Kinematic Analysis of Six-Legged Robot

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***Abstract*—Nowadays, robots are applied in many fields which means flexibility in robot movement is always in high demand. A walking robot is a form of a mobile robot that is gentle to the environment, and it is possible to move through various settings while selecting landing points. In this study, a systematic approach for dealing with a controlling algorithm is proposed for the six-legged walking robot. A mathematical model is applied for studying the kinematics and gaits of the six-legged robots based on parallel and serial kinematic mechanism theory. The kinematic analysis is based on classical kinematic theory, which uses a formulation that is helpful in computer algorithms. The experiment results show that the effectiveness of robot design and control algorithms are responsive to different movements.**

***Keywords*—legged robot, hexapods, six-legged robot, kinematics, gait**

I. Introduction

With the development of control algorithms, much research has been done to replace humans in performing dangerous, difficult, or boring tasks [1–3]. Different approaches have been proposed to deal with different problems such as agricultural classification, assisting doctors in medicine, traffic, etc. [4–6]. Robots are used to conquer extreme terrain, new places need to be explored is the purpose of creating walking robots [7]. Robots become more sophisticated, they will be applied to a greater range of applications, many of which will require high mobility. In recent years, the study of walking robots has been widely studied in labs and institutes around the world. A walking robot is a robot that has legs and can move around with its legs. Some fields can be applied to wheel mobile robots, however, there are many environments and areas of activity that only a walking robot can move on complex such as: rocky, hilly, and muddy, etc. These conditions are not suitable for wheel mobile robots. Therefore, studies of walking robots will have advantages over wheel robots. While studying robots that move by joints, chains, or wheels, robots with wheels are easy to control and achieve high stability, easy to design with intelligence algorithms [8, 9], but the disadvantage is that it requires the ground plane to be flat. Hence, a walking robot is proposed in this study. Nowadays, many researchers have been making efforts to apply controlling algorithms to multi-legged robots [10, 11]. This robot has very complicated structures and is difficult to control, but they also have some advantages compared to other robots such as can walk over obstacles, can move on complex terrain and slippery surfaces. The above advantages show that the future of walking robots will be widely applied in industry, inspection, testing, the space industry, and rescuing human life. Research and development of algorithms for the 6-legged robot are performed in this work.

II. Structure of Hexapod

Objectives of multi-legged robots are to provide a motion platform moving following a specific trajectory and to allow a complete decoupled motion from irregularity grounds. So, it is necessary to have six legs connected between the robot's body and the ground.

A. *Performance of Robot*

Developed Hexapod is a 6-legged robot (see Fig. 1), which can move on 3 legs or more for each step. Therefore, if one leg of the hexapod is broken, the robot can keep still walking. With a triangular gait, the 6-legged robot can move faster than a 4-legged robot [12]. And it achieves high speed when the gait is stable. However, triangular gait is usually more unstable than waveform gait. Therefore, increasing stability requires strong actuators as well as large torques, 6 legs of the robot are divided into 2 groups for control. For example, we break down into groups and communicate by master slaver instead of controlling all legs based on a microcontroller.

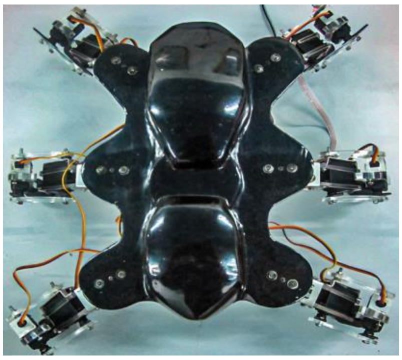

Fig. 1. Designed 6-legged robot.

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B. Leg Structure of Robot

The total weight and each leg of the robot need to be considered carefully when designing the mechanical structure of each leg. Because a robot whose legs need to take into account energy efficiency and requires less torque at the same time. In order to have flexible movement, the motors on the robots must be relatively independent of each other. Therefore, it is necessary to choose a structure with stability and energy efficiency. Three servo motors are used in each leg as shown in Fig. 2. The servo motors of the second and third joints rotate around 2 horizontal axes and the motor of the first joint rotate on a vertical axis.

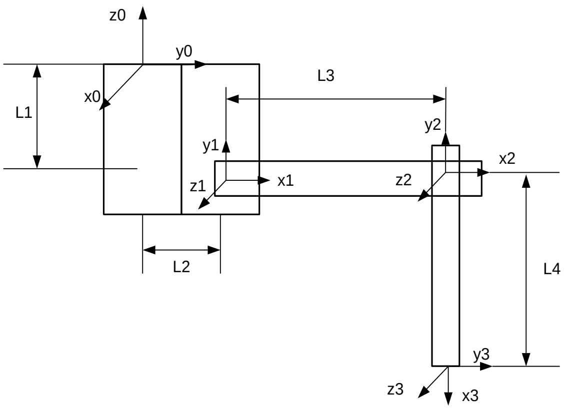

Fig. 2. Configuarion of each leg.

III. EQUATIONS THE TYPE OF WALK OF HEXAPOD

A. Design the Gaits of Robot

At the first, the gait of the robot to move in a straight line often is studied, then the stability and the change of foot position are analyzed based on the robot's gait [13]. The change of foot position should be determined to give the trajectory moving of the robot's body. In order to control a walking robot, it is important that the robot legs do not touch each other, so choosing the type of walk that we must avoid the legs being entangled in the movement to ensure the required speed and stability. There are two types of walks that a 6-legged robot can do: the triangular gait and the waveform gait. Each way is suitable for different types of terrain, with each type of terrain only a certain way to move.

Triangular gait means that the robot is used for moving on a plane with fast-moving speed. The robot is always in balance because the robot always has at least 3 legs in contact with the ground. This gait is made up of 2 phases, raised by 3 legs then they are lowered to lift the other 3 legs. When the 3 raised legs are pushed back and the body moves forward and so on, the following cycles continue as described in Fig. 3. This is the simplest and most stable gait of a 6-legged robot. The main rule of triangular gait is that we divide the robot legs into two different groups but perform the same moves at half the cycle. However, this way is not the best way for a stationary robot with 6 legs.

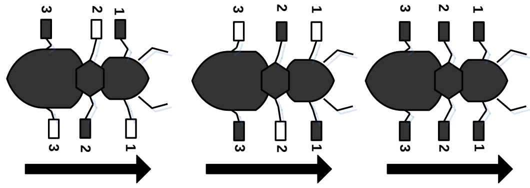

Fig. 3. Triangular gait of 6-legged robot.

With waveform gait, the first move is at the last leg of one side. As the legs move, the order of the leg that step forward spreads like a wave forward of the body and continue with the other legs starting from the last rear leg. This means that the robot always has 5 legs that come into contact with the ground at all times as described in Fig. 4. This is the slowest way of walking as described above but it has the most stability. and can move on complex rugged environments such as mountain and large obstacles. The purpose of the research is to control the robot to go straight at low speed.

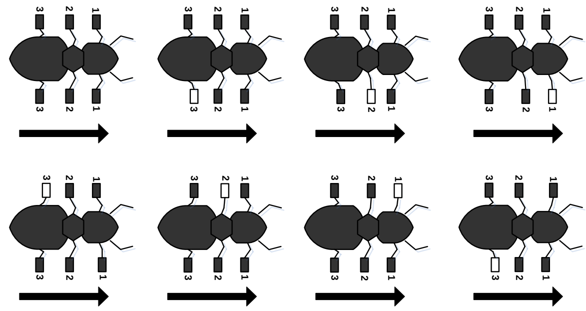

Fig. 4. Waveform gait of 6-legged robot.

With the aforementioned problems, the physical properties of the robot are proposed with the robot's nervous system to be the electronic control unit, where it processes all the information that is given and makes decisions to control the actuators. Electrical signals are converted into pulse signals that go into the microprocessor to process related signals. The microprocessor then processes these signals and makes decisions about the surrounding environment. It will then turn into a control signal making the actuators make the motion. There are 2 levels of control for the robot. Low-level controls include all the gait the leg moves. High-level control is controlling appropriately all data of the surrounding environment, in this way the robot must meet the requirements according to the input data from the signals of the sensors to put figuring out the proper gait to move. The robot carries 12 motors, 6-foot mechanisms, processing controllers, and batteries on its body, so the most efficient use of energy in robot motion is necessary. The energy efficiency of walking robots is calculated in Eq. (1).

$$\rho = \frac{E}{W \cdot L} \tag{1}$$

where E is the energy consumed in motion; W is the mass of the robot; L is the distance traveled.

When the robot is moving vertically, the typical resistance is 1. The overall performance of the robot is moving horizontally at a constant speed on a friction surface with a drag coefficient of 0. When the foot slides on the surface On the other hand, the characteristic drag coefficient is the friction coefficient. Human walking at normal speed has a typical coefficient of 0.3–0.4. In the above, we realize that it is difficult to determine the parameters such as mass and energy consumption. Here we see mass and energy are the load and energy consumed during the move.

B. Method to Push the Body to Move

The robot's gait is based on the movements of the robot's legs to create moves. The control algorithm is developed in the triangular gait means that the legs of the robot are divided into 2 groups. The first group of pins includes PA, TB, and PC pins. The remaining legs are the second group of legs. There are 2 options to create foot movement. Firstly, the pivots are fixed at the footing point, and rotating motor number 1 backward makes the robot body pushed forward, with this movement the kinetic energy and potential of the robot are constant which is shown in Fig. 5. And the pivots will be fixed and motors number 1, 2, and 3 move in such a way that the trajectory of the center of the robot is straight. In option 2, the kinetic energy and potential of the Robot are changed according to each position of the center of attention so as to ensure the preservation of mechanical energy which is described in Fig. 6. The robot has 6 legs and 3 motors are used to control a leg. The motors rotate vertically at axis 1 so that the body or legs move forward or backward we call the angular θ_1 and the motors to raise the leg up or lower the foot we call the angular θ_2, and θ_3. If the leg is perpendicular to the body, then we have the value θ_1 as 0. If the leg moves forward, we have the angle θ_1 positive and backward negative. The angular value θ_2, and θ_3 is 0 when horizontal and positive if the pins are far from the ground.

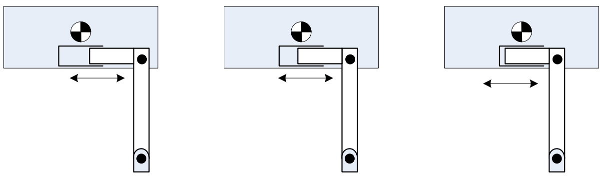

Fig. 5. Constant kinetic and potential energies.

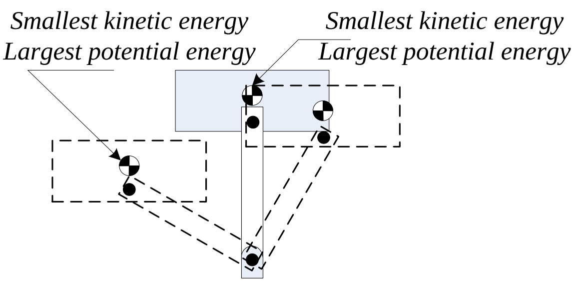

Fig. 6. Different Statements of energy in robot's movement.

C. Straight Motion Algorithm

Control algorithms are developed in a way that changes triangles. The legs of the robot are divided into two groups of legs including leg *L1* (first leg on the left), *R2* (second leg on right), and *L3* (third leg on left) in the first group, and the remaining legs in group two. The control algorithm is given as follows. First, the robot is in the initial state then the first leg group is raised angles θ_2, θ_3 off the ground, then the second group pins two turns back with rotation angle θ_1. This makes the robot's body is moved forward. Shortly thereafter, the first leg group turns in the direction that the second group of legs rotated at an angle of θ_1. At this time, the second leg group is lowered by turning the motor $-\theta_2$, $-\theta_3$ to the new position. After all the motor feet touch the ground, the second leg group is raised to an angle of θ_2, θ_3, rotate the first leg group 1 by $-\theta_1$, and the robot continues to move up. The second group will rotate and lower the foot to the new position. So, the robot's legs are back to their original position and the robot has moved 2 steps. The final position is made by following the above steps.

Considering the 6-legged robot is operating on a plane with a large degree of inclination according to triangular gait with a moving trajectory in a straight line so the trajectory of the coordinate system and a_i is the trajectory of the center of the robot. In order for the center to move a segment Δy along the y axis, the motion trajectory of the coordinate bi of the leg is also Δy. Assuming the initial angle of the foot is the waving angle θ_{10} and the leg lifting angle is θ_{20} so that the moving leg creates the movement trajectory of the body based on the straight line, which is defined in Eqs. (2)–(4). Besides, the flowchart of the process of straight motion is defined in Fig. 7.

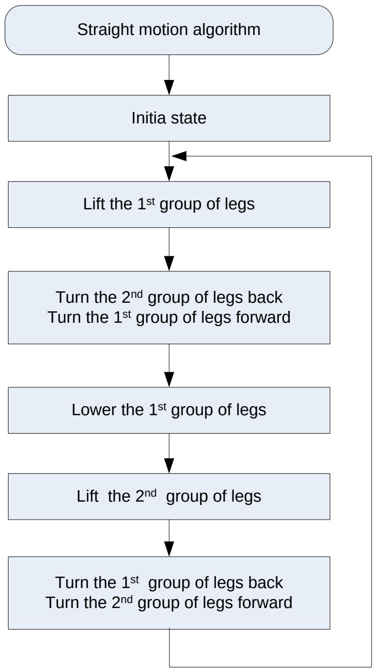

Fig. 7. Straight motion algorithm.

Let the offset move horizontally to zero.

$$\cos\theta_2 = \frac{c\,\theta_{10}\cdot c\,\theta_{20}}{c\,\theta_1} \tag{2}$$

In order to move a segment S with n steps for the Robot, then:

$$S = 2\cdot L2\cdot n\cdot\cos\theta_2\cdot s\theta 1 = 2\cdot n\cdot L2\cdot\cos\theta_{10}\cdot\cos\theta_{20}\cdot\tan\theta_1 \tag{3}$$

where:

$$\theta 1 = arctg\left(\frac{S}{2\cdot n\cdot c\theta_{10}\cdot c\theta_{20}}\right)$$

$$\theta 2 = arctg\left(\sqrt{\frac{1-k^2}{k^2}}\right)$$

$$k = \frac{c\theta_{10}.c\theta_{20}}{c\theta_1}$$

Number of moves of the robot must satisfy the condition after the angle $\alpha_{min} < \theta_1 < \alpha_{max}$.

$$\frac{S}{2\cdot n\cdot L2c\theta_{10}\cdot c\theta_{20}\cdot tg\alpha_{\max}} < n < \frac{S}{2\cdot n\cdot L2c\theta_{10}\cdot c\theta_{20}\cdot tg\alpha_{\min}} \tag{4}$$

Because θ_1 and θ_2 are reciprocal functions over time. According to the motion diagram, the robot moves up, the angle θ_1 decreases and θ_2 increases, for the robot to move back, the angle θ_2 decreases and θ_1 increases. When the three legs of the robot touch the ground and start pushing the body forward, the angles of "waving" and "lifting" the legs will rotate at the same angle to create straight motion. With this movement, the robot body bobs so the potential will change. When the motor rotates with the speed $\dot{\theta}_1$, the lift motor's speed will depend on the angular speed of the rotating motor as Eq. (5).

$$\dot{\theta}2 = \frac{-tg\theta 1\cdot\dot{\theta}1\cdot k}{\sqrt{c^2\theta 1 - k^2}} \tag{5}$$

The body is pushed forward when the robot is moving in a straight line as shown in Fig. 8. When manipulating to push the leg up or move the body forward, the legs waved forward and back. This causes the body to move forward a horizontal line from the center and the line of straight motion.

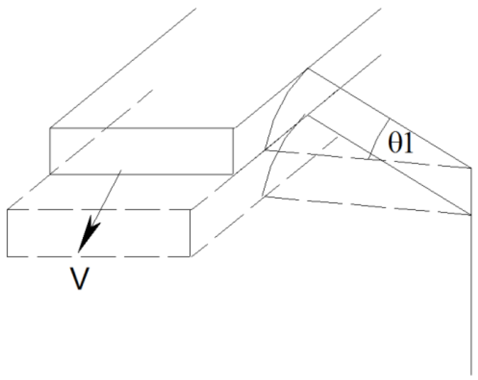

Fig. 8. The body is pushed forward when the robot is moving in a straight line.

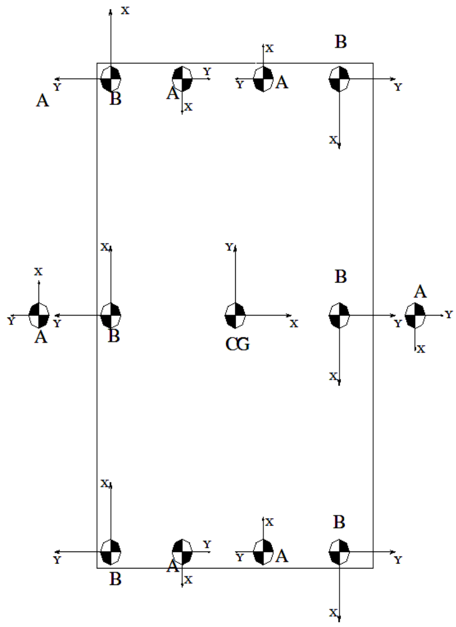

Fig. 9. The arrangement of pins for kinetic and potential energy is constant.

A wave angle of θ_1 and a radius of wave is $L_2\cdot\cos\theta_2$. So, the motion length of a cycle is defined in Eqs. (6) and (7).

$$L = L_2\cdot\cos\theta_2 \tag{6}$$

And the horizontal deviation *i*:

$$\Delta L = L_2\cdot(1-\cos\theta_1) \tag{7}$$

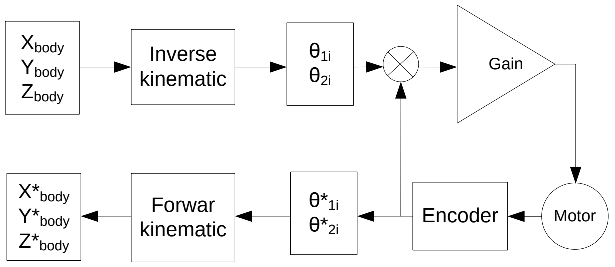

Fig. 10. Controlling schematic of each leg.

Based on the value of horizontal deviation after a cycle, the horizontal deviation according to the proposed algorithm is zero. In order to determine the location of the robot center, all positions and initial conditions of the robot must be known. If all the steps are the same, we only need to calculate one step and then multiply by the number of steps to the final position of the robot. With this mode of movement, the robot moves in a straight line. In the case of the robot moving with different steps, the robot will move at an angle depending on the difference between the steps with each other. The kinematic of each step is calculated to deduce the position of the center of the robot at that time. Initially, we have to determine the initial parameters of the robot. Before the robot body moves, the kinetics are analyzed to find the position of the legs and feet. At this time, when the foot is raised, turn and step down. So to determine the inverse kinetic analysis problem to find the new position of the body after the body has moved. Because the relationship between the robot center and the foot position is fixed, when the robot body moves through the contact parameters between the leg and the mind, we can determine the new position of the robot center. Then, the foot position to be found is added to the parameters of the waypoint coordinates.

D. Control the Robot at a Low Level by the Program

A robot's motion control is not only a matter of controlling the movement of one leg but a combination of controlling the motion of the legs according to a certain law of motion. It is like controlling many mechanical mechanisms that move according to a certain rule and under the same load that its body and the engines it carries on its body. In the case of a robot with legs, the legs are regarded as a mechanical arm that is attached to the body with the body sometimes moving and sometimes fixed. Many methods of robot movement from the activities of animals in nature are drawn. In the case of stationary motion, the motion of the foot mechanisms is controlled. Through the calculation of the positive dynamics of the legs, the movement of the robot is controlled. That includes distributing the motion of the feet and determining the footing position on the ground depending on the terrain. Accurate and reasonable control of body movement for the degrees of body freedom is one of the main requirements of the design of the robot control part.

The robot control system moves in a straight line according to the diagram in Fig. 7. Firstly, the required coordinates are entered, then based on inverse kinematic analysis to find the value. The requirements of the θ_{1i}, θ_{2i} motors of the pins, i.e the lifting and turning angles, control the motors of the foot groups. With the rotation angle sensor, it gives the actual value of the actuator's angles θ_{1i}, and θ_{2i}, from these values the position of the robot body can find to compare with the reference axis system, so the value of the error between reality and theory is visible.

E. Robot Control Scheme by Program

Above, the controlling robot according to the position is presented, however, for precise control, the torque-moment robot control method is applied. The moment vector τ from the required values of the Robot position is computed based on the control algorithm. The robot's angle sensor allows the controller to read the vector of the position θ and the joint velocity $\dot{\theta}$. The proposed robot is a 6-legged robot with 3 degrees of freedom each, so the robot is controlled based on the Lagrange kinematic model to calculate the control force, which allows us to calculate the correlation force between dynamic joints and use feedback relationship to determine the moment of calibration force so that robot movement as required. Dynamic equations are used to calculate the moment for the trajectory of motion. The values $\theta_{1i},\theta_{2i},\dot{\theta}_{1i},\dot{\theta}_{2i},\ddot{\theta}_{1i},\ddot{\theta}_{2i}$ are given by the processor to calculate the moment needed to control the robot according to the following kinematic Eq. (8).

$$M(\theta_{1i},\theta_{2i}).\begin{bmatrix}\ddot{\theta}_{1i} & 0\\ 0 & \ddot{\theta}_{2i}\end{bmatrix}+B(\theta_{1i},\theta_{2i})\begin{bmatrix}\dot{\theta}_{1i}.\dot{\theta}_{21}\end{bmatrix}+ C(\theta_{1i},\theta_{2i})\begin{bmatrix}\dot{\theta}_{1i}^{\,2}\\ \dot{\theta}_{2i}^{\,2}\end{bmatrix}+G(\theta_{1i},\theta_{2i})=\begin{bmatrix}\tau_{1i}\\ \tau_{2i}\end{bmatrix} \tag{8}$$

The calculation of this moment is used to control the electric current creating motion for the robot as required. If the dynamic model is accurate and correct and there is no noise, the movement of the robot is as required.

IV. Results and Discussion

To evaluate the error, a robot path is set up to evaluate the error of the robot. Fig. 11 is a predefined movement pattern for the robot. The dashed line is the expected path and positions the robot to move. Position 1 is the starting position of the robot. When it comes to position 2, the robot moves at an angle of 5 degrees from the 1–2 lines available. Similarly, the remaining lines are skewed. n general, the moving robot follows the desired trajectory. The errors are evaluated for reasons such as it depends on inaccurate mechanics (when moving the legs still slip), the motor used is an RC servo, so the open-loop control is not accurate. However, these causes can be remedied by basic methods such as making a non-slip base for the foot mechanism and attaching a force sensor on each leg. Using open-loop controlled motors such as servo motors, encoder DC motors, etc. Fig. 12 shows the result of an experiment when the robot operates according to trajectory in Fig. 11. The robot is located at point 1 and is set to move along a predetermined trajectory.

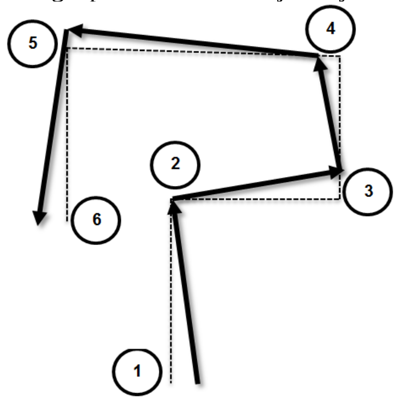

Fig. 11. The predefined movement pattern for the robot.

In brief, a method for dealing with the six-legged walking robot's controlling algorithm is presented. A mobile robot that is capable of moving across a variety of environments while setting up the trajectory as a walking robot. First, a mathematical model for examining the kinematics and gaits of six-legged robots utilizing serial and parallel kinematic mechanism theory is summarized. The kinematic analysis is founded on classical kinematic theory, which makes use of a formulation that is advantageous to computer algorithms. The outcomes of the experiment demonstrate that varied motions may be accommodated by robot design and control algorithms. This robot can be used in many different fields such as exploring dangerous areas, traveling to extreme places to survey the environment, or observing and tracking uneven terrain [14, 15]. Besides, with the development of intelligent control algorithms today, many methods can be applied in robot control that is more expected in the future.

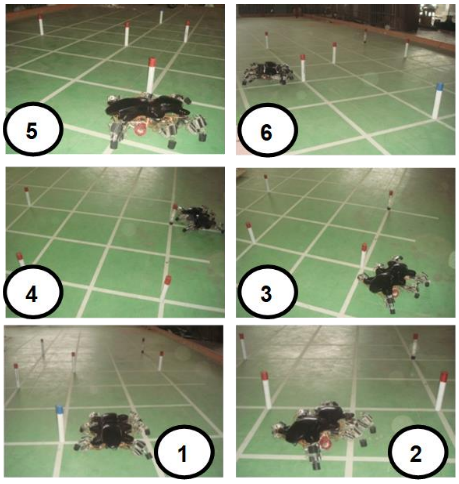

Fig. 12. Experimental results with given path.

V. Conclusion

This paper introduces a simple three-step strategy for the robot and a strong three-step framework. A six-legged robot’s stride is designed with the intention of navigating challenging terrain. This helps to expand the robot's workspace. The good adaptation of the robot is shown in the experiment when the robot moves to follow the predetermined trajectory with a fast response time. The robot errors can be easily overcome by the presented suggestions. This work is primarily concerned with kinematic issues and control methods. The experiment results of this method offer specific control algorithms applicable to robots with legs. This algorithm will overcome the shortcomings in the movement of the 6-legged robot and the robot with legs in general.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

N.T.T., N.M.T., and T.T.Q conceptualization and methodology; N.M.T., T.T.Q. wrote the manuscript; N.T.T and T.T.Q. writing, review and editing; and N.T.T. supervised; N.T.T. project administration; all authors had approved the final version.

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