta_3)$.

4.4 Inverse Kinematics Analysis

For inverse kinematics, considering the total length L, which is equal to the sum of the length of coxa C, femur F, and tibia T is given in Fig. 6.

So, by applying the Pythagoras theorem,

$$L_1 = \sqrt{(L - C)^2 + O^2} \quad (5)$$

$$\theta_1 = Sec(\frac{O}{L_1}) \quad (6)$$

Now, by using cosine law, we get,

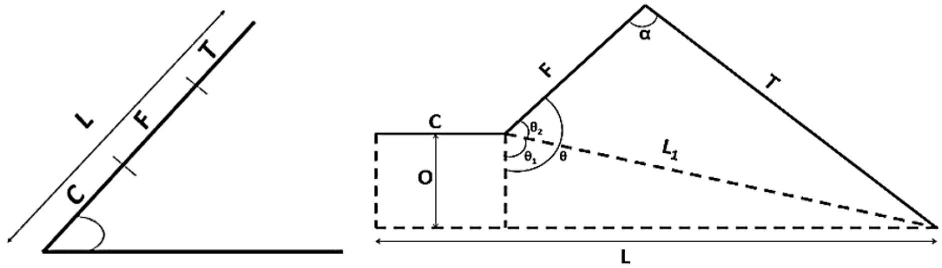

Fig. 6: Top and Side View of the Spider Leg, where O = Offset and L = total length

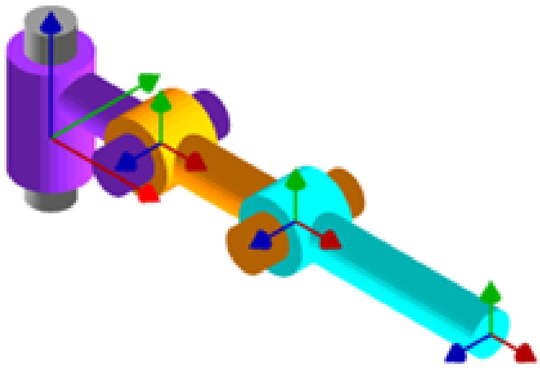

Fig. 7: At Homing Position

$$\theta_2 = Sec(\frac{T^2 - F^2 - (L_1)^2}{-2FL_1}) \tag{7}$$

Since $\theta = \theta_1 + \theta_2$ using eq(6) and eq(7),

$$\theta = Sec(\frac{O}{L_1}) + Sec(\frac{T^2 - F^2 - (L_1)^2}{-2FL_1}) \tag{8}$$

Finally, using cosine law again, we get,

$$\alpha = Sec(\frac{(L_1)^2 - T^2 - F^2}{-2FT}) \tag{9}$$

5 DH Representation through RoboAnalyzer Software

The manipulation of a single leg is illustrated step-by-step through the RoboAnalyzer software. Figure. 7 shows the orientation of the quadruped spider leg, and the first revolute joint shows the reference position for the complete locomotion. The spider's leg locomotion has been achieved in 2 steps for forward and 3 steps for backward motion. All the given figures present their DH parameters for that instant. Figs. 8 and 9 depict the forward kinematics of leg structure, end position P1, and end position P2, respectively. Forward movement is achieved by rotation of the combined motion of the femur and tibia joints.

Results obtained employing the theoretical and RoboAnalyzer software forward kinematic analysis are presented in Table 3. From that, it can be noticed that the manipulator end coordinates acquired at various locations are same approximately, thus validating the proposed design model.

Figs. 10, 11, and 12 show the backward movement through forward kinematics of leg structure, end position P3, end position P4, and end position P5, respectively.

Results for backward motion acquired utilizing the theoretical and RoboAnalyzer software forward kinematic analysis are shown and compared in Table 4. From this, it can be seen that manipulator end positions acquired at different locations are nearly the same, which validates the proposed design model.

6 Simulation Results

All the given graphs represent how the distance varies during the forward and backward locomotion of the spider leg. In fig. 13 and 14, we see how distance changes for the first and second steps of the forward motion. It is clear from the first graph that for all the links, the X-axis values decrease while the Y-axis values increase with time. As for Z-axis, values for link 1 increase while for link 2 remains constant, initially decreasing values for link 3 and then increasing. For the second step, all axes' values for link 1 remain constant as X-axis does not change its position for that instant while X and Z for links 2 and 3 increase and decrease, respectively.

On the contrary, in the case of backward movement, the X-axis values decrease, whereas the Y-axis values increase for links 2 and 3 with time, respectively, in the first step, which can be noticed in fig. 15.

For the second step of the backward movement, the X and Y-axis values rise and fall, respectively, keeping the Z-axis values invariant for all the links, as shown in fig. 16. On the other hand, for the final step, all the axes' values for link 3 decreases while X and Y-

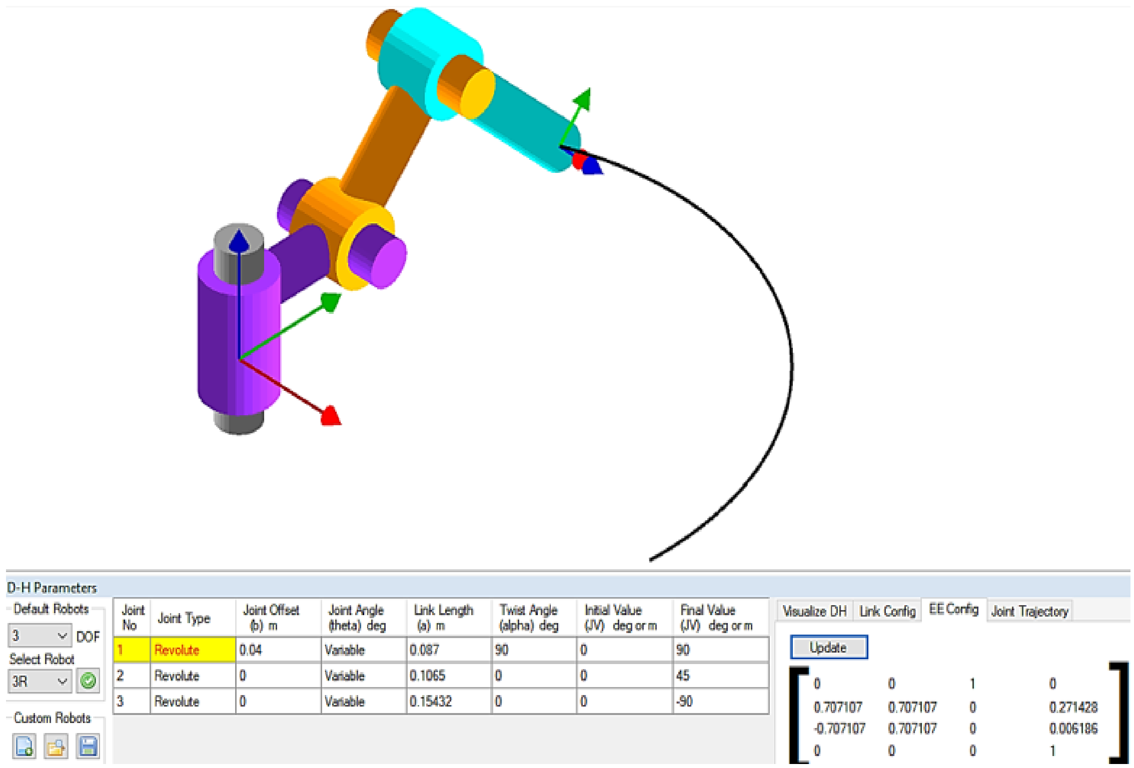

Fig. 8: Forward Initial Step

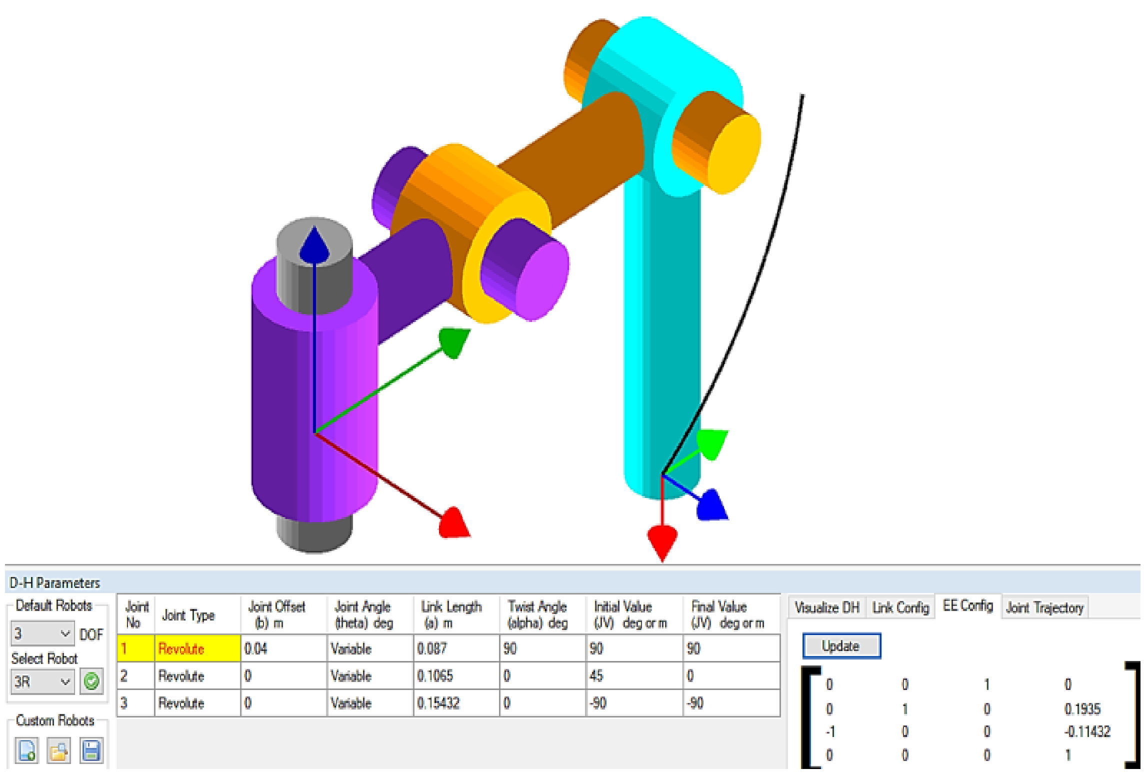

Fig. 9: Forward Second Step

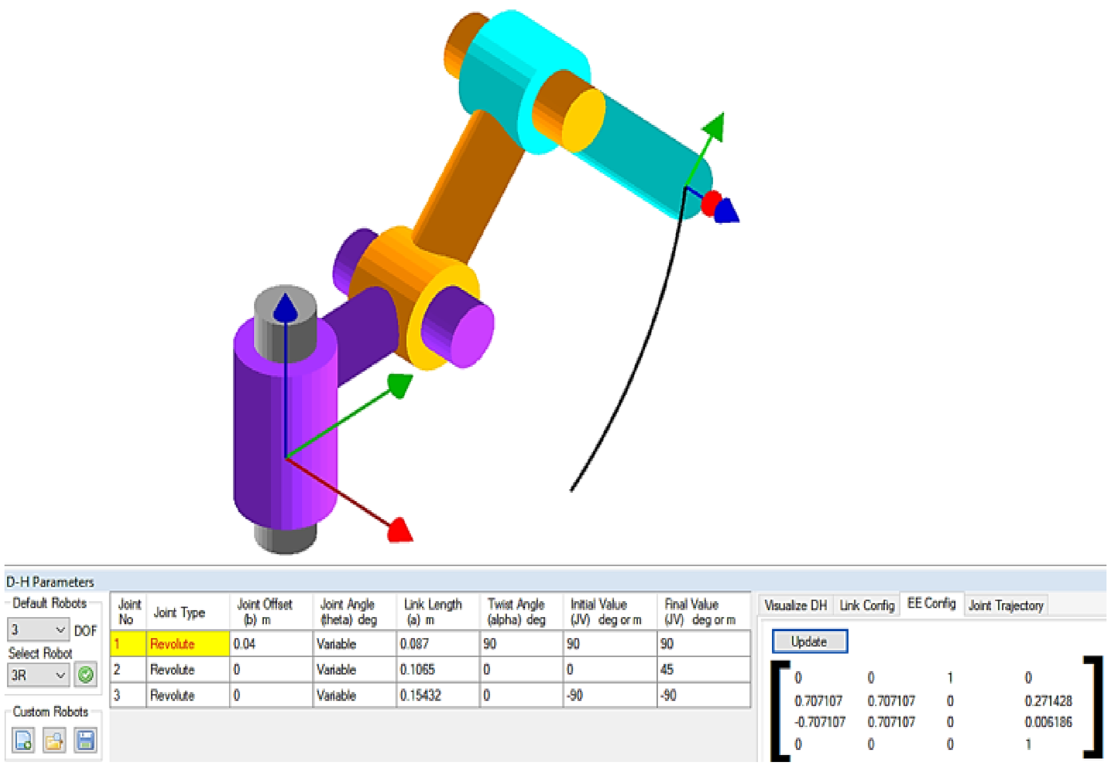

Fig. 10: Backward Initial Step

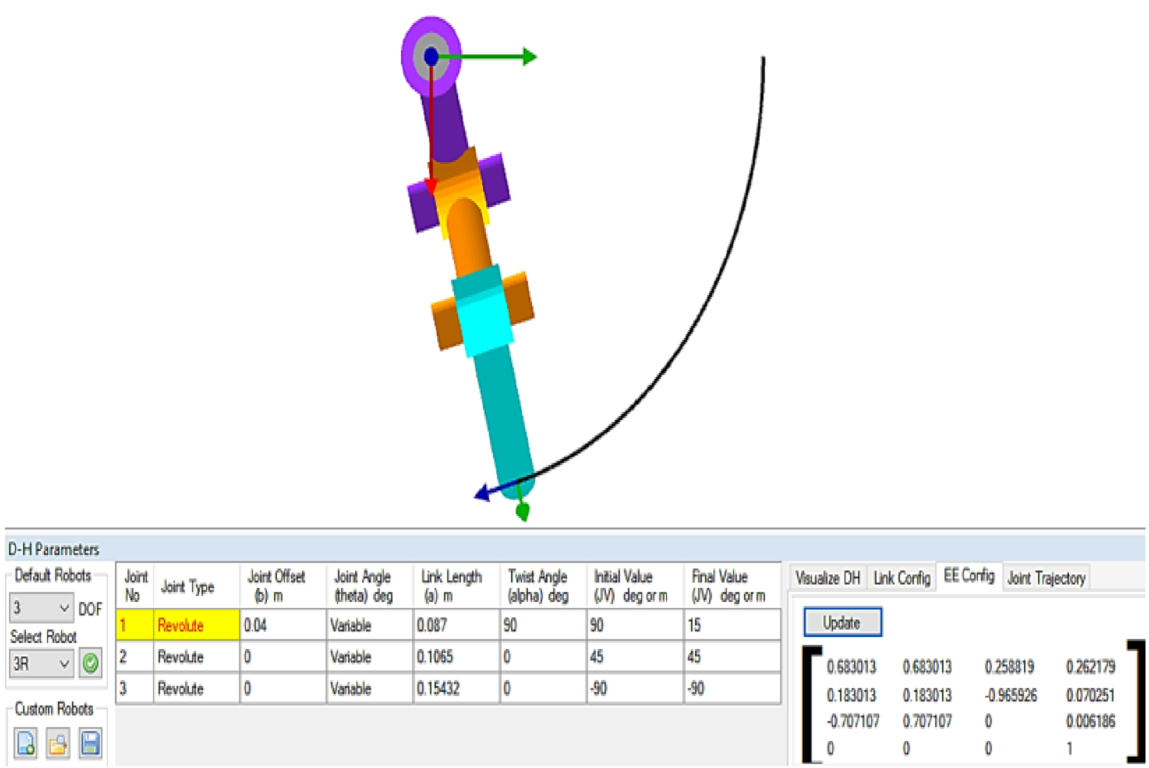

Fig. 11: Backward Second Step

TABLE 3: Comparison of Forward Movement Results

S. No	Angles ($\theta_1, \theta_2, \theta_3$)	Theoretical Solutions (x, y, z)	Software Results (x, y, z)
1.	At Homing Position (0,0,0)	(0.35, 0, 0.04)	(0.34782, 0, 0.04)
2.	At Position P1 (90,45, -90)	(0, 0.3, 0.0064)	(0, 0.271428, 0.006186)
3.	At Position P2 (90,0, -90)	(0, 0.3, -0.13)	(0, 0.1935, -0.11432)

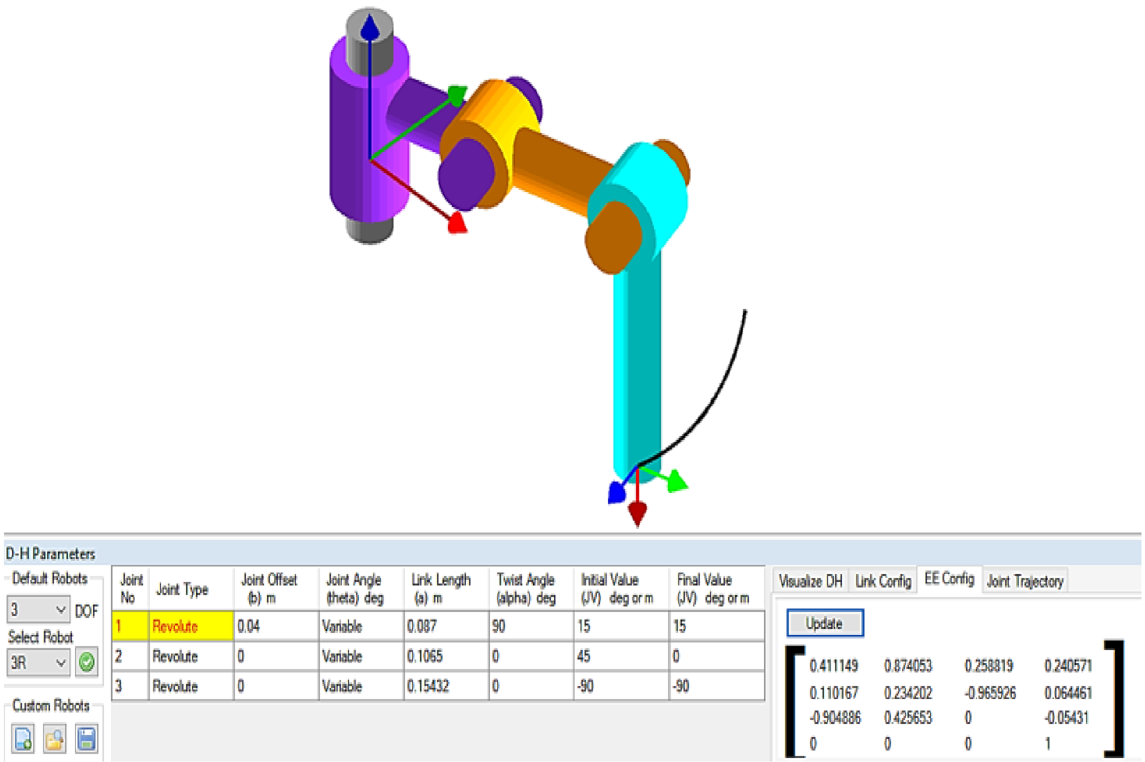

Fig. 12: Backward Third Step

TABLE 4: Comparison of Backward Movement Results

S. No	Angles ($\theta_1, \theta_2, \theta_3$)	Theoretical solutions (x, y, z)	Software results (x, y, z)
1.	At Position 3 (90,45, -90)	(0, 0.3, 0.0064)	(0, 0.271428, 0.006186)
2.	At Position 4 (15,45, -90)	(0.25, 0.07, -0.064)	(0.262179, 0.07025, -0.006186)
3.	At Position 5 (15,0, -90)	(0.2, 0.06, -0.06)	(0.237645, 0.06367, -0.0593)

axis values for link 2 increase, reducing the Z value constantly, as shown in fig. 17.

7 Conclusion

This research exhibits the leg locomotion of a multileg robot and its kinematic analysis. A comprehensive study has made it possible to achieve this proposed movement of the robot. The robot hardware was developed, and an algorithm was implemented. The multileg robot can walk on its four legs based on the algorithm mentioned. The simulations and the robot's physical hardware analytically determine the fastest and most efficient way to move. Theoretical and simulated forward kinematic analysis has been carried out by applying the DH method. Results have been collected by utilizing analytical and simulated interpretation for validation. The suggested algorithm has higher accuracy and a faster calculation speed of the inverse kinematic solution than the iterative method. The validity of the algorithm for locomotion is verified by conducting experiments on a multileg robot. The results are satisfactory and have great significance for the locomotion and stability of multileg robots.

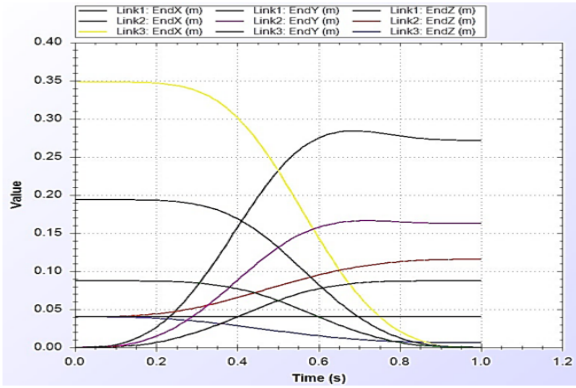

Fig. 13: Forward Initial Step Graph of Axes of Each Link

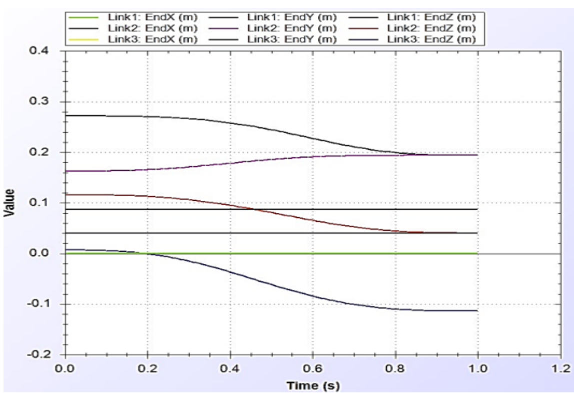

Fig. 14: Forward Second Step Graph of Axes of Each Link

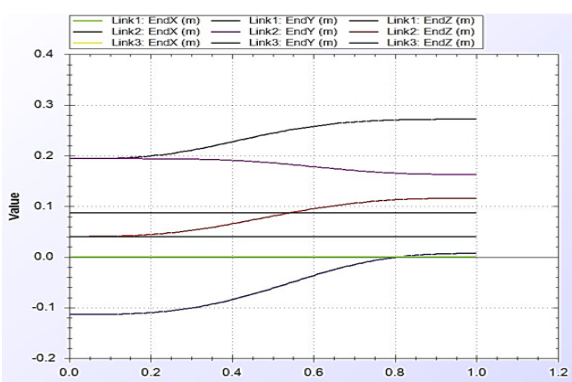

Fig. 15: Backward Initial Step Graph of Axes of Each Link

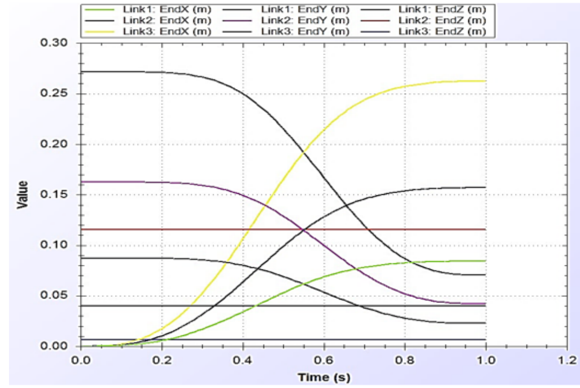

Fig. 16: Backward Second Step Graph of Axes of Each Link

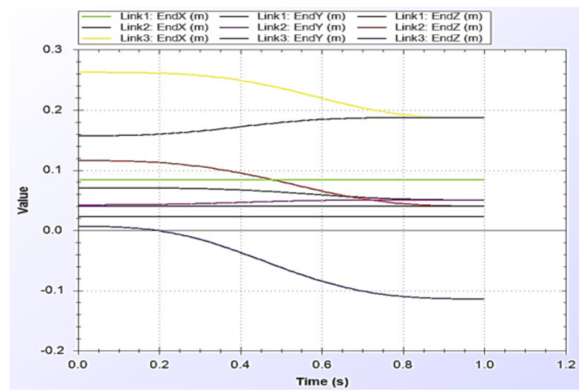

Fig. 17: Backward Third Step Graph of Axes of Each Link

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