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Development of an 8DOF quadruped robot and implementation of Inverse Kinematics using Denavit-Hartenberg convention

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Abstract

Quadruped robots can mimic animal walking gait and they have certain advantages like walking on terrain and extremely rough surfaces. Obstacles can impede the movement of wheeled vehicles, where a quadruped can adapt to avoid obstacles by adjusting its height. A quadruped robot is designed and developed for in this paper, which could be controlled by the Android operating system. The Inverse Kinematics Solutions are derived for the developed structure using Denavit-Hartenberg convention and using those solutions the movements are simulated using a custom-made 3D software. An Android application is developed, which is able to control the robot using Bluetooth. The robot currently has following six different movements: front, back, left, right walking, clockwise and anti-clockwise rotation. The robot uses the ultrasound sensor to detect any obstacle closer than 300 cm (maximum) and if an impediment appears, the robot will automatically move parallel to the obstacle until it is avoided. Currently, it can move at a speed of 15.5 cm/s (approximately). To complete a full rotation of 360°, it takes 6 seconds. It can be used to develop and implement any autonomous path-planning algorithm.

Keywords: Computer science, Electrical engineering, Mechanical engineering

1. Introduction

The necessities of mobile robots for complex and dangerous environments have initiated the development of dynamic quadruped machines, which exploit the potential advantages of the legged locomotion and enhanced mobility in unstructured terrains [1]. Such a versatile system with high maneuverability should be labor efficient, cost-effective, and indispensable in industries. As its name suggests, Quadruped Robots have four legs or limbs and follow the gait patterns of quadruped animals. They are faster and more stable than biped robots. Depending on their leg structure, they can be broadly classified into two categories, Mammal-type and Sprawling-type. The Mammal-type robot, in its standard posture, has its legs in a vertically downward position from the base. Advantages of this leg-configuration include faster walking capability [2]. The joints in this configuration require a less amount of torque compared to its Sprawling-type counterparts. The shape also helps the robot to walk in a comparatively narrow region as it possesses smaller footprint. The Sprawling-type robot has the first segment of its leg, which is the thigh, placed in the horizontal direction and the second half, the shank, placed in the vertical direction. This configuration offers several advantages over the Mammal-type. They have better stability and also have a dynamic range of feet placement. Also, the moving direction is not constrained to a certain direction, rather they can walk in any of the four directions instantly. They have a low center of gravity and as a result, in case it topples over, the damage to the body is considered to be minimal [2]. This feature is of paramount importance if the robot is to be employed for carrying objects. Considering the stability and dynamic movement facility of the structure, the development of a Sprawling-type Quadruped robot is selected for this experiment.

In the early twenty-first century, Kimura et al. [3] developed an adaptive dynamic walking technique for a quadruped robot on both irregular terrain and natural ground [1, 3]. Later, an adaptive locomotion control for compliant quadruped robot was also developed and successfully experimented by Buchli and Ijspeert [4]. Their system was capable to constantly track body properties and readjust along with the gait parameters being dependent on the geometry and movement of the robot. During this time frame, Tekken, another quadruped robot was built by Fukuoka and Kimura to walk on irregular terrain with a medium speed [5, 6]. It included joints containing PD-controller, which inspired virtual spring-damper system similar to the visco-elasticity model of the muscle. These early initiatives encouraged Boston Dynamics to develop BigDog [7, 8, 9, 10], which could capture the mobility and speed of a natural four-legged animal. BigDog could move on very steep, rutted, rocky, wet, muddy and snowy surfaces and could be used to carry objects as well. At the same time, another quadruped robot named LittleDog [11, 12, 13, 14] was built which possessed negotiation capabilities with incoming obstacles of height up to

7.5 cm (about 40% of the robot's leg length). As the technology matured, a versatile quadruped robot named HyQ is developed that was able to perform highly dynamic motions using its 12 torque-controlled joints powered by hydraulic and electric actuators [30]. This hydraulic actuation allowed the powerful dynamic motions that were harder to achieve with the traditional electrically actuated robots [15]. In addition to the walking technique, another engineering concern is the design of the robot leg. A well-known contribution to this problem is the work of Boston Dynamics, in which engineers designed optimum leg mechanism to walk/run or climb in inclined and vertical surfaces [16]. Finally, an efficient physical system requires robust software, which should be built upon a peer-analyzed mathematical model. Ito et al. presented such model of the adaptation of locomotion patterns to a variable environment [17]. Among popular kinematics solutions, the Inverse Kinematics is often exploited in quadrupedal walking [18]. An efficient approach to derive Inverse Kinematics Solutions is to use Denavit-Hartenberg convention [19, 20, 21, 22]. Further controlling of velocity can be performed by using velocity kinematics solutions [23, 24, 25]. The underlying kinematics can be enhanced by introducing PID [26] or Fuzzy controller [27] to improve the movement of the robot. The objective of this paper is to design and develop the hardware for a Sprawling-type quadruped robot that has the ability to walk on a relatively smooth surface. The movement of the joints of the robot is controlled by using the Inverse Kinematics Solutions that are derived for that particular structure. The Inverse Kinematic solution is derived using Denavit-Hartenberg convention and employed to control the locomotion of the robot. After designing the structure of the robot, a custom-made simulation software is used to replicate the movement of the designed structure using the solutions. Successful results of the simulation indicate the applicability of the solutions, so the robot can be constructed as designed after that. In addition, obstacle sensing is of paramount importance to this work. Among many forms of detection technology, image processing camera, ultrasound sensor and infrared detector are more popular [28, 29, 30]. Despite the advantage of recognizing the surroundings by a camera, we have taken account the simplicity and the overall cost of the system and thus ultrasound sensors are chosen for this work. Finally, since Android-based smartphones and handheld devices are widely available, the feature to control the robot via an Android app [31] using Bluetooth technology is added. The Android-based control system is robust for control and manipulation and it increases the portability to test the robot in different environments. The robot proposed in this work is, at its conceptual level, interesting for experimental research.

Although better quality quadruped robots are available, the costs of those are beyond reach for general researchers from a developing country. Insufficient fund discourages students and general researchers to work on robotics and related field. The designed robot is very cheap compared to the similar robots available. This robot can be easily constructed from materials available locally. In addition, the hardware

design and software is available publicly so that interested people can work on their related research using these resources. Other students are currently using the developed robot that is used for this paper, for research purposes.

The paper is organized as follows: in Section 2, we discuss the methodology of the system development. Section 3 presents structure design and system model, followed by the experimental details, results and analysis in Section 4. The concluding remarks are presented in Section 5.

2. Model

2.1. Mathematical model

The quadruped robot has four legs and each one has two degrees of freedom (2DOF). These 2 degrees of freedom are for the hip joints and knee joints of the legs and in this case, revolute joints are considered. The robot has, in total, eight degrees of freedom (8DOF). The Forward and Inverse Kinematics for each leg need to be calculated to move them along the desired trajectory. But before applying the Inverse Kinematics Solutions, simulating the result is helpful to detect whether there are any errors in the solution. If the simulation is successful, those equations will be applied to the robot. For each of the four legs of this robot, a mathematical model is developed and the structure is used, as shown on the geometrical model given in Fig. 1. Here, a_1 and a_2 are constants; represent the length of thigh and leg respectively. The variables t_1 and t_2 are the angles for rotatory joints of the hip pitch joint and knee pitch joint respectively. If t_1 is to change, then the hip joint needs to rotate so that it can achieve the desired angle and same goes for t_2 and knee joint too. The (x, y, z) coordinate on the Figure represents the endpoint of the structure. By varying the angles mentioned above, the position of the endpoint will be changed. An exact implementation of proper Inverse Kinematics Solutions will move the structure's endpoint in order to perfectly follow a previously defined path.

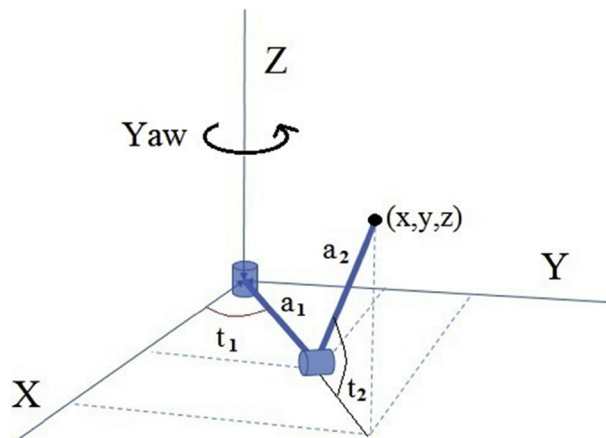


Fig. 1. Mathematical model for 2DOF leg structure.

2.2. Kinematic solutions for the 2DOF leg using Denavit-Hartenberg convention

The Forward and Inverse Kinematics Solutions for the designed 2DOF leg of the quadruped robot is derived by using the Denavit-Hartenberg Convention. These solutions will be applied to simulate and control the robot's movement. Four DH parameters (Denavit-Hartenberg) [17] are used to determine the Kinematics and Inverse Kinematics Solution for each leg. In order to define a relative position and orientation of two fixed axes (axes which do not move), *link length* (also link distance or common normal) (a) and *link twist* (α) are required. If there are more than two fixed axes, the neighboring common normals in general case will not intersect the common axis at the same point. Hence, a new parameter called *link offset* (d) is necessary. The *angles* of the joint (T) will be determined using the Inverse Kinematics Solutions. Only one of these four parameters will be variable for a single link and others will remain constant. Since the structure uses only revolute joints, in this case only the *joint angles* (T) are variable. As mentioned earlier, the joint angles are defined as t_1 for hip joint rotation and t_2 for knee joint rotation and, a_1 and a_2 are the length of thigh and leg respectively. The parameters for each leg are given in Table 1.

Since the structure has no prismatic joint, *link offset* (d) for both the links are zero. Also, the Z-axis of the second link is 90° twisted with respect to the Z-axis of the first link which is the value of *link twist* (α) for the first link. To represent the equations in an easier way, $\cos(t_1)$ and $\cos(t_2)$ are defined as c_1 and c_2 , also s_1 and s_2 represent $\sin(t_1)$ and $\sin(t_2)$ respectively.

Homogeneous transformation matrix H_1^0 for hip joint and H_2^1 for knee joint are given in Eqs. (1) and (2):

$$H_1^0 = \begin{bmatrix} c_1 & 0 & s_1 & a_1 \times c_1 \\ s_1 & 0 & -c_1 & a_1 \times s_1 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

$$H_2^1 = \begin{bmatrix} c_2 & -s_2 & 0 & a_2 \times c_2 \\ s_2 & c_2 & 0 & a_2 \times s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (2)$$

Table 1. The Denavit-Hartenberg parameters (* represents variable).

Link	a	A	d	T
L_1	a_1	90	0	t_1^*
L_2	a_2	0	0	t_2^*

The above matrices are to be multiplied to determine the total transformation matrix (H_2^0) which will represent the complete system. The total transformation matrix T is given in the Eq. (3) where, $T = H_2^0 = H_1^0 \times H_2^1$:

$$T = \begin{bmatrix} c_1 \times c_2 & -c_1 \times s_2 & s_1 & c_1(a_1 + a_2 \times c_2) \\ s_1 \times c_2 & -s_1 \times s_2 & -c_1 & s_1(a_1 + a_2 \times c_2) \\ s_2 & c_2 & 0 & a_2 s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

In the following equations, x , y , and z are the final coordinates of the corresponding axes of the endpoint for Quadruped's leg. The base motor situated on the origin of Fig. 1 rotates the leg on the Yaw axis/Z axis. Transformation matrix T is used to determine the Inverse Kinematics Solutions. The first three values of the fourth column represent the value of x , y , and z respectively. The Kinematics solutions for the following structure is given in Eqs. (4)–(6):

$$x = (a_1 + a_2 \cos(t_2)) \cos(t_1) \quad (4)$$

$$y = (a_1 + a_2 \cos(t_2)) \sin(t_1) \quad (5)$$

$$z = a_2 \sin(t_2) \quad (6)$$

The Inverse Kinematics Solutions are given in Eqs. (7) and (8):

$$t_1 = \text{atan2}(y, x) \quad (7)$$

$$t_2 = \text{atan2}\left(z, \left(\sqrt{x^2 + y^2} - a_1\right)\right) \quad (8)$$

Inverse Kinematics equations (Eqs. (7)–(8)) are necessary because they describe the necessary angles for the motors to change the position of the end of the leg to any desired point.

2.3. Equations for quadruped

To establish the Kinematic chain for the whole body, defining the coordinates of the legs and body is required. The baseplate or body of the robot is a square shaped quaternary link where the four legs are connected to its four corners. In this experiment, the center of the body is considered as the origin of the whole quadruped and denoted as O_c . The red arrows and red texts are showing detailed information about the axes. Similarly, the origin of any leg is considered on the legs hip joint and denoted as O and the Blue arrows and blue texts represent that coordinate's details. In Fig. 2(A), these coordinates are demonstrated. In the above section, the Inverse Kinematics (IK) solutions for a 2DOF leg structure are deduced (Eqs. (7)–(8)). To move the quadruped robot, the legs should follow a previously defined path with respect to

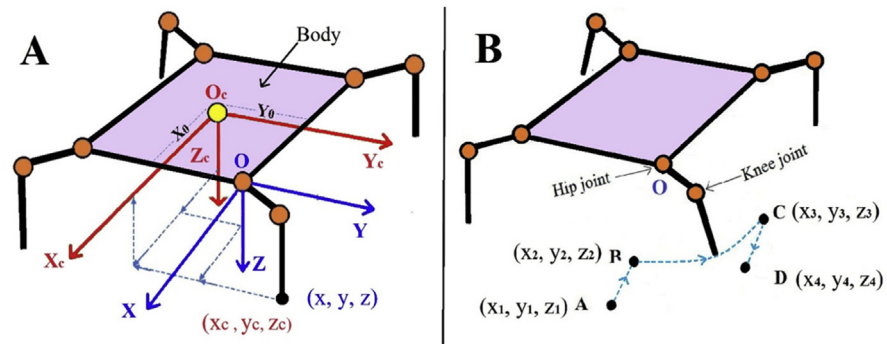


Fig. 2. Mathematical model of the Quadruped robot (A) and the trajectory of the endpoint legs (B).

the center of the body of the robot but to implement the IK equations the coordinates with respect to the hip joint of the leg is necessary. Equations that will transform the 'coordinates with respect to body origin' to 'coordinates with respect to leg origin' need to be defined. Since the body dimensions are constant and the legs are attached to the body at a fixed distance, the distance of the body origin and leg origins are fixed. This is shown in Fig. 2(A). The distance along X coordinate from O_c to O is considered as " x_0 " and similarly, " y_0 " is the distance for the Y coordinate. Let's consider the coordinates of the endpoint of the leg with respect to the center of the body, origin O_c is (x_c, y_c, z_c) and with respect to the legs coordinates, origin O , is (x, y, z) . Now the transformation equations to change the leg's endpoints coordinates from the body structure to leg structure is given in Eqs. (9)–(11):

$$x = x_c - x_0 \quad (9)$$

$$y = y_c - y_0 \quad (10)$$

$$z = z_c \quad (11)$$

Since the origins are on the X-Y plane the value for the Z-axis will remain same for both coordinates as shown in Eq. (11).

2.4. Leg trajectory and implementation of Inverse Kinematics

To represent how the IK solutions are implemented, we considered a trajectory path for the endpoint of a leg. In Fig. 2(B), this trajectory path is shown with the dotted line and the arrow represents the direction of the movement. It should be mentioned here that the 2DOF structure has some limitations such as the structure will not be able to move straight toward Z axis without affecting the X and Y coordinates values. But the levitation of endpoint can be effectively performed in this procedure to move the robot's position. In this case, the endpoint will start from point A (x_1, y_1, z_1) and it will move from there to point B (x_2, y_2, z_2) and then to C (x_3, y_3, z_3) and the movement will end on point D (x_4, y_4, z_4) . To move from point A to point

B, the software on the controller will first calculate the angles of the hip joint and knee joint (t_{1A} , t_{2A}) for point A and then it will calculate same angles (t_{1B} , t_{2B}) for point B. The difference between the hip joint angles of point A to point B is the angle (t_{hip}) that the hip joint motor needs to rotate to move the leg from point A to point B. The same procedure goes for the knee joint motor to determine the rotation angle (t_{knee}). This procedure is followed for every point to point movement of the endpoint of the leg. Equations for calculating the angles to move the leg from point A to B are given in Eqs. (12)–(13):

$$t_{hip} = t_{1B} - t_{1A} \quad (12)$$

$$t_{knee} = t_{2B} - t_{2A} \quad (13)$$

3. Methodology

3.1. Design of the structure

As described earlier, the robot contains four legs and each one has two degrees of freedom of its movement. These two rotational points are the hip joint (which moves both the thigh and leg together on Z-axis) and the knee joint that only moves the leg. A 3D representative model of the robot is given in Fig. 3, where the left image shows the top view of the design and the right one shows the bottom. Here, the cylinders represent the rotation axis for every joint and hence the positions of the motors. The whole structure contains eight rotating freedom points. The length of the thighs and legs are 5.5 cm and 9 cm respectively. A square-shaped base with the dimension of 7 cm on each side, holds four legs on its corners. The controller board along with other circuits and sensor will be attached to the top of the base and the power source will be added on the lower side.

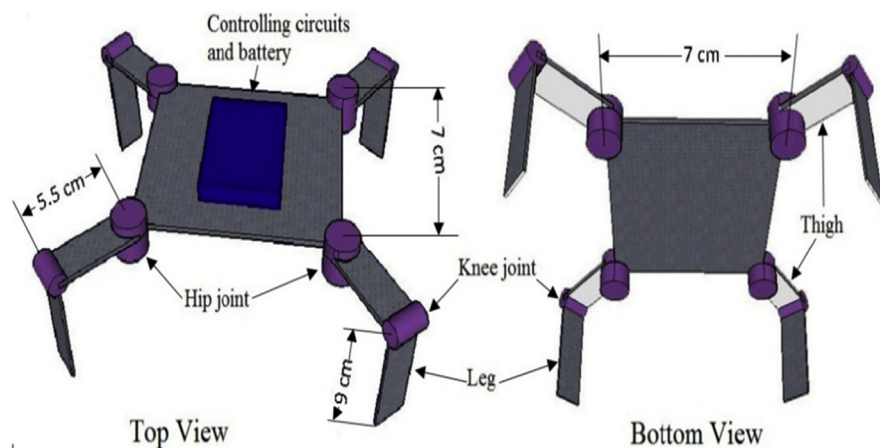


Fig. 3. Quadruped Robot design and dimension.

3.2. Model of the system and software interface

The robot is controlled from Android environment by using a custom-made Android software. The interface of the software is given in Fig. 4 (right). Using this software backbone, the user will be able to turn on/off the control panel communication using the On and Off button. It will enable six different movements of the robot, which are: forward movement, backward movement, left movement, right movement, clockwise rotation and anti-clockwise rotation. These movements will be performed by using the buttons Front, Back, Left, Right, R-Right, and R-Left. The speed of the robot could also be controlled by the software using the sliding button. HT-05 Bluetooth transceiver will be used with a microcontroller to establish the communication. The microcontroller will control eight servo motors of all rotating points of the robot. On the front side of the robot, an ultrasound transceiver is connected which will be used to measure the distance of any obstacle. This will be useful to avoid any collision of the robot with any object when it is moving toward it. If the robot detects any obstacle, it will move to the right or left until the obstacle is avoided. A simple model of the total system is given in the Fig. 4 (left).

3.3. Walking algorithm

The walking algorithm of the robot is almost the same for the four directional movements (i.e., Front, Back, Left and Right). The rotation movement in both directions follows a slightly different movement pattern of the motors. Every movement follows six steps (from A to F) sequentially, as illustrated in the diagram of Fig. 5. The limbs are numbered from 1 to 4, as given in the Figure, will be used to describe the process. At the first step, the robot will be at a stand position (rest position). During step B, leg 1 and 3 will be moving up towards Z axis. Since leg 1 and 3 are above the ground, the movement of the other legs will move the whole body with respect to

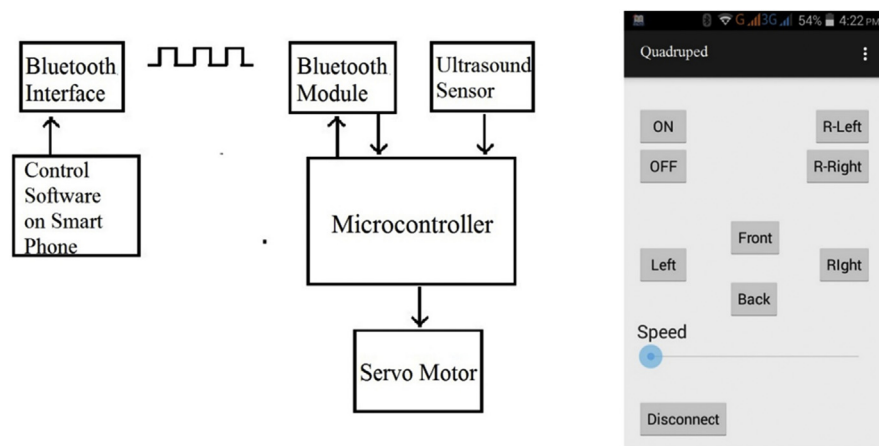


Fig. 4. Block Diagram of the system (left) and Android Software interface (right).

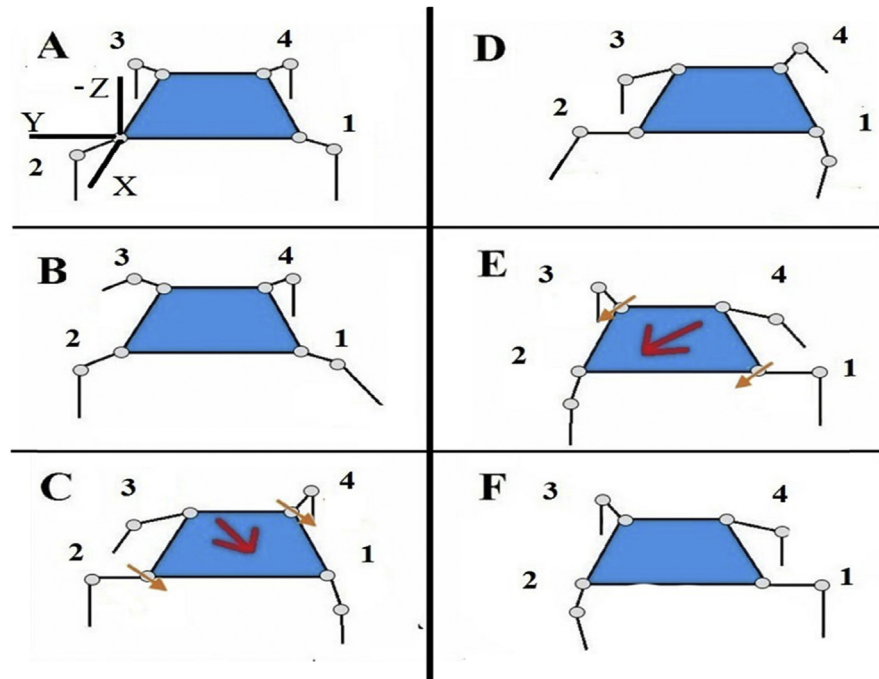


Fig. 5. Diagram for the forward walking algorithm.

the ground. In step C, the hip joints of leg 2 and 4 will change their coordinates toward the forward-left direction, while the endpoints will stay attached to the ground. Since leg 1 and 3 are levitated the whole body will move with this movement toward the forward-left direction. On step D, the endpoints of leg 1 and 3 will touch the ground and 2 and 4 will move up with respect to the ground. After that, a similar movement like the step C will be performed on step E and this time the movement of the body will be dependent on leg 1 and 3 and the body will move in the forward-right direction. On step F, all of the legs will touch the ground so that robot can stand on the ground and be stable. The body will move twice in the whole process; first in the forward-left and second in forward-right direction. With a combination of these movements, the robot will move in the forward direction. Just after the levitation of two legs on step B and D, the body moves forward, which keeps the robot balanced.

Although the robot is unable to keep its balance only on a pair of legs while resting, the entire kinematic process will take place within a short span of time where the body will move forward and thus the balance of the whole structure will be maintained. If the robot stops its movement at any point, it will always balance on all fours. Also, the wide ends of the legs will provide a sufficient support base to keep it from toppling over.

To move right, backward or left this same algorithm will be applied, just by considering the numbers of the limbs 1–4 shifted. For example, if the robot wants to move right the limb 4 will be 1, 3 will be 4, 2 will be 3 and 1 will be 2. For rotation, the

above-described steps will be followed except for the steps C and E, where all the legs will move to a certain direction on step C and in an opposite direction to that on step E to rotate the robot in the anti-clockwise direction and vice versa for clockwise rotation.

4. Results & discussion

4.1. Software simulation

The Inverse Kinematics Solutions deduced (Eqs. 7 And 8) to calculate the value of t_1 and t_2 are simulated using a custom-made three-dimensional software interface (Fig. 6). The software is designed using “Processing” Programming language. Here, a 2 DOF structure is placed with the appropriate coordinate system where the origin is situated on the hip joint. These coordinates are similar to the robot’s leg coordinate system shown in Fig. 2. In this software, the structure can be viewed from different angles by using the mouse pointer and buttons.

The user is able to change the three-dimensional Cartesian (X, Y, and Z) position values of the endpoint of the structure and the software will calculate the angles for the two joints (hip and knee) using the Inverse Kinematics Solutions. By pressing the ‘Right Arrow’ and ‘Left Arrow’ on the keyboard, the user will be able to change the position of the X-axis of the legs endpoint position. The Y-axis value will be varied by using the ‘Up Arrow’ and ‘Down Arrow’ key. For Z-axis the ‘+’ and ‘-’ key will be used. The software will only rotate the angles of the hip and knee joint. The structure’s endpoint will be moved to the given coordinate by rotating the joints with the calculated angles. The software will also show the real-time values of the variables (x , y , z , t_1 , t_2) on the X-Y plane.

The output of the simulation software gives the predicted results, which concludes that these equations can be used to move the limbs of the quadruped to any

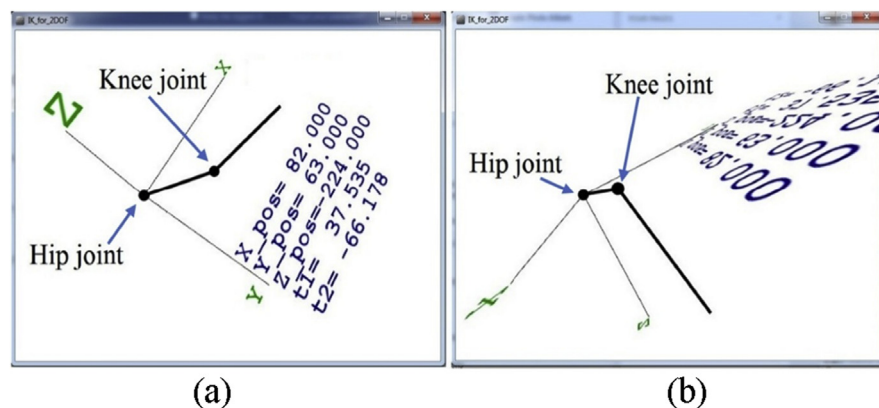


Fig. 6. Simulation software output for 2DOF structure: (a) and (b) are depicting two screens of the simulated output.

predetermined position by rotating the motors with the calculated angles from the solutions.

4.2. Developed hardware

The developed hardware with the full setup is shown in Fig. 7. Fig. 7(a) and (b) are showing different views of the developed quadruped robot. The structure of the robot is designed and shaped by hand from 1.5 mm aluminum sheet. Every piece was drilled at a certain distance to reduce the weight of the robot. Nuts and bolts are used to connect different parts together. To attach the battery on the bottom of the robot glue gun is used. A thin foam is placed between the circuits and base of the robot, which will void any short-circuit phenomenon due to the metallic base of the robot.

4.3. Automatic obstacle avoidance

The Ultrasound sensor (Ping) can detect any obstacle within 2 cm–300 cm approximately. The sensor has an ultrasound signal transmitter and a receiver combined with one circuit. The microcontroller will send a predefined sequence of a signal using the transmitter and will wait for the receiver to pick up the signal with the same sequence. After that, the delay between and transmission and receiving the signal is multiplied by the velocity of sound to calculate the distance of any unwanted obstacle situated in front of the robot. The robot uses this obstacle sensing to avoid any impediment automatically and dodges any collision. This automatic obstacle avoiding system can help the robot to move along a guided path and reach any destination. This is also usable in case the robot needs to find any object in any open field. The distance 300 cm is 1500% of the total length of the robot, which is approximately 20 cm, including the legs. There is a problem associated with the whole system, which is if any obstacle has a smooth surface and the angular position with

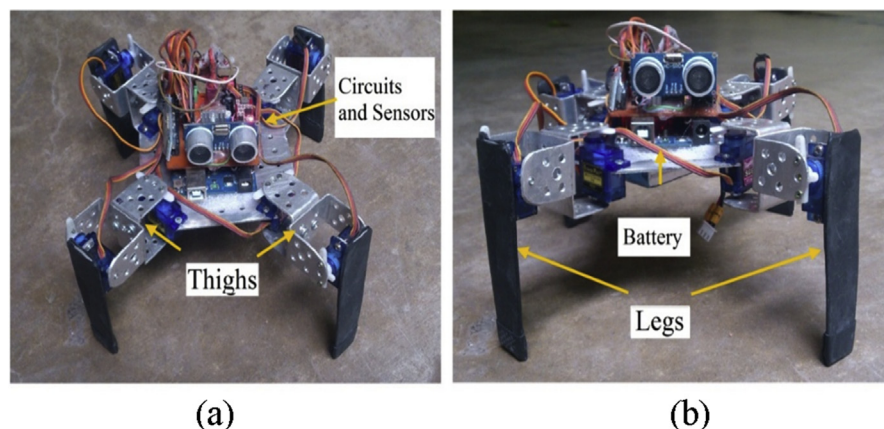


Fig. 7. The developed Quadruped Robot: (a) and (b) are showing different views.

respect to the robot in such a way that, it will reflect the sound signals in directions opposite to the robot, the probability of the robot to detect the distance successfully before colliding low. However, considering that situation is rare, the obstacle avoidance system is a success in reducing the collision of the robot during forwarding movement.

4.4. Speed measurement

The robot responds to the given command from the Android environment as designed. The Robot was made to move forward alongside a scale of 0 cm–100 cm and a camera recorded this movement of the robot. The displacement is recorded from the scale and the time duration is calculated from the video and these are used to calculate the speed of the robot. Four different images of the robot's movement from 0 second to 6 seconds on the video are given in Fig. 8. The Quadruped robot designed in this experiment has a speed of about 15.5 cm/s on Formica board shown in the image. To complete a full rotation of 360° on both rotations (clockwise and anticlockwise) it roughly takes 6 seconds.

The speed and moving ability of the quadruped robot are tested for different surfaces and best speed was recorded on Formica board mentioned above (15.5 cm/s). On slightly rough soil the speed was recorded 10 cm/s. The speed of the robot on asphalt is about 8.5 cm/s. On the cemented floor, the speed is about 10.7 cm/s. The movements of the robot in different surfaces are given in Fig. 9.

The robot is using the ultrasound sensor to measure obstacles. Currently, it is programmed to avoid any obstacle that is closer than 20 cm to the robot's front side. If it detects any obstacle within the 20 cm range, it will move either left or right until the obstacle is avoided (or not within 20 cm), and then it will move forward again. For the time being the sensor is fixed on the structure, but it can be attached to a servo motor so that obstacles can be detected in other directions too.

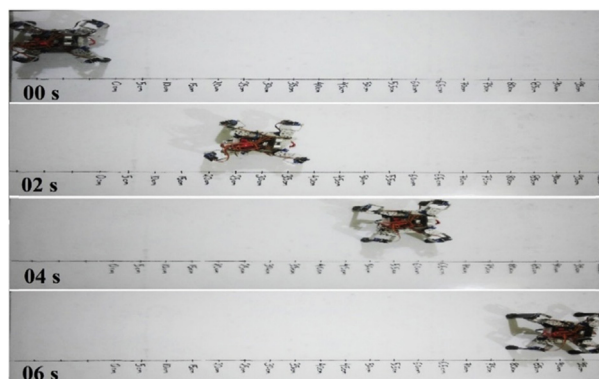


Fig. 8. Time-lapse images of forward walking of the Quadruped.

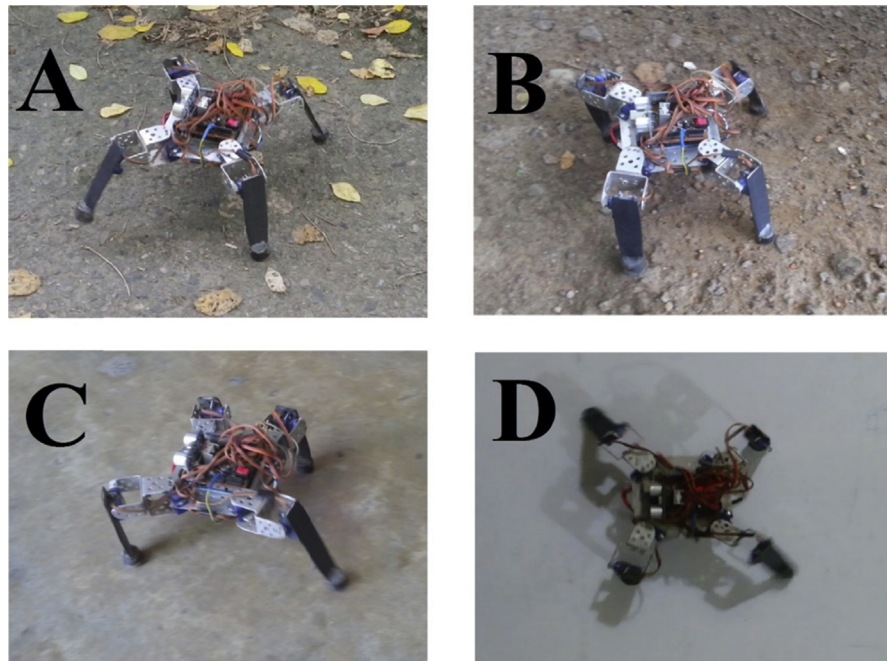


Fig. 9. Quadruped robot moving on different surface. (A. Asphalt, B. Rough Soil, C. Cemented floor, D. Formica Board).

5. Conclusions

In this paper, a quadruped robot is designed that can be controlled by an Android operating system. The custom-made three-dimensional software simulates the 2DOF leg of the robot. The movement of the leg on simulation software is performed using the Inverse Kinematics Solutions that are obtained using the Denavit-Hartenberg convention. The simulation demonstrates that the expected results of the movement and these equations could be used to control the movement of the robot's limbs. This robot can move in any of the four directions almost instantly without full body rotation, which makes the robot more dynamic. It can move at a speed of approximately 15.5 cm/s. It can successfully detect obstacles within 300 cm and will avoid them if they are closer than 20 cm. The robot will be able to move on a guided path sensing the obstacles previously placed to create the path. Remote controlling from the Android operating system along with its automatic obstacle avoiding feature makes the robot efficient to reach any destination as desired. The robot faces some difficulty walking through slippery surfaces. The endpoint of the leg of the robot needs to be mechanically improved so that it would be able to create enough friction even on slippery surfaces. Current structure cannot walk on very rough terrain and walk on such surface can be implemented if the robot is designed in 3DOF limb structure instead of 2DOF limbs. Designing the structure with more degrees of freedom can give the robot more advantages like climbing

stairs [32, 33] or complex balancing [34] in difficult situations. Additionally, this robot can be constructed with a low budget and hence const effective.

The future plan is to develop an efficient path planning algorithm and apply the algorithm using this robot. It can be employed to perform a task, such as carrying objects autonomously to remote places. An improved design of this quadruped robot (designed with 3DOF leg structure instead of 2DOF structure used in its current design) will provide more versatility on movement. Also, the Android software will be developed to be more dynamic and will show more real-time information and feedbacks from different sensing devices attached to the robot. Other sensors like GPS, accelerometer and gyro meter can be added to provide more features and also will provide a more dynamic control over the robot.

Declarations

Author contribution statement

Md. Moin Uddin Atique: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Md. Rafiqul Islam Sarker: Conceived and designed the experiments; Performed the experiments; Contributed reagents, materials, analysis tools or data.

Md. Atiqur Rahman Ahad: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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The authors declare no conflict of interest.

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References

- [1] Y. Fukuoka, H. Kimura, A.H. Cohen, Adaptive dynamic walking of a quadruped robot on irregular terrain based on biological concepts, *Int. J. Robot Res.* 22 (3–4) (2003) 187–202.
- [2] S. Kitano, S. Hirose, A. Horigome, G. Endo, TITAN-XIII: sprawling-type quadruped robot with ability of fast and energy-efficient walking, *ROBO-MECH J.* 3 (1) (2016) 1.
- [3] H. Kimura, Y. Fukuoka, A.H. Cohen, Adaptive dynamic walking of a quadruped robot on natural ground based on biological concepts, *Int. J. Robot Res.* 26 (5) (2007) 475–490.
- [4] J. Buchli, A.J. Ijspeert, Self-organized adaptive legged locomotion in a compliant quadruped robot, *Aut. Robots* 25 (4) (2008) 331–347.
- [5] Y. Fukuoka, H. Kimura, Y. Hada, K. Takase, “Adaptive dynamic walking of a quadruped robot ‘Tekken’ on irregular terrain using a neural system model.” in *Robotics and Automation, 2003*, in: *Proceedings. ICRA’03, IEEE International Conference on*, 2, IEEE, September 2003, pp. 2037–2042.
- [6] Y. Fukuoka, H. Kimura, Dynamic locomotion of a biomorphic quadruped ‘Tekken’ robot using various gaits: walk, trot, free-gait and bound, *Appl. Bionics Biomechanics* 6 (1) (2009) 63–71.
- [7] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, T.B. Team, Bigdog, the rough-terrain quadruped robot, *Proc. 17th World Cong.* 17 (1) (July 2008) 10822–10825.
- [8] D. Wooden, M. Malchano, K. Blankespoor, A. Howardy, A.A. Rizzi, M. Raibert, “Autonomous navigation for BigDog.” in *robotics and automation (ICRA)*, in: *2010 IEEE International Conference on*, IEEE, May 2010, pp. 4736–4741.
- [9] D.V. Lee, A.A. Biewener, BigDog-inspired studies in the locomotion of goats and dogs, *Integr. Comp. Biol.* 51 (1) (2011) 190–202.
- [10] L. Ding, R. Wang, H. Feng, J. Li, Brief analysis of a BigDog quadruped robot, *Zhong Guo Ji Xie Gong Cheng (China Mechanical Engineering)* 23 (5) (2012) 505–514.

- [11] J.R. Rebula, P.D. Neuhaus, B.V. Bonnlander, M.J. Johnson, J.E. Pratt, A controller for the littledog quadruped walking on rough terrain, in: *Robotics and Automation, 2007 IEEE International Conference on*, IEEE, April 2007, pp. 1467–1473.
- [12] M.P. Murphy, A. Saunders, C. Moreira, A.A. Rizzi, M. Raibert, The littledog robot, *Int. J. Robot Res.* (2010), 0278364910387457.
- [13] A. Shkolnik, M. Levashov, I.R. Manchester, R. Tedrake, Bounding on rough terrain with the LittleDog robot, *Int. J. Robot Res.* (2010), 0278364910388315.
- [14] P. Filitchkin, K. Byl, Feature-based terrain classification for littledog, in: *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*, IEEE, October 2012, pp. 1387–1392.
- [15] C. Semini, N.G. Tsagarakis, E. Guglielmino, M. Focchi, F. Cannella, D.G. Caldwell, Design of HyQ—a hydraulically and electrically actuated quadruped robot, *Proc. IME J. Syst. Contr. Eng.* (2011), 0959651811402275.
- [16] Buehler, M. and Saunders, A., Boston Dynamics, “Robot and robot leg mechanism.” U.S. Patent 7, 734,375, 2010.
- [17] S. Ito, H. Yuasa, Z.W. Luo, M. Ito, D. Yanagihara, A mathematical model of adaptive behavior in quadruped locomotion, *Biol. Cybern.* 78 (5) (1998) 337–347.
- [18] J.A. Buford, R.F. Zernicke, J.L. Smith, Adaptive control for backward quadrupedal walking. I. Posture and hindlimb kinematics, *J. Neurophysiol.* 64 (3) (1990) 745–755.
- [19] M.M.U. Atique, M.A.R. Ahad, Inverse Kinematics solution for a 3DOF robotic structure using Denavit-Hartenberg Convention, in: *Informatics, Electronics & Vision (ICIEV), 2014 International Conference on*, IEEE, May 2014, pp. 1–5.
- [20] C. Villard, P. Gorce, J.G. Fontaine, Study of a distributed control architecture for a quadruped robot, *J. Intell. Rob. Syst.* 11 (3) (1994) 269–291.
- [21] V.J. Santos, F.J. Valero-Cuevas, Reported anatomical variability naturally leads to multimodal distributions of Denavit-Hartenberg parameters for the human thumb, *Biomed. Eng. IEEE Trans.* 53 (2) (2006) 155–163.
- [22] K. Abdel-Malek, S. Othman, Multiple sweeping using the Denavit–Hartenberg representation method, *Comput. Aided Des.* 31 (9) (1999) 567–583.

- [23] M.W. Spong, S. Hutchinson, M. Vidyasagar, *Robot Modeling and Control*, John Wiley & Sons, Inc., 2006.
- [24] M.Z. Huang, S.H. Ling, Y. Sheng, A study of velocity kinematics for hybrid manipulators with parallel-series configurations. In *Robotics and Automation*, 1993, in: *Proceedings. of, 1993 IEEE International Conference on*, IEEE, May 1993, pp. 456–461.
- [25] A. Kelly, N. Seegmiller, A vector algebra formulation of mobile robot velocity kinematics, in: *Field and Service Robotics*, Springer Berlin Heidelberg, 2014, pp. 613–627.
- [26] P.T. Doan, H.D. Vo, H.K. Kim, S.B. Kim, A new approach for development of quadruped robot based on biological concepts, *Int. J. Precis. Eng. Manuf.* 11 (4) (August 2010) 559–568.
- [27] X. Chen, K. Watanabe, K. Kiguchi, K. Izumi, An ART-based fuzzy controller for the adaptive navigation of a quadruped robot, *Mech. IEEE/ASME Trans.* 7 (3) (2002) 318–328.
- [28] E. Jumentoro, A.H. Alasiry, H. Hermawan, Stability optimization on quadruped robot using trajectory algorithm, in: *Engineering Technology and Applications (IES-ETA)*, 2017 International Electronics Symposium on, IEEE, 2017, September, pp. 93–98.
- [29] K. Izumi, K. Watanabe, M. Shindo, R. Sato, Acquisition of obstacle avoidance behaviors for a quadruped robot using visual and ultrasonic sensors, in: *Control, Automation, Robotics and Vision*, 2006. ICARCV'06. 9th International Conference on, 2006, pp. 1–6.
- [30] K. Izumi, R. Sato, K. Watanabe, M.K. Habib, Selection of Obstacle Avoidance Behaviors Based on Visual and Ultrasonic Sensors for Quadruped Robots, INTECH Open Access Publisher, 2007.
- [31] Z. Shaikh, P. Gaikwad, N. Kare, S. Kapade, M.V. Korade, A implementation on—surveillance robot using Raspberry-PI technology, in: T. Boaventura, C. Semini, J. Buchli, M. Frigerio, M. Focchi, D. Caldwell (Eds.), *Dynamic Torque Control of a Hydraulic Quadruped Robot*, IEEE ICRA, 2017, pp. 1889–1894, 2012.
- [32] A. Zamani, M. Khorram, S.A.A. Moosavian, Stable Stair-climbing of a Quadruped Robot, 2018 arXiv preprint arXiv:1809.02891.
- [33] G. Lan, Y. Wang, M. Yi, Novel design of a wheeled robot with double swing arms capable of autonomous stair climbing, in: *Proceedings of the 2018*

International Conference on Mechatronic Systems and Robots, ACM, 2018, May, pp. 110–114.

- [34] J.A. Castano, E.M. Hoffman, A. Laurenzi, L. Muratore, M. Karnedula, N.G. Tsagarakis, A whole body attitude stabilizer for hybrid wheeled-legged quadruped robots, in: 2018 IEEE International Conference on Robotics and Automation (ICRA), IEEE, 2018, May, pp. 706–712.