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Reconfigurable multi-legs robot for pipe inspection: Design and gait movement

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This paper focuses on studies on reconfigurable multi-legs robotic system. The aim of this paper is to identify and acquire findings on how multi-legs robot can walk, climb vertical pipe and walk along the horizontal pipe after climbing. Three degrees of freedom (3DOF) multi-legs robot is designed and built to replace human involvement either at hazardous pipeline or to check on vertical and horizontal pipes. The robot system is tested to climb the vertical pipe and then move along horizontal pipe for inspection or other purposes. This can reduce the cost and percentage of human risk exposure during inspection on outer pipe. This multi-legs robot has more movement gaits compared to wheeled robot, but in terms of speed, wheeled robot possesses greater advantages. Therefore, this system design has combination of both wheel and multiple legs ensure that the to system has higher stability, more gait movement, and higher speed manoeuvrability. The gaits analysis for the system movement includes angle of the legs to move and selection of certain legs to perform a given operation, either walking, climbing or hanging. The target result is the system able to climb 500 mm height with 85 mm radius pipe. The potential applications for the system are: *(i) to move along either on surface or underwater pipe and (ii) to be equipped with ultrasonic sensor to inspect the pipe.*

[**Keywords:** *Multi-legs robot; Reconfigurable system; Climbing mechanism; Pipe Inspection; Underwater pipe*]

Introduction

Robots are segmented in to a few categories, namely, industrial robots, agricultural robotics system, tele-robots, mobile robots, and service robotics system. Most of these robotics systems play pivotal roles in many areas such as automotive assembly line, crop monitoring and fertilizing plant, surgery and transporting materials at warehouse, etc. This paper is focused on multi-legs robot listed in the mobile robot segment in terms of its adaptability to troublesome territory, where wheeled robots are unable to access. Wheels robots exceed expectations on level surfaces or uniquely arranged surfaces; however they do not perform well when the terrain is uneven. Even though many researches had been conducted for several decades about multi-legs robots, but reconfigurable robotics area is still immature. The scope of this research is about multi-legs robot that can walk using tripod gait method and then change its configuration to become a vertical and horizontal climbing robot. Another scope set for the research is that when the robot is configured from hexa-legs to climbing mechanism system, the robot is expected to climb about 500 mm height and 85 mm radius pipe. Figure 1 shows the robot in the walking pattern position, Figure 2 shows the robot when pattern change to climbing method, and Figure 3 shows the robot during climbing pipe.

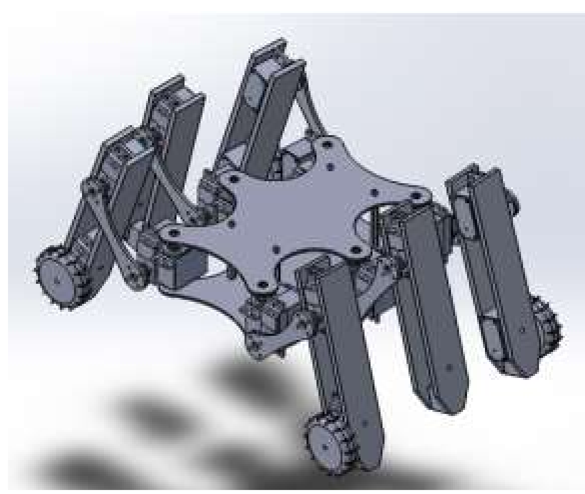

Fig. 1

Motivation

This paper is motivated by various researches conducted on walking type robot decades ago. Most of these research activities are about walking robots which can be categorized into a few sections: *(i) Design of multi-legs robots, (ii) modelling of the system, and (iii) controller algorithm and robot's performance*. In one paper[1], the author designed a system based on the biologically inspired morph-able mechanism which was a small multi-legged robot, and characteristic of the mechanism at the system was used to stabilize during climbing convex or cylindrical structures. The design depicted that the robot able to climb was using static stability while climbing the structures. In another paper, the author produced a plan and fabricated a robot that could effectively climb a tree[2]. In another system developed, the robot was able to climb with high mobility, adaptability and adjustment to non-level surfaces[3]. *Omni Climber II* was an evolution of *Omni Climber I*, a novel climbing robot with high mobility to inspect using ferromagnetic 3D human made structures. After that, in another research, the researchers designed a robot able to climb staircases, move inside unfilled channels and funnels, ascend ropes and shafts of shifting cross segments, and even bounce over obstructions with legitimate movement coordination[4]. It likewise moved inside thin paths by reconfiguring itself. The design of a reconfigurable robot capable of traversing a wide range of unconventional terrains was the novelty in this invention.

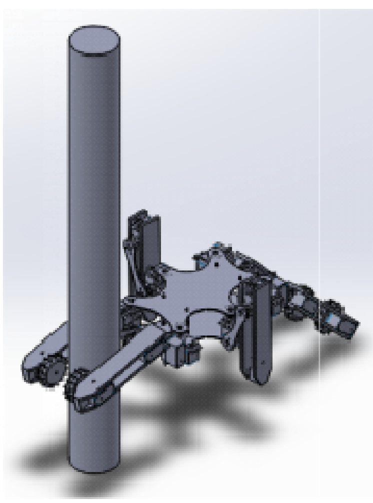

Fig. 2

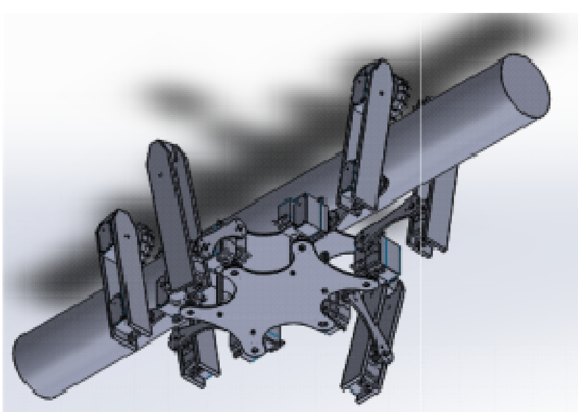

Fig. 3

Another system design portrayed level of cement surface harshness[5]. It was a study on the force on the hook-like and the researchers proposed two mechanical models for the associations between sharp paws and micro protuberances. The outline technique for the tips of the sharp hooks was then tested.

In addition, a robot was designed to accomplish tasks, as *climbing vertical structures and controlling articles*[6]. This robot used two controllers that can grip a handle on both structures.

Further, a little scale dexterous divider climbing robot was established to explore smooth surfaces of any vertical and upset surfaces, which utilizes glue elastomer materials for its holding method[7]. A different type of working model was outlined and executed including leg and feet configuration and walk control. Meanwhile, a rope climbing robot caterpillar was planned and accomplished by emulating the strolling style of a regular caterpillar. The greater part of the movement qualities of the robot caterpillar were defined to attain the climbing action[8].

The next designed project was about a climbing robot with the ability to control and to access three-dimensional (3D) human-made structures[9]. The system's configuration improved pipe climbing robot with least degrees of flexibility. Another author designed robot with three principle modules, which were adaptable magnetics treads, joining connections with torsion springs torque-controlled servos, and a dynamic tail at the end of robot[10].

The researchers also developed a climbing robot that had an actuation system suitable to carry payload[12]. Another design exhibited diverse sorts of climbing robot's mechanism which were prototypically produced for mechanical and business utilization[13]. In another paper, the authors formulated the instrument motivated from the headway of a worm called STOMATAPOD, which used its entire body as conveyed foot encouraging it to proceed onto any landscape and had high spryness on a customary tree environment[14].

Finally, another study explained a design of climbing robot by using servo gripper, which has the capabilities to move across a pipe. The author proposed two designs of gripper for gripping the pipe by using servo motors[15].

Methodology

The initial stage of this research uses Solid work software to simulate and imitate the movement of the multi-legs robot system. The robot is simulated to move in the horizontal plane, then, change its configuration to grip a pipe and finally move along a rope. The simulation is crucial before the robot is fabricated and is programmed accordingly. Then, another simulation is required to see the movement of robot's actuators which comprise 22 servo motors. Next stage of this research is fabricating a reconfigurable multi-legs robot and programming it to move as pre-planned. Figure 4 shows the connection of servo motors at the robot using ISIS Professional software.

The system for this research is equipped with microcontroller ATmega 2560 with 54 digital input/output pins, and the actuator to actuate movement are servo motors with metal gear servo with 17 kgcm torque.

Results and Discussion

The reconfigurable multi-legs robot gait planning is divided into three sections: *(i) Gait planning for forward movement, (ii) gait planning for vertical pipe climbing, and (iii) gait planning for horizontal pipe climbing*. Every leg has different motion when it moves on a horizontal plane, and when robot encounter a pipe, another subroutine program helps the robot change to climbing motion. After it reaches end of the pipe, an ultrasonic sensor will sense any pipe existence for the robot, which using another subroutine program changes motion to pipe climbing.

Gait planning for forward movement

Figure 5 shows the flowchart of gait forward planning for the multi-legs robot while Figures 6-14

Fig. 5 — Gait planning for forward and horizontal plane multi-legs robot movement

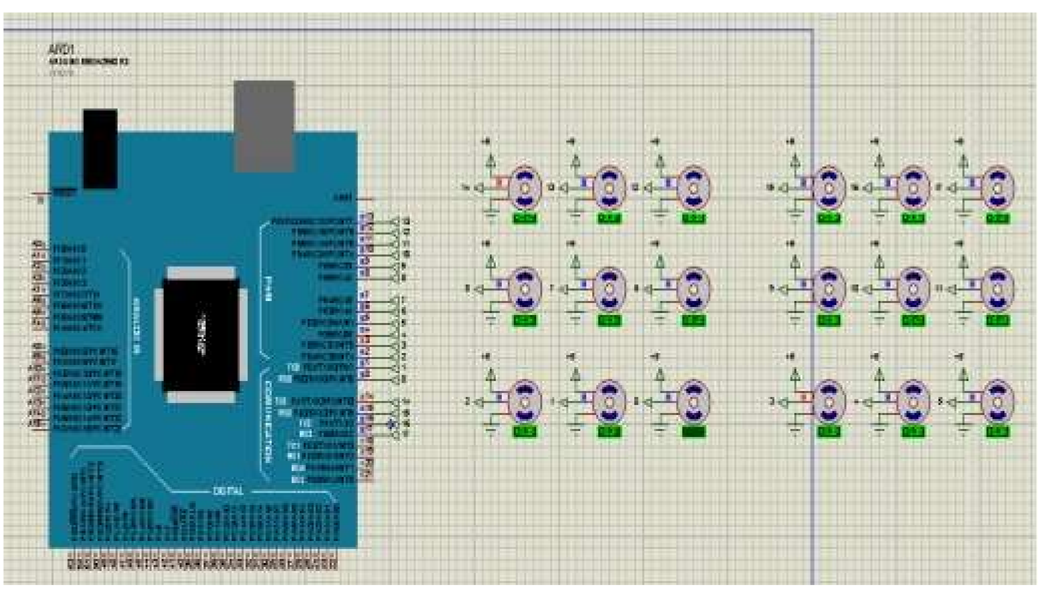

Fig. 4

elucidate the view of robot during initial condition and walking mode. The robot needs nine steps for one complete movement; and angle for every leg needs to change before it can walk in a stable motion. Movement steps are shown by arrow direction in each figure. Multi-legs robot turns into star shape at both front legs and both back legs. Then, robot lifts up from the ground and the multi-legs robot is ready to move. After that, the front right leg, back right leg, and left middle leg are lifted to move forward using tripod gait movement. Then, the front left leg, back left leg, and right middle leg are lifted to move forward also by using tripod gait movement. After the tripod movement cycle is complete, the multi-legs robot is back to initial position of the leg. In the figures,

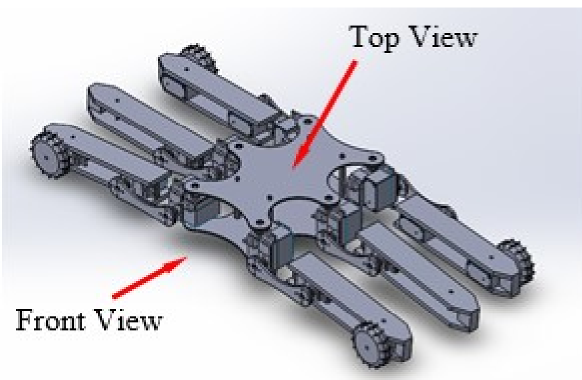

Fig. 6 — Initial position of robot before activation in isometric view.

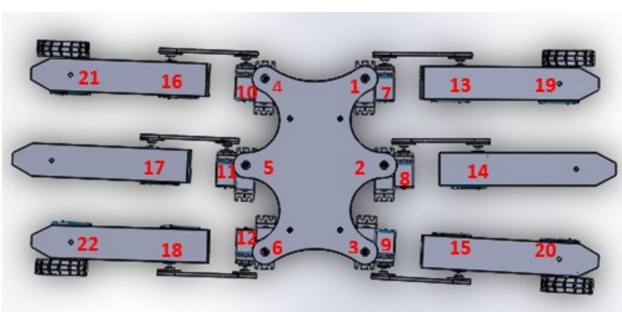

Fig. 7 — Initial position of robot in top view with number of servo motors position.

movement of legs indicated by Leg No, and servo motor to move legs is indicated by M. For example, **Leg 1(M1)** means leg 1 moves using servo **M1**.

Initial position of the robot

The robot initially at rest before the system switch is activated. Figure 6 shows the system in the isometric view before controller activation. Figure 7 shows the top view of the robot, wherein every servo at the robot is numbered as shown by red numbers. Figure 8 shows front view of the system.

Gait movement of the robot in the horizontal walking mode

After controller at the robot is activated, the robot will make a star gait. Servo motors at the robot with servo numbers 1, 3, 4, and 6 will rotate 30° each. Figure 9 shows the position of the robot in the top view after activation, while Figure 10 shows location of servo number to move the robot in the first gait movement. Table 1 & 2 exhibits angle for each servo during the first movement.

Next stage of the horizontal gait movement is to make the robot to lift up. Servo numbers 7,8,9 ,10,11 and 12 need to rotate 90° each to lift up system's body. Figures 11-13 shows the top, front and

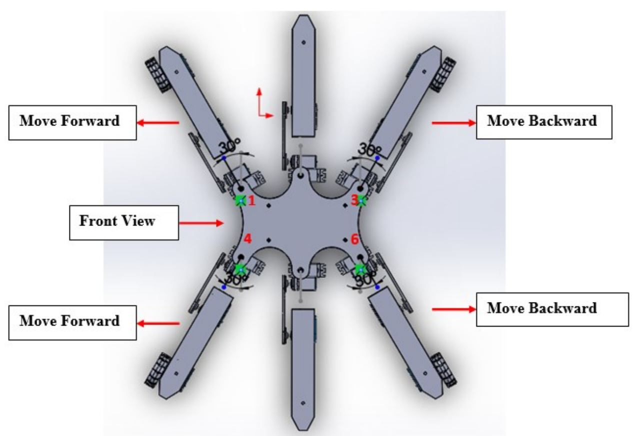

Fig. 9 — Top view of the robot's gait after system activation.

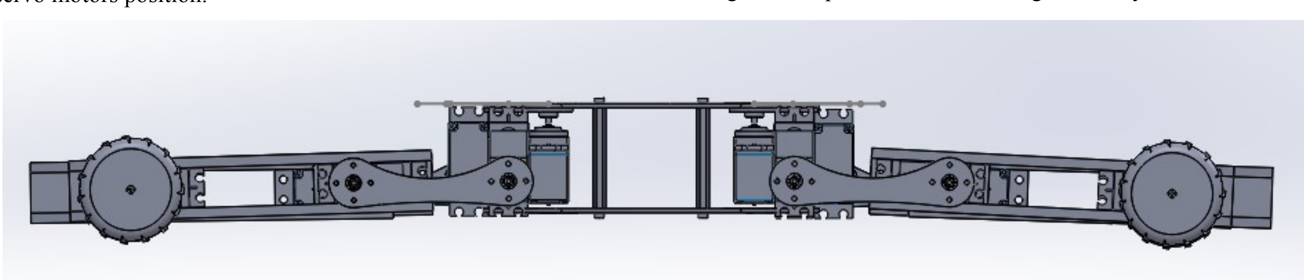

Fig. 8 — Initial position of robot in front view.

isometric view of the robot during lift up gait movement. After lift up motion gait has been accomplished, next gait to make the robot stable is by pushing all legs to the horizontal plane. The stable gait coordination is shown in Figures 14-16. Table 3 shows the legs movement and angle involved to ensure the stability is achieved.

Next step for the gait movement of this robot during horizontal walking mode is elaborated by Figures 17-19. From Figure 17, leg no. 1, leg no 3 and leg no 5 lift up by rotating servo motor no.7, 9 and 11 about 45^o each.

Forward gait movement is then continued by moving rotating servo motor no. 1, 3 and 5 about 20^o while servo motor 7, 9 and 11 maintain at the previous angle 45^o. The servo motor 1, 3 and 5 rotation causes legs 1, 3 and 5 to move forward. Forward walking gait movement is shown in Figure 20.

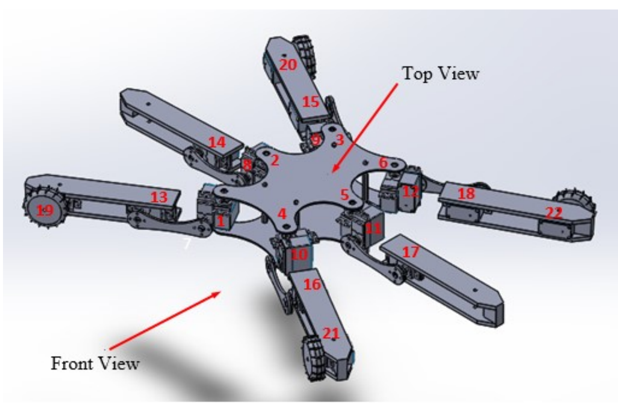

Fig. 10 — Isometric view of the robot's gait after system activation.

Table 2

Leg	*Servo Number*	*Angle of Rotation*
1	1	30^o
2	0	0
3	3	30^o
4	4	30^o
5	0	0
6	6	30^o

Table 2 — Robot's Leg, Servo Numbers and angle for each servo to lift up system's body.

Leg	*Servo Number*	*Angle of Rotation*
1	7	90^o
2	8	90^o
3	9	90^o
4	10	90^o
5	11	90^o
6	12	90^o

The forward walking gait is again continued by rotating servo motor 8, 10, and 12 at 45^o to lift up legs 2, 4 and 6 while the other three legs 1, 3, and 5 are still at the ground (Fig. 21).

The step four for forward gait mode is shown in Figure 22, where servo motor 1, 3, and 5 rotate back at 20^o from initial position, while servo motor 8, 10, and 12 are still lift up at 45^o.

Figure 23 is step five in the forward gait movement

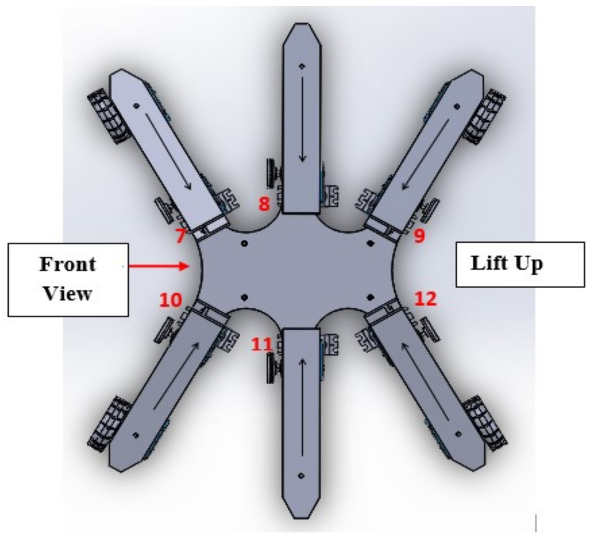

Fig. 11 — Top view of the robot's gait to lift up the body.

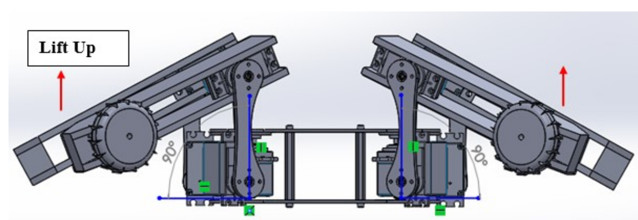

Fig. 12 — Front view of the robot's gait to lift up the body.

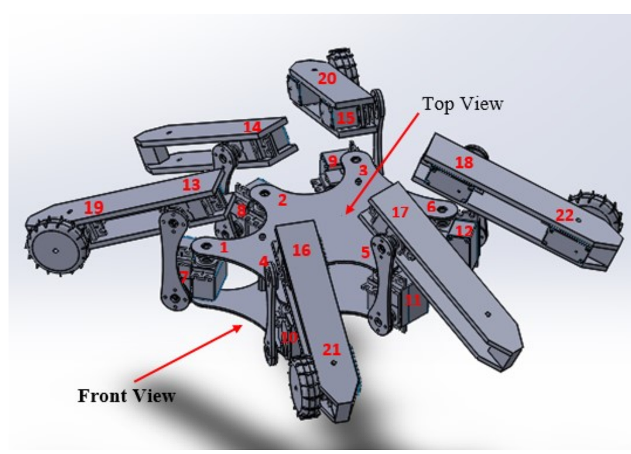

Fig. 13 — Isometric view of the robot's gait to lift up the body.

where servo motor 2, 4, and 6 rotate at 20^o while servo motor 8, 10, and 12 are still lift up at 45^o. Figure 24 is the step six of the forward gait movement and this step is considered last step before step 1 is repeated until step 6. Step 6 is accomplished by

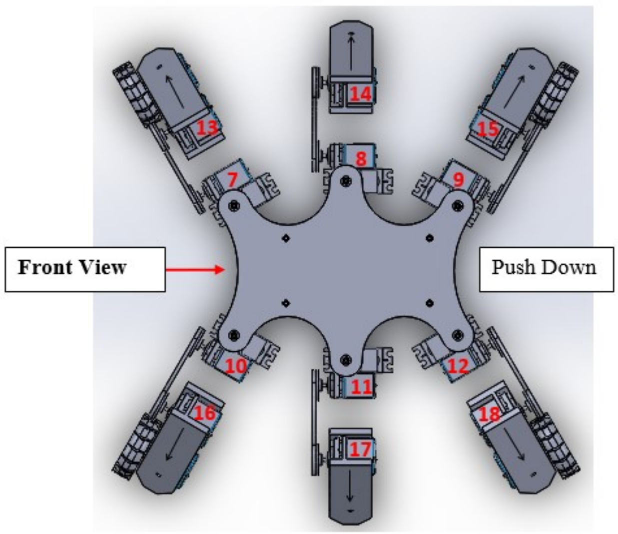

Fig. 14 — Top view of the robot's gait to stabilize posture.

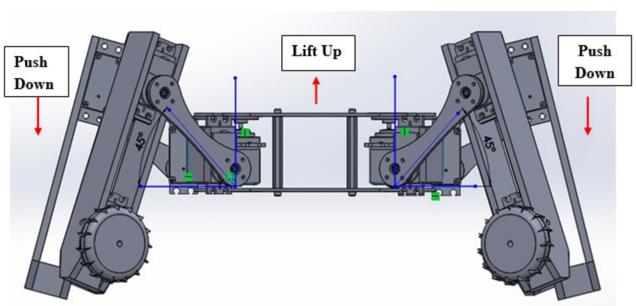

Fig. 15 — Front view of the robot's gait to stabilize posture.

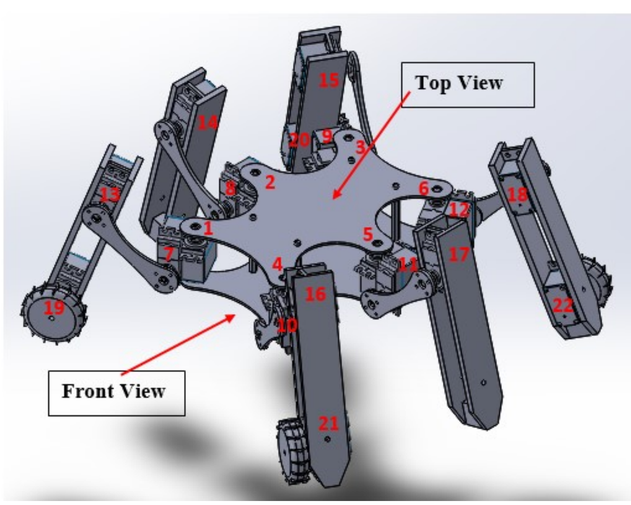

Fig. 16 — Isometric view of the robot's gait to stabilize posture.

ensuring servo motor 2, 4, and 6 rotate back at 20^o as initial position angle and touch the ground.

The forward gait movement for this robot is summarized as a flowchart. Figure 25 elucidates flowchart for the robot's movement in the horizontal plane.

Gait movement of the robot to climb vertical pipe

After forward walking gait is accomplished and when the robot encounters a pipe, final point A in flowchart in Figure 25 will continued in another

Table 3 — Robot's Leg, Servo Numbers and angle for each servo stabilize robot's posture.

Leg	*Servo Number*	*Angle of Rotation*
1	7, 13	45^o,30^o
2	8, 14	45^o,30^o
3	9, 15	45^o,30^o
4	10, 16	45^o,30^o
5	11, 17	45^o,30^o
6	12, 18	45^o,30^o

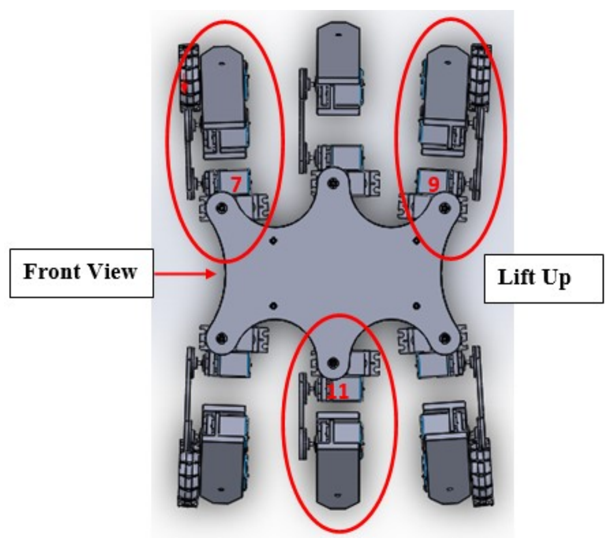

Fig. 17 — Top view of the robot's gait to move first forward.

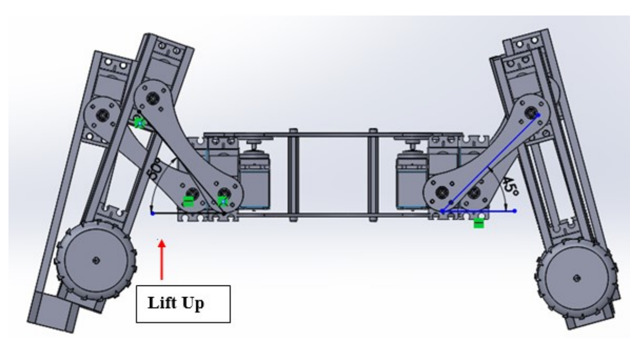

Fig. 18 — Front view of the robot's gait to move first forward.

flowchart as in Figure 26. In order for the robot to climb pipe, initially pipe will be gripped by front legs, then, middle and back legs will expand. Front legs will pull backward while back legs push downwards. After the legs operation has been done, the robot's body will come closer to pipe and robot will start climbing or going down the pipe.

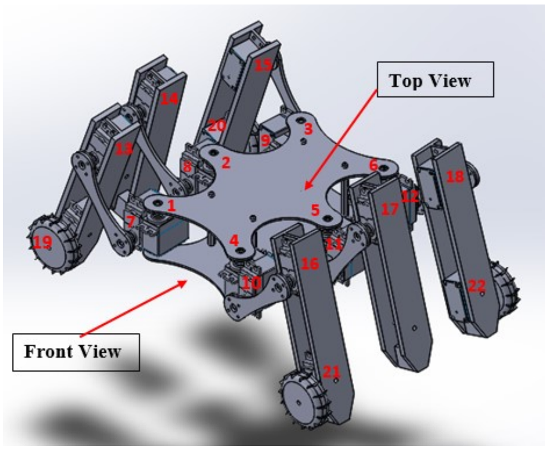

Fig. 19 — Isometric view of the robot's gait to move first forward.

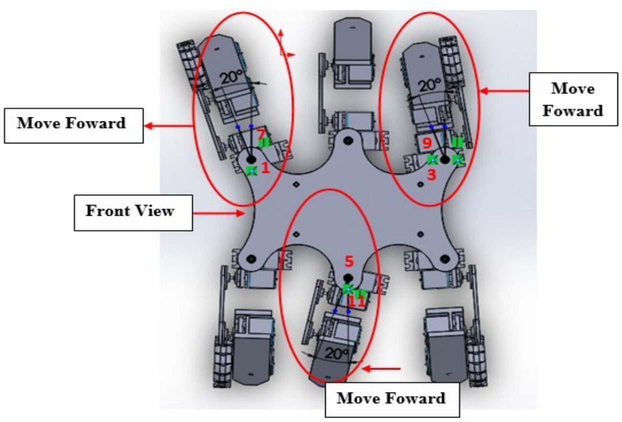

Fig. 20 — Top view of the second step of robot's gait to move forward.

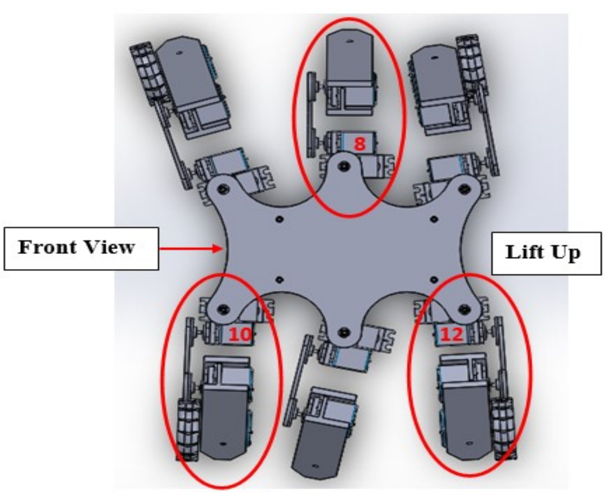

Fig. 21 — Top view of the third step of robot's gait to move forward.

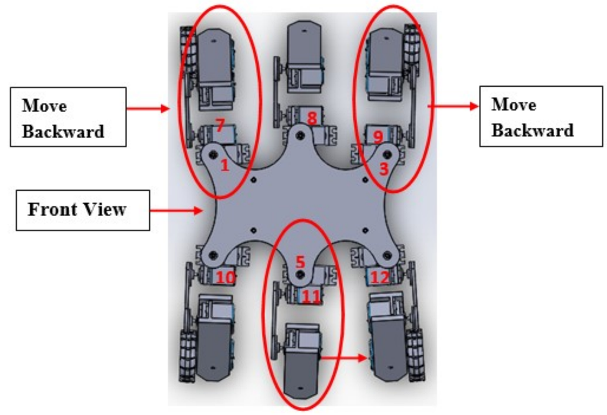

Fig. 22 — Top view of the fourth step of robot's gait to move forward.

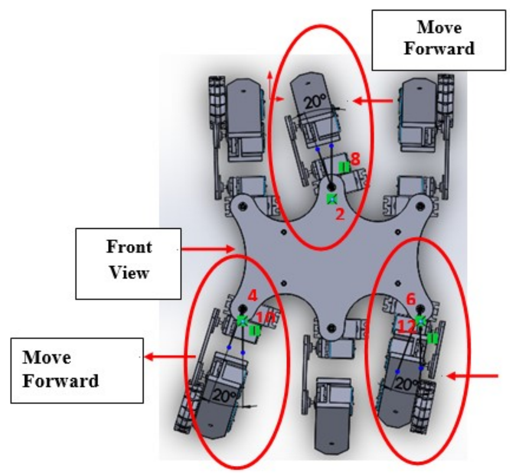

Fig. 23 — Top view of the fifth step of robot's gait to move forward.

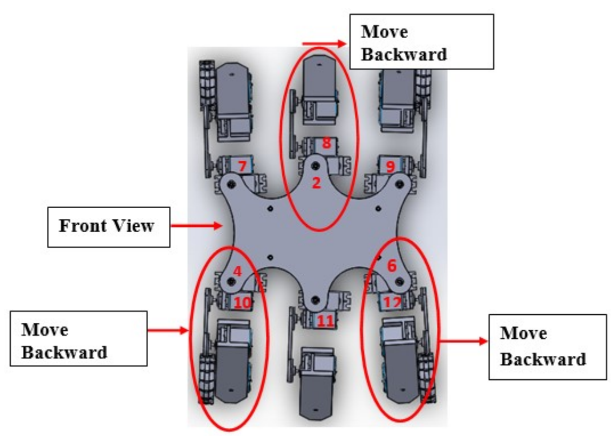

Fig. 24 — Top view of the six step of robot's gait tomove forward.

Figures 27 and 28 show the top view and isometric view of initial condition of legs and motor's numbers at the robot when it encounters pipe. Once robot detects pipe, climbing gait mode is activated.

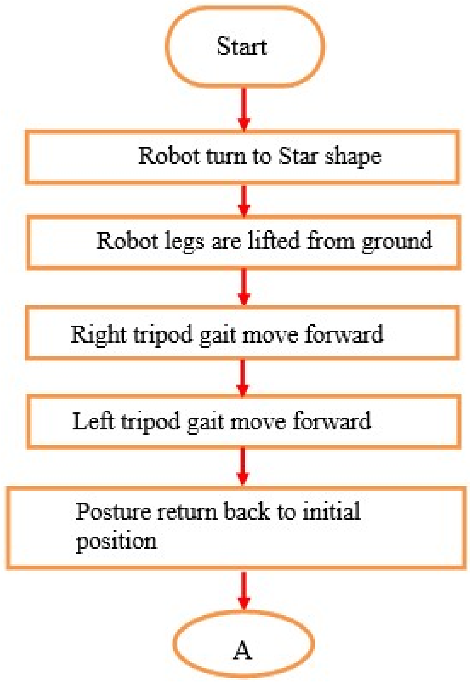

Fig. 25 — Flowchart summary for forward gait movement.

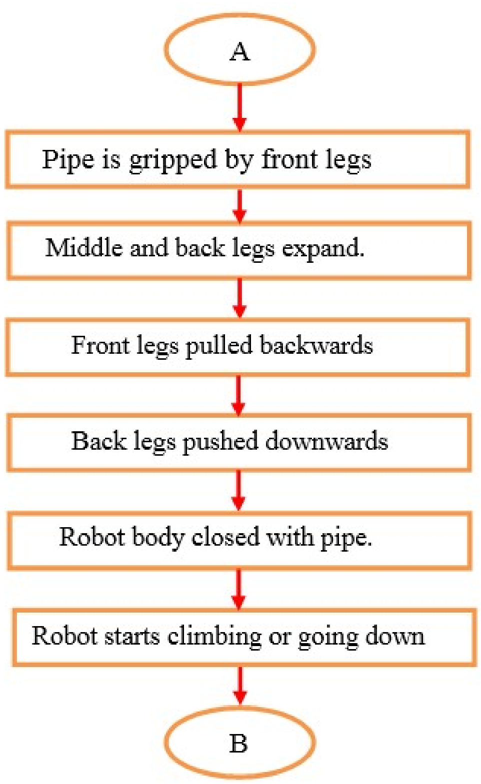

Fig. 26 — Flowchart for multi legs robot climbing.

Figures 29,30 and 31 demonstrate how the legs expand once the climbing gait mode is activated. Leg 1 and leg 4 will expand and lift up using servo motor no. 13 and no. 16 by about 60^{o}.

Figures 32 and 33 display the step 2 in the climbing gait mode for this reconfigurable robot's system. Leg no.1 and Leg no. 4 rotate forward by utilizing servo motor no. 1 and 4. During this operation, pipe is clamped by the legs while roller wheels are at another side of pipe.

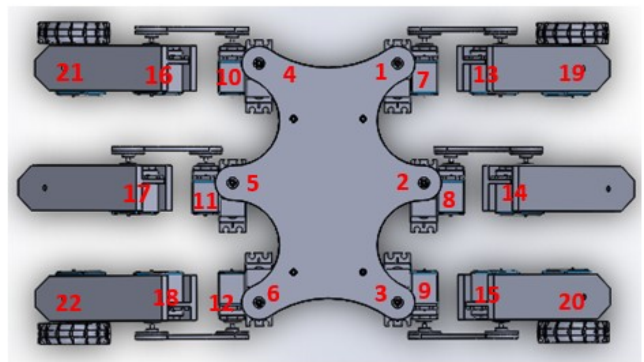

Fig. 27 — Initial condition of legs and servo motors before climbing

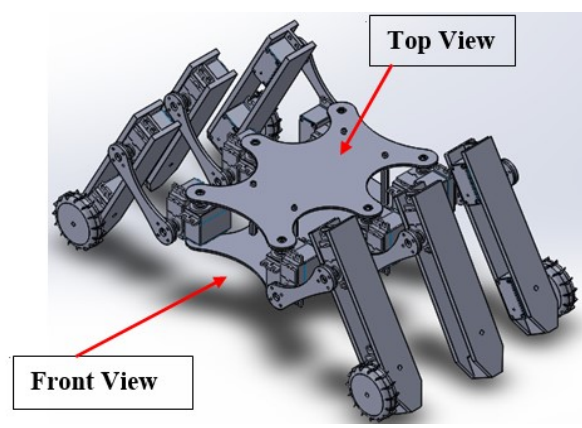

Fig. 28 — Isometric view of initial condition of legs and servo motors before climbing pipe.

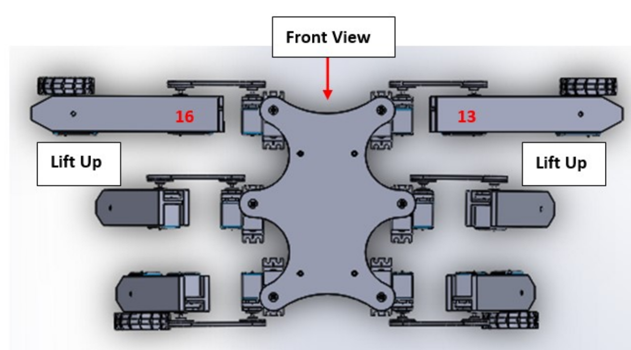

Fig. 29 — Leg 1 and Leg 4 expand to start step 1 for climbing gait.

The next step to ensure the robot can climb pipe involves, leg no. 2, 3, 5 and 6 to push downward. The operation is accomplished by using servo motor no. 8, 9, 11 and 12. This step is elucidated in Figures 34 to 36.

Step 4 for climbing gait is shown in Figures 37 and 38. This step involves leg no.1, 3, 4 and 6. The servo will rotate at front roller to push robot upward while back roller will rotate clockwise to push robot's body upward.

Final step in this climbing gait is shown in Figures 39 to 41. During this operation, front rollers rotate upward, middle legs push up and back legs push down.

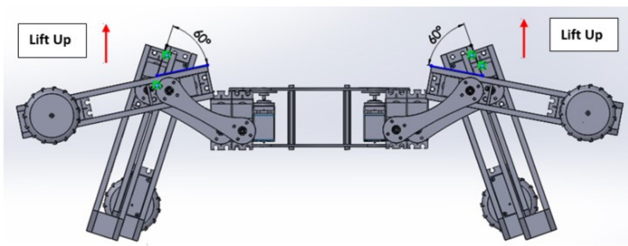

Fig. 30 — Leg 1 and Leg 4 lift up to start step 1 for climbing gait.

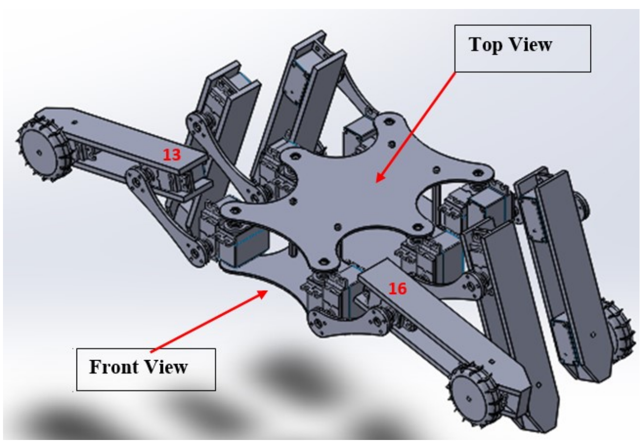

Fig. 31 — Isometric view for step 1 in climbing gait mode

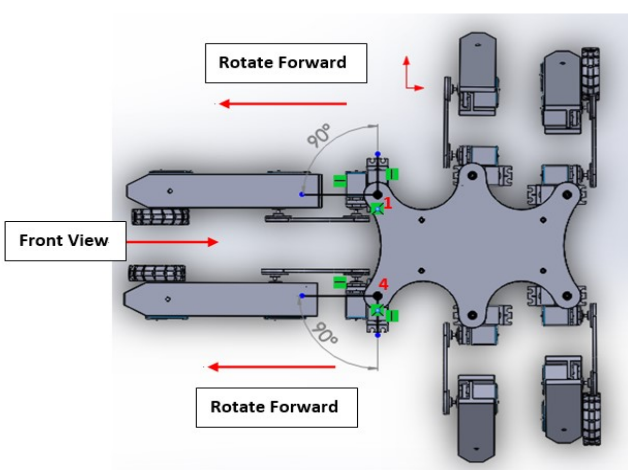

Fig. 32 — Step 2 climbing gait- leg 1 and leg 4 rotate forward.

Gait movement of the robot to hanging and moving along circular pipe

After climbing gait has been completed, these follows another gait which is hanging and moving along circular pipe. The hanging and moving along circular pipe gait is demonstrated by a flowchart in Figure 42. Initially, the pipe layout needs to be gripped by front and back legs. Then, all tires rotate to move

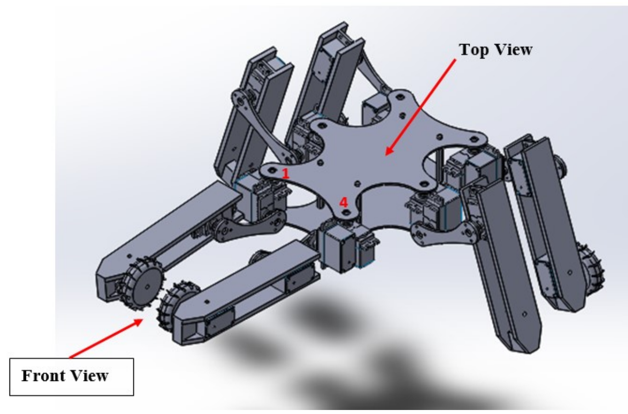

Fig. 33 — Isometric view of Step 2 climbing gait- leg 1 and leg 4 rotate forward.

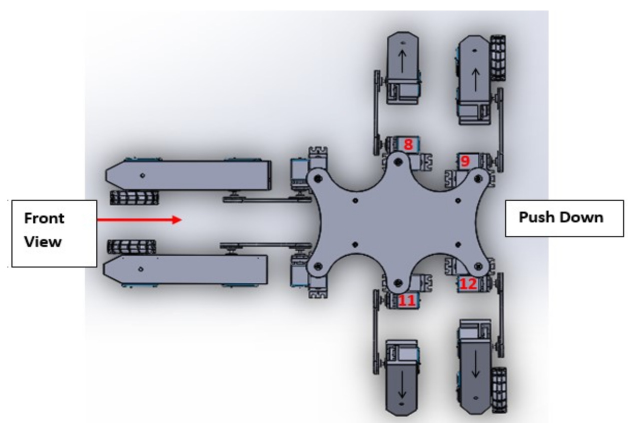

Fig. 34 — Step 3 for climbing gait – leg no.2,3,5,6 operate.

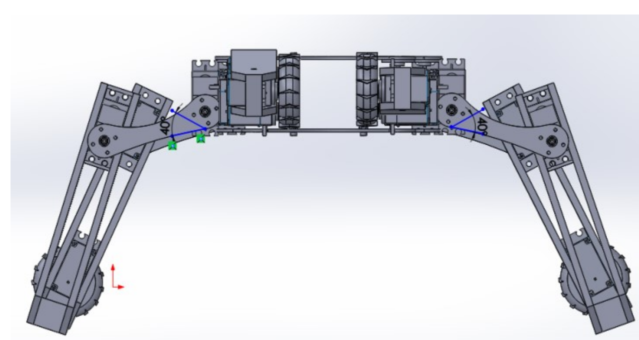

Fig. 35 — Front view for climbing gait – middle legs and back leg push downward.

the robot along the pipe. Then, once hanging gait is completed, sub-routine climbing is called by controller to climb down the pipe. Figure 43 shows top view for hanging and moving along pipe(Figs 44 & 46).

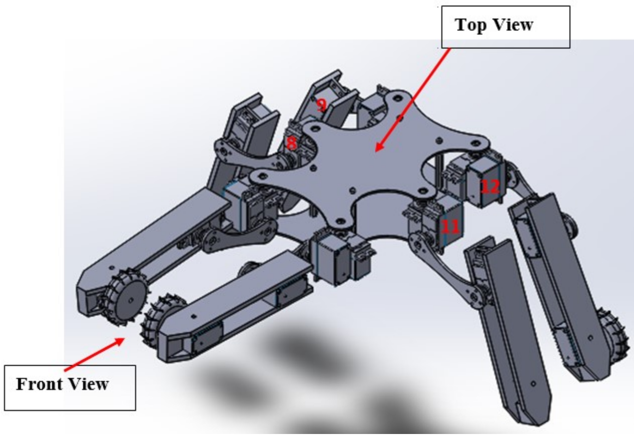

Fig. 36 — Isometric view for climbing gait – middle legs and back leg push downward.

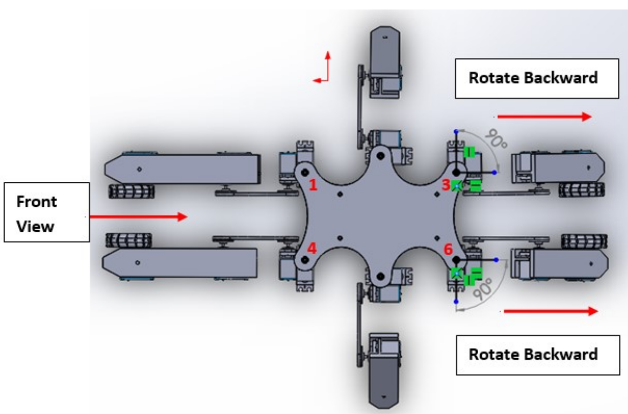

Fig. 37 — Step 4 – roller wheel rotate backward and front roller will roll upward.

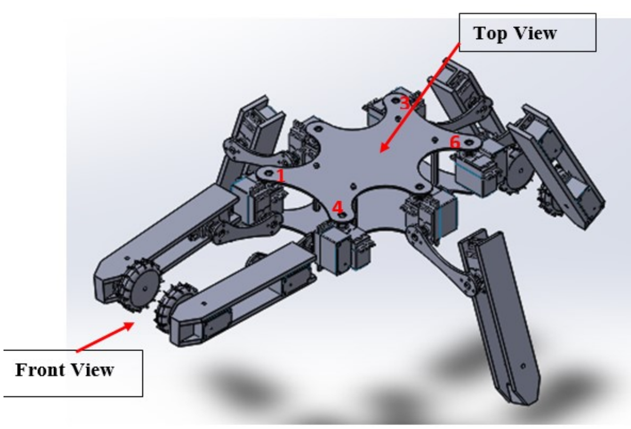

Fig. 38 — Isometric view for Step 4 – roller wheel rotate backward and front roller will roll upward.

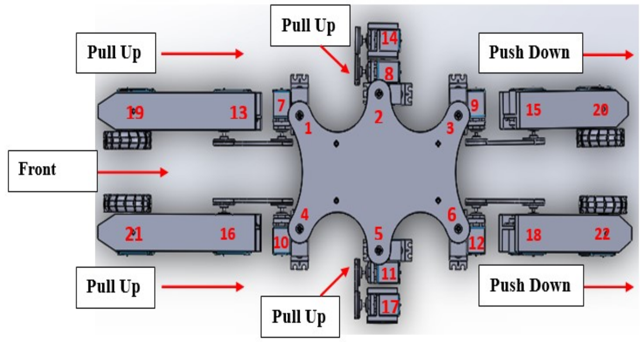

Fig. 39 — Step 5 – front rollers rotate upward, middle legs push up and back legs push down

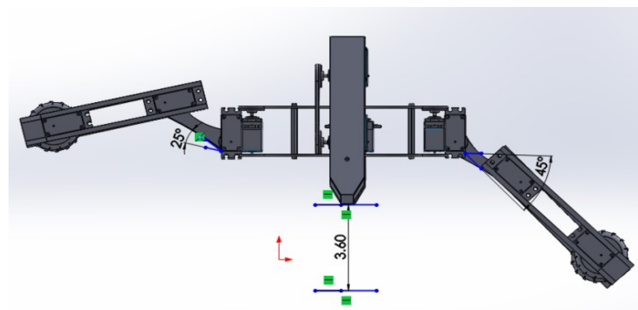

Fig. 40 — Side view for step 5 – climbing gait.

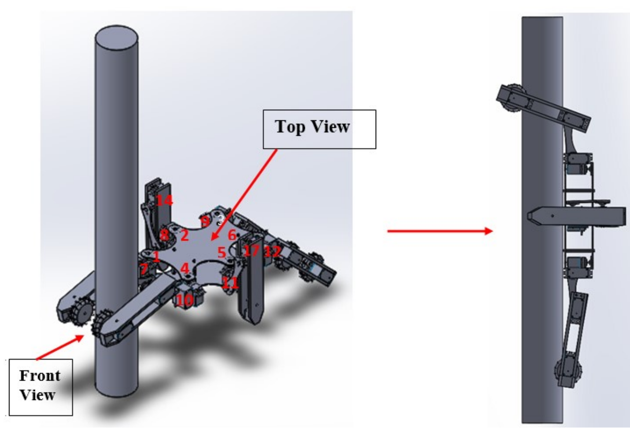

Fig. 41 — Isometric view and side view for climbing gait.

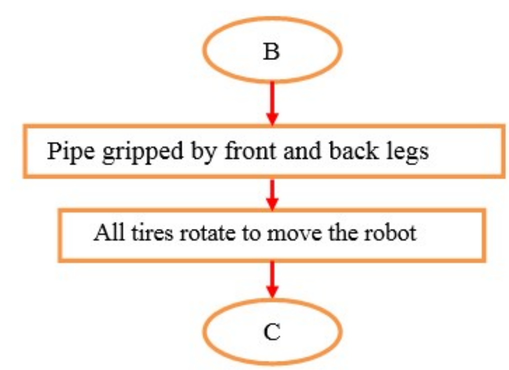

Fig. 42 — Flowchart for hanging and moving along circular pipe.

Experimental Result

Part A: Gait movement of the robot walking on horizontal plane: The gait walking as mentioned previously is tested using real hardware reconfigurable robotic system. The robotic system is built by using polycarbonate material to ensure that the robot's weight is minimal. The legs are actuated by metal gear servo motor and controller hardware is ATMEL microcontroller and 1 ultrasonic sensor.

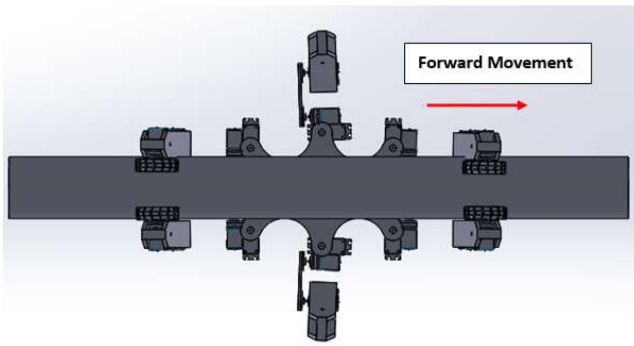

Fig. 43 — Top view for hanging and moving along pipe.

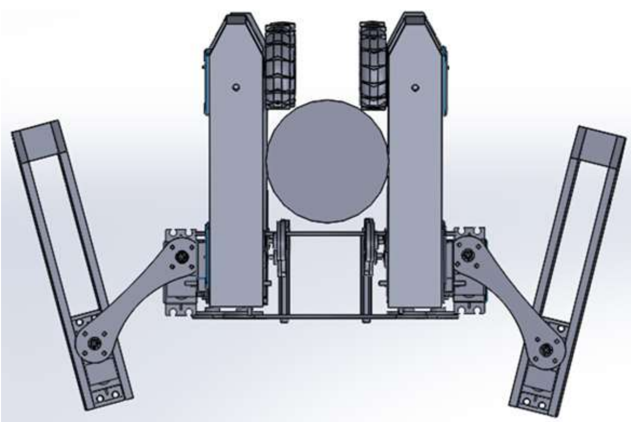

Fig. 44 — Front view for hanging and moving along pipe.

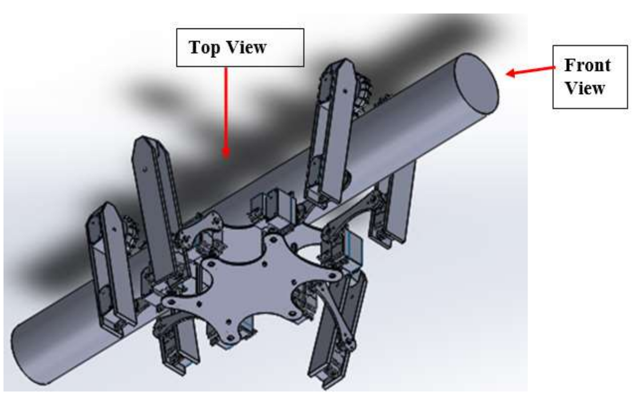

Fig. 45 — Isometric view for hanging and moving along pipe.

Figure 46 shows step-by-step walking gait for this system.

*Part B: Gait movement of the robot climbing vertical pipe***:** Another experimental test conducted is climbing pole gait mode. Figure 47 depicts step by step climbing operation by the robot.

*Part C: Gait movement of the robot hanging on circular pipe***:** Final test to prove the gait movement of this reconfigurable system is shown in Figure 48. Figure 48 shows the robot position during hanging and moving along circular pipe.

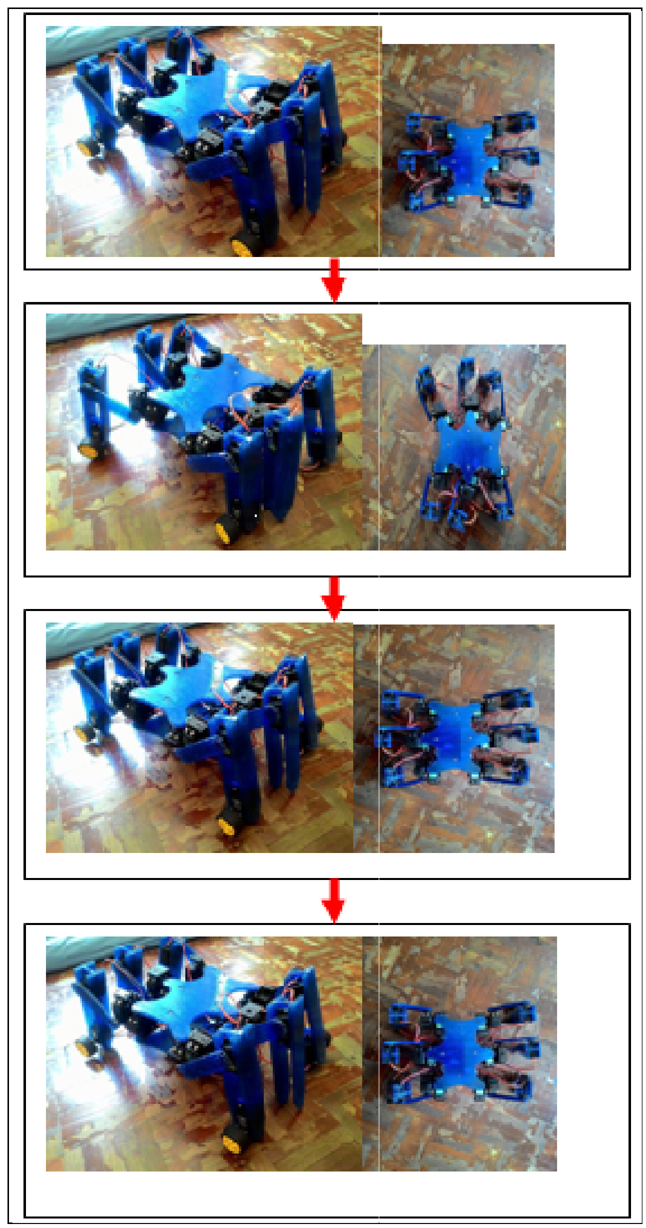

Fig. 46 — Walking gait mode for the reconfigurable robot.

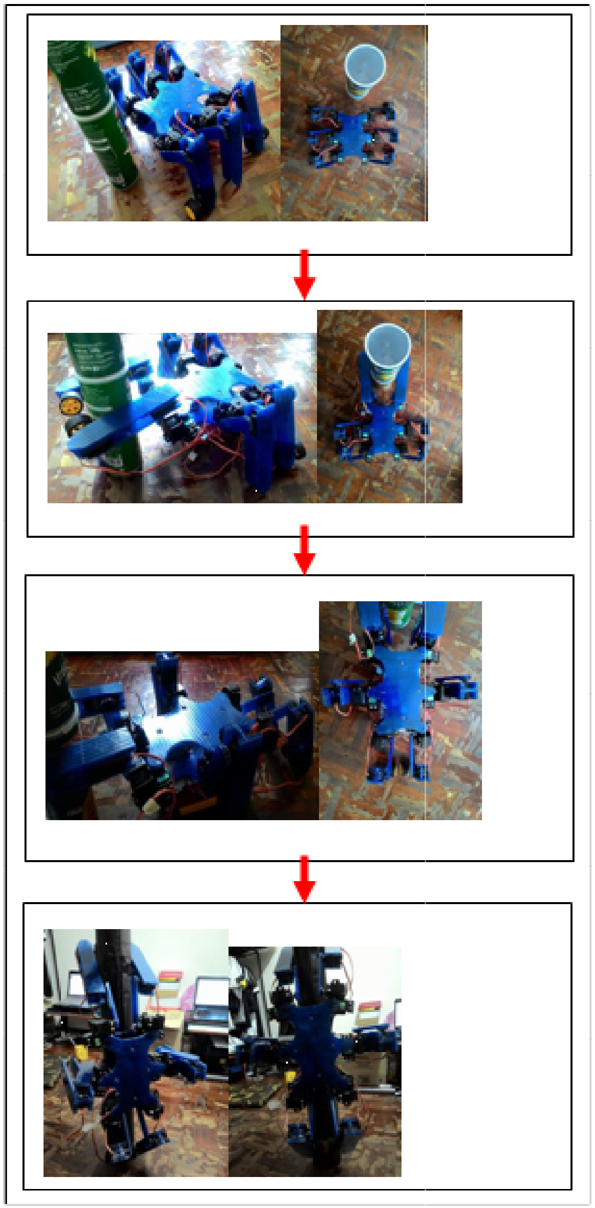

Fig. 47 — Climbing gait mode for the reconfigurable robot.

Fig. 48 — Hanging and moving along circular pipe gait mode for the reconfigurable robot.

Conclusion

Based on planning path mentioned, all the angles are set up on the controller hardware at the multi-legs robot to test the functionality of the system's *movement on horizontal plane, climbing a pipe and then hang along a pipe*. This proves that multi-legs robot can be reconfigured to accomplish multitasking and does not require different robots to handle different tasks. The robot's legs are attached with tires to do pipe climbing and pipe hanging by changing certain angles on certain legs. By comparing the required angle for each leg to move and actual measured angle during experimental study, it is shown that the errors are less than 10%.

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