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Research Article

Design and fabrication of Bioinspired Quadruped Mesh Climbing Robot (MCR) and determining stability of MCR using Edge Impulse software

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Four step signal.

Abstract:

The field Robotics has evolved a drastic development in this new technology era. Particularly considering the climbing robots which can be used for many applications in industries like performing nondestructive testing, painting, servicing, surveying etc. These climbing robots are also used on climbing rocks and exploring the possibility of existence of extraterrestrial in other planets like MARS, JUPITER etc. The two important features which has to be considered while designing a wall climbing robot are locomotive types and adhesive mechanism. Many researchers have proposed their own design either by focusing on locomotive mechanism or by focusing on adhesive mechanism. In this paper an attempt is made to design a bioinspired quadruped mesh climbing robot using Coppelia Sim and verifying the simulation result with respect to fabricated hardware testing result. The performance of the MCR is measured with respect to the time taken to climb the particular height. The various possible gait of the quadruped with four step signals are considered and their stability is studied with the help of Edge impulse Software where the motion of the MCR is captured with respect to x, y and z axis

1. Introduction

As shown in Figure 1, the decision tree analysis is presented showing different types of locomotive mechanism and adhesive mechanism of climbing robot. The design parameters of climbing robots' changes with respect to the surface where it is supposed to climb. Most of the wheel type and crawling type climbing robots are perfect for flat surface. Whereas the legged mechanism is more effective for surface with obstacles, discontinuity etc. In this work, the mesh surface is considered for climbing and for this legged mechanism is considered in our quadruped bioinspired robot. As mentioned by Rajendran et al [1], the MCR is designed using the Coppelia Sim software as shown in Figure 2 and its performance while climbing the mesh is noted for comparison with that of hardware one. There are 3 servo motors in each leg and for four legs (naming it as A, B, C, D), there are 12 servo motors. Let the servo motors in each leg be named as A0, A1, A2, B0, B1, B2, C0, C1, C2, D0, D1 and D2 as shown in Figure 3.

Wang et al [2] has proposed beetle claw inspired mesh climbing robot which walks smoothly having the mesh with angle of 30o and rough surface inclined with an angle of 55^o

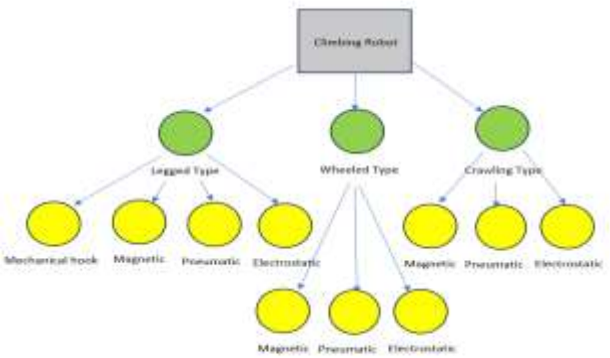


Figure 1. *The Ishikawa Diagram showing the reason for Chennai Flood*

2. Theoretical background

Bilal et al [3] proposed walking gait for quadruped climbing robot having suction cups as end effector for each leg. Bell et al [4] discussed the path planning and grasping technique for a toy climbing robot over the wall of pegs. Uckert et al [5] presented LEMUR which is a rock-climbing robot possessing four legs used to identify extra-terrestrial living organism in the gaps of the rocks. Zi et al [6] proposed a multimodel and adaptive rock-climbing robot. Akhtaruzzaman et al [7] introduced TRAIN wall climbing robot which navigate the smooth vertical wall overcoming the obstacle issues using pneumatic system and suction force as adhesive mechanism. Menon et al [8] came up with gecko type bioinspired wall climbing robot with synthetic dry adhesive medium. Nadan et al [9] proposed a novel wall climbing robot with force-controlled gripper, here the optimization technique introduced enhanced the bot to overcome the unexpected detachment issue. Maempel et al [10] discussed a climbing robot over different substrate. The test was performed varying the materials and finally the developed bot performed better for pipelike structures. Parness et al [11] came up with LEMUR3 having micro spine grippers and gecko adhesive grippers. Linder et al [12] developed a low-cost climbing robot that operated with road map algorithm to determine the climbing route. Uckert et al [13] proposed an upgraded Astro biological robot with automated stacking algorithm enhance an improvised signal to noise ratio in order to reduce the operation time. Rajendran et al [14] proposed an innovative method of using Coppelialism software for designing a wall climbing robot and evaluating its performance before getting into fabrication. Wang et al [15] introduced Robosimian human scale climbing robot with array of micro spines. Xu et al [16] developed an innovative suction based adhesive mechanism with hook like Claws. Owaki et al [17] proposed interlimb coordination and the speed of quadruped with various gait like walking, trotting, canter, galloping. Gong et al [16] developed gait parameter extraction method which can determine the gait frequency, gait duty cycle and trajectory.

3. Simulation Design and Modeling

Coppelia Sim software is used as shown in Figure 2 to design the quadruped bioinspired MCR allowing it to climb the mesh. The height climbed by the MCR for the given time is noted by varying the weight of the MCR. The distance climbed can be checked with the help of distance check option. The Figure 3 shows the fabricated model with the help of 3D print. As already mentioned, there are 3 servo motors in each leg and hence totally 12 servo motors. The formula to measure the force required to climb the vertical wall

$$F = mgSine\boldsymbol{\theta} \quad \text{---------}\mathbf{1}$$

Where m is the mass of the MCR and here that value is considered to be 1000 gm, g is the acceleration due to gravity and $\boldsymbol{\theta}$is the angle of inclination of the mesh with respect to the ground. The required climbing force at for various angle of inclination ($\boldsymbol{\theta}$ value) of mesh wall is calculated by using the equation 1 and the values are as tabulated in the table 1.

And it is clear that highest value of required Climbing Force (f) is obtained by considering the $\boldsymbol{\theta}$ as 90o and hence Sine (90o) value is 1. As per the equation 2, the required force to climb the vertical Mesh wall is 2.9 kgm2.

The torque for exerted by the chosen servo motor is 1.8 kgm2 and since we have considered 12 motors (1.8 x 12 =21.6 kgm2). Hence the proposed MCR exerts high climbing torque more than the required one. Consolidated value of the required F for various angle of inclination is as shown in Table 1.

$$F = 300\ x\ 9.8x\ (1) = 2940\ gm2\ = 2.9kgm2$$

---------2

Table 1: *Required Climbing Force at various inclination angle*

	M (gm)	G (m/s2)	Sine θ	F in kgm2
θ=0°	300	9.8	0	0
θ=30°			0.5	1.5
θ=45°			0.71	2.1
θ=60°			0.86	2.6
θ=90°			1	2.9

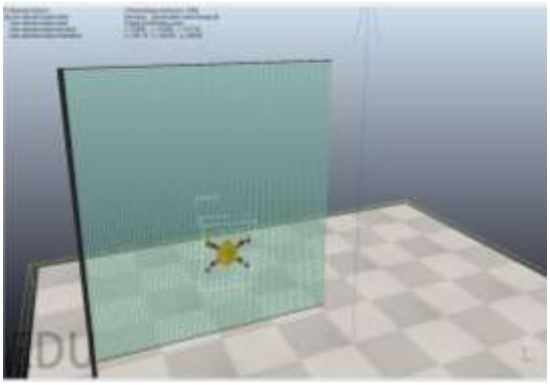


Figure 2. *Coppelia Sim model of Quadruped MCR*

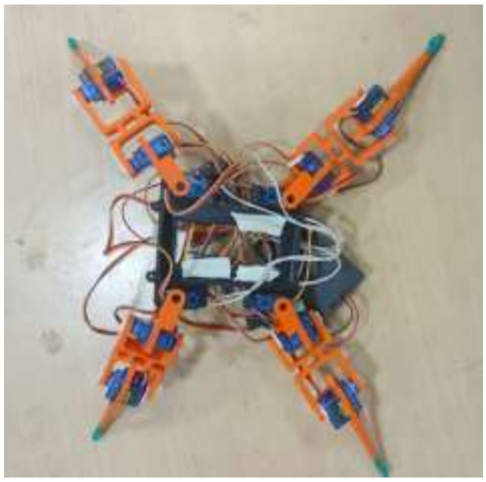


Figure 3. *Actual fabricated Quadruped MCR*

The Table 15 shows the height value obtained in both simulation and real time experiment.

The Figure 5 also portraits that the time taken to climb the given height on the mesh during simulation testing is more or less in line with that of the real time testing for the standard weight of MCR.

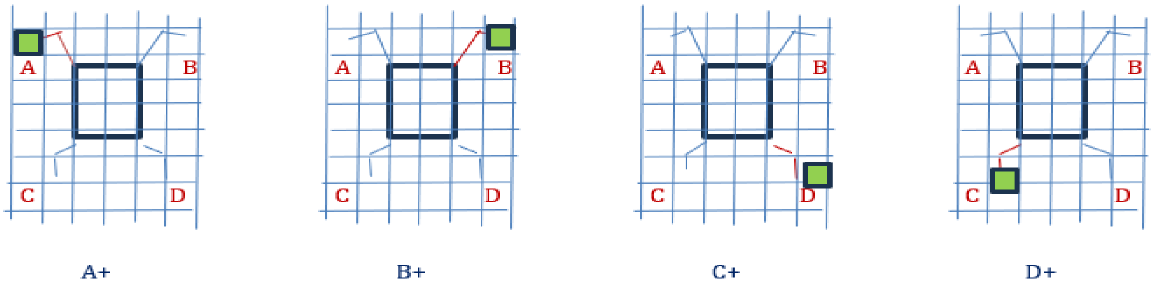


Figure 4. **Case 1: A+ → B+ → D+ → C+**

Table 2. *Case-1- Servo motor activation*

Step signal	A1	A2	B1	B2	C1		C2	D1	D2
Signal 1									
Signal 2									
Signal 3									
Signal 4									

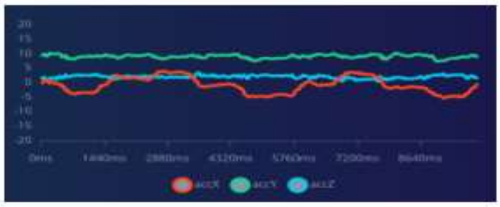


Figure 5. *Stability graph -Inverted C Gait*

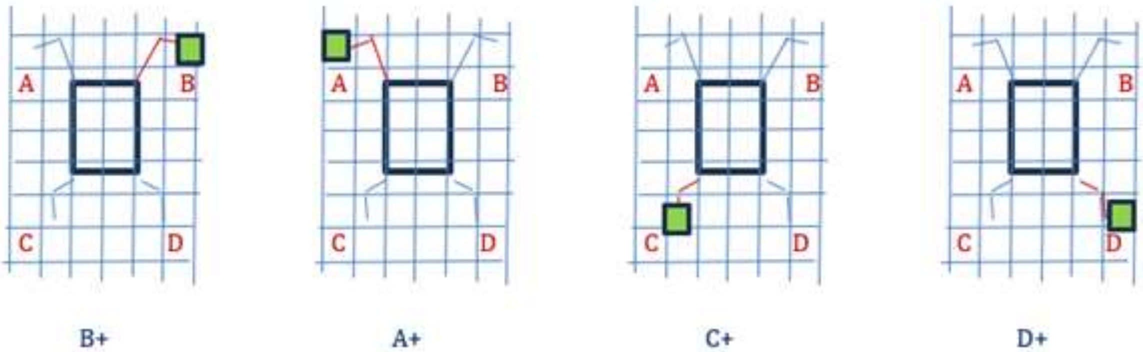


Figure 6. *Case 2: B+ →A+ →C+ →D+*

Table 4. *Case -3- Servo motor activation*

Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1								
Signal2								
Signal3								
Signal4								

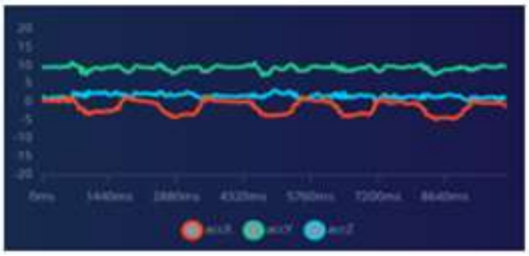
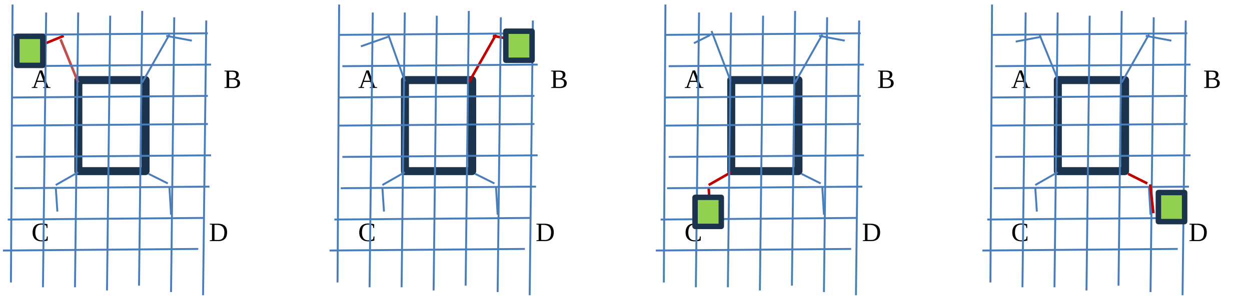


Figure 7. *Stability graph Z gait*



A+ B+ C+ D+

Figure 8. **Case 3: A+ → B+ → C+ → D+**

Table 4. *Case-3- Servo motor activation*

Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1								
Signal2								
Signal3								
Signal4								

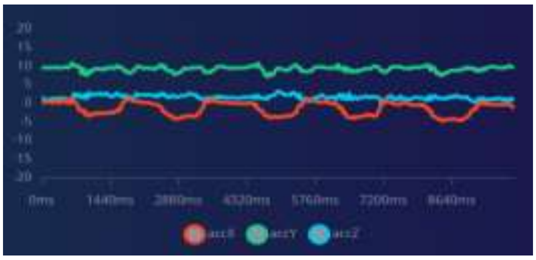
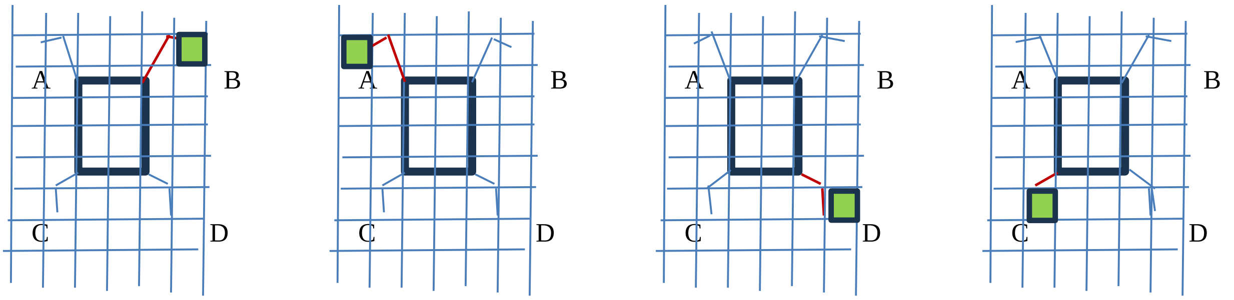


Figure 9. Stability graph - Z Gait



B+ A+ D+ C+

Figure 10. **Case 4: B+ → A+ → D+ → C+**

Table 5 : *Case-4- Servo motor activation*

Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1								
Signal2								
Signal3								
Signal4								

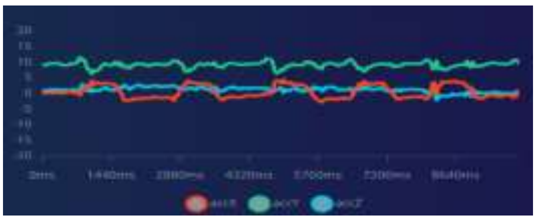
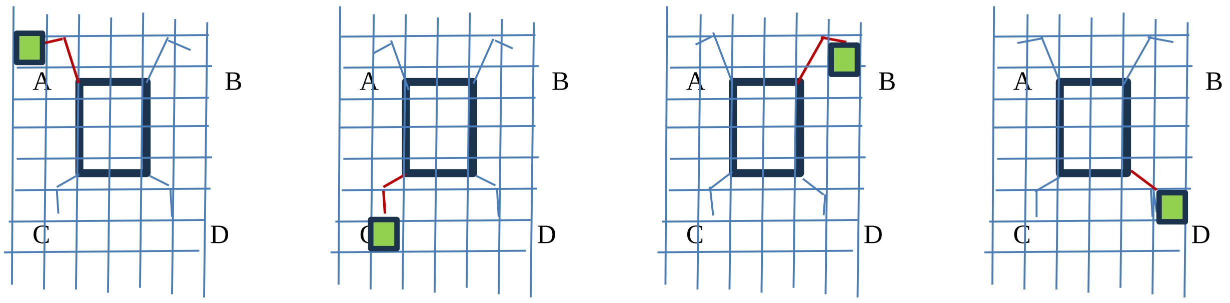


Figure 11. Stability graph – Inverted Z Gait



A+ C+ B+ D+

Figure 12. **Case 5: A+ → C+ → B+ → D+**

Table 6 : Case-5- Servo motor activation								
Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1								
Signal2								
Signal3								
Signal4								

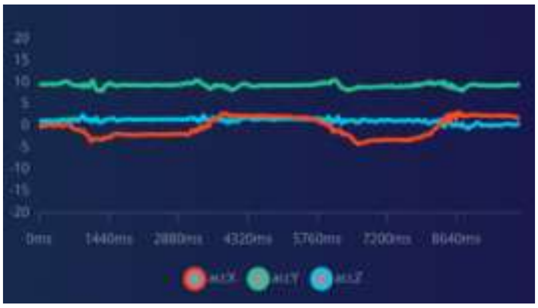
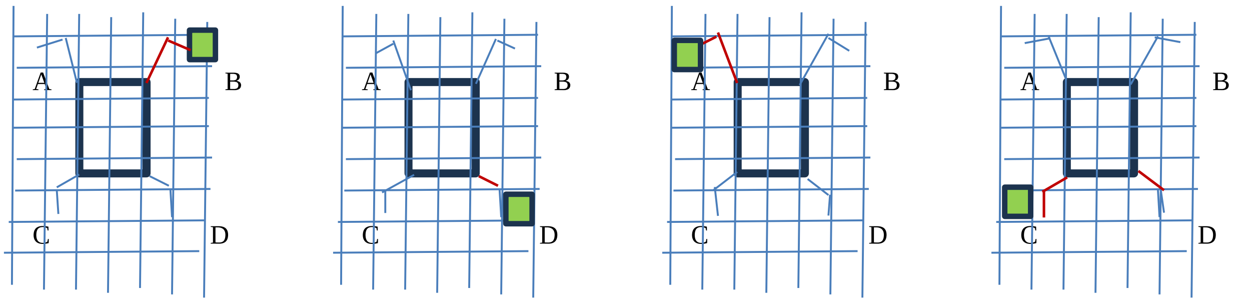


Figure 13. Stability graph – left-right marching **gait**



A+ C+ B+ D+

Figure 14. **Case 6: B+ → D+ → A+ → C+**

Table 7 : Case-6- Servo motor activation								
Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1								
Signal2								
Signal3								
Signal4								

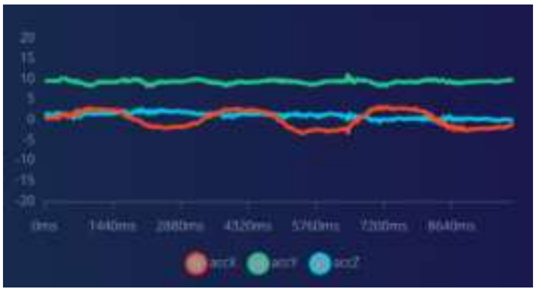


Figure 15. Stability graph – right-left marching **gait**

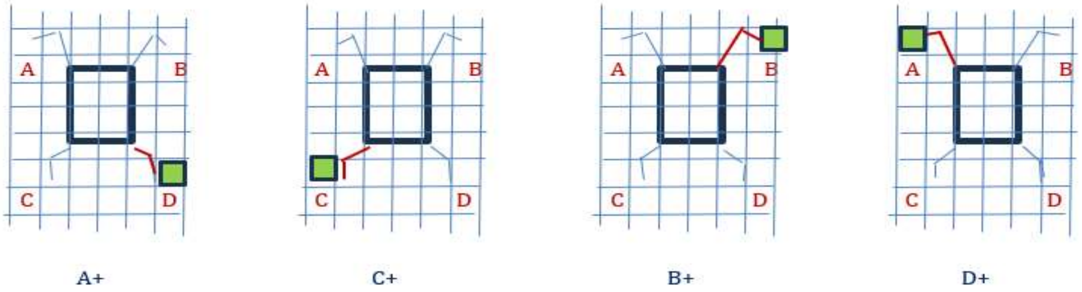


Figure 16. **Case 7: B+ → D+ → A+ → C+**

Table 8 : Case-7- Servo motor activation								
Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1							■	■
Signal2					■	■		
Signal3			■	■				
Signal4	■	■						

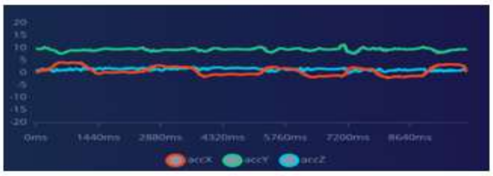


Figure 17. Stability graph – right-left marching gait

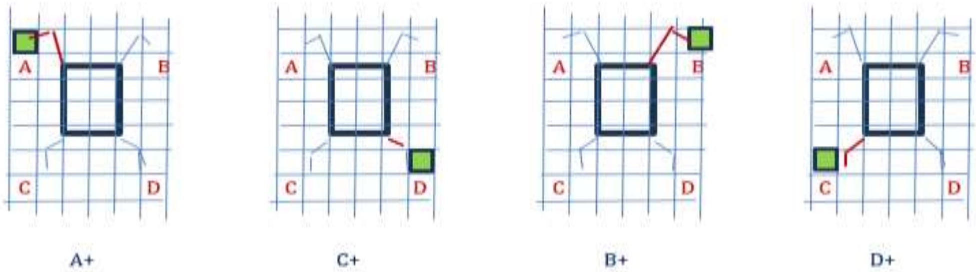


Figure 18. **Case 8: A+ → D+ → B+ → C+**

Table 9 : Case-8- Servo motor activation								
Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1	■	■						
Signal2							■	■
Signal3			■	■				
Signal4					■	■		

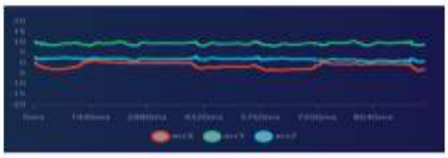


Figure 19. Stability graph – left first x cross gait

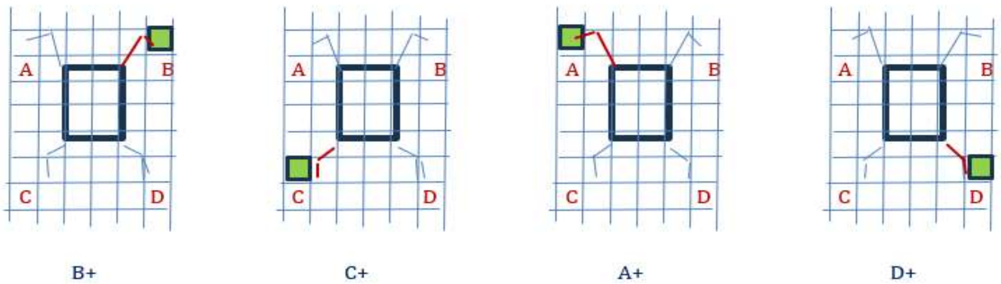


Figure 20. **Case 4: B+ → C+ → A+ → D+**

Table 10 : Case-9- Servo motor activation								
Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1			■	■				
Signal2					■	■		
Signal3	■	■						
Signal4							■	■

Figure 21. Stability graph – right first x cross gait

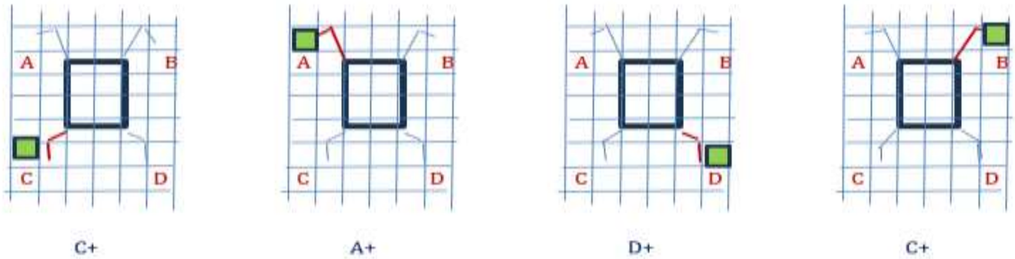


Figure 22. **Case 10: C+ → A+ → D+ → B+**

Table 11 : Case-10- Servo motor activation								
Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1								
Signal2								
Signal3								
Signal4								

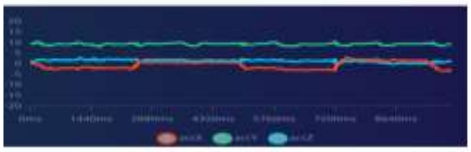


Figure 23. Stability graph – N Gait

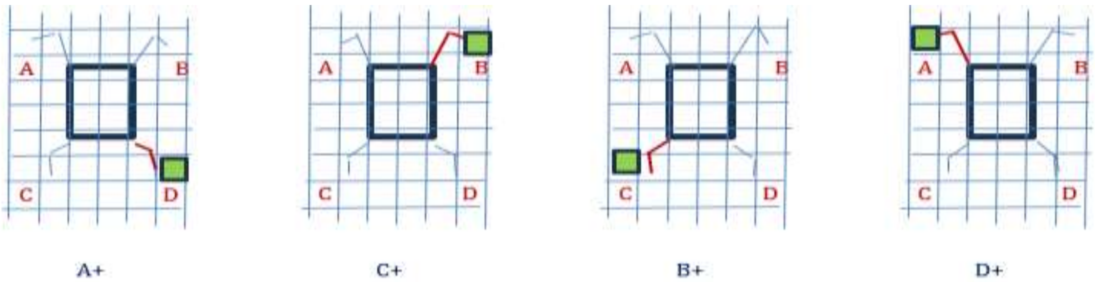


Figure 24. **Case 11: D+ → B+ → C+ → A+**

Table 12 : Case-11- Servo motor activation								
Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1								
Signal2								
Signal3								
Signal4								

Figure 25. Stability graph – Inverted N Gait

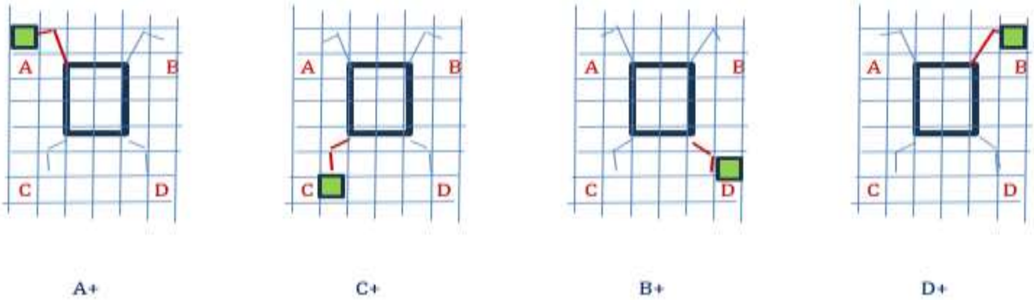


Figure 26. **Case 12: A+ → C+ → D+ → B+**

Table 13: Case-12- Servo motor activation								
Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1								
Signal2								
Signal3								
Signal4								

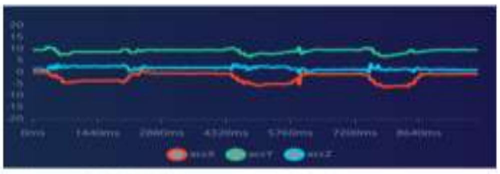


Figure 27. Stability graph – U Gait

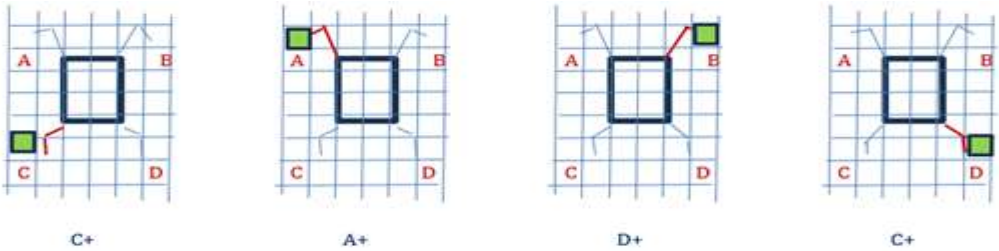


Figure 28. Case 13: C+ → A+ → D+ → B+

Table 14 : Case-13- Servo motor activation								
Step signal	A1	A2	B1	B2	C1	C2	D1	D2
Signal1								
Signal2								
Signal3								
Signal4								

Figure 29. Stability graph – Inverted U Gait

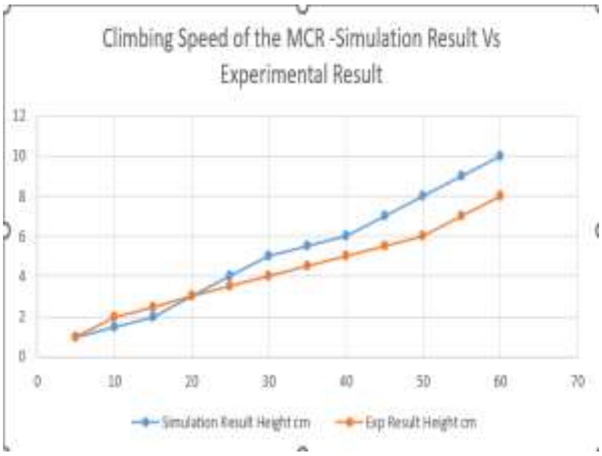


Figure 30. *Simulation result Vs Experimental result*

Table 15. *Simulation Vs Exp result*		
	Simulation Result	Exp Result
Time	Height	Height
seconds	cm	cm
5	1	1
10	1.5	2
15	2	2.5
20	3	3
25	4	3.5
30	5	4
35	5.5	4.5
40	6	5
45	7	5.5
50	8	6
55	9	7
60	10	8

Climbing Gait Methodology

The possible climbing gait of the proposed quadruped MCR is discussed in detail under 9 cases. The case 1 to case 14 as shown in Figure 4,6,8,10,12,14,16,18,20,22,24,26,28, to Figure 29 works with four different step signals to complete one cycle of climbing. The mode of servo motor excitation with respect to the step signals are as shown in table 2 to 14 respectively for each cases. The gait movement with two and three step signals are not considered here in this experimental study. The accelerometer and gyroscope sensor attached with MCR is linked to the Edge impulse software and the stability of the MCR with respect to each cases are extracted and studied as shown in figure 5, 7, 9, 11, 13, 15, 17, 19, 21, 23.

3. Discussions

Thus, the stability graph obtained for various gait as shown in figure 5,7,9,11,13,15,17,19,21,23. All these gaits are obtained by considering four step signals to complete one cycle of motion. The oscillation in x axis is meagre in LEFT FIRST X CROSS GAIT, RIGHT FIRST X CROSS GAIT, Inverted U GAIT which says that the stability are having more when compared to other GAIT system. The other GAIT methods shows that there the oscillation frequency in x axis is found to be more in a rhythmic way which would be a challenging factor as the MCR climbs to height. The mesh square size considered in software and hardware may not be same. Similarly other environmental factors which influence in real time testing may not be consider in the physical engine chosen while doing simulation in Coppelia Sim software.

Author Statements:

- **Ethical approval:** The conducted research is not related to either human or animal use.
- **Conflict of interest:** The authors declare that they have no known competing financial interests or personal relationships that could

have appeared to influence the work reported in this paper

- **Acknowledgement:** Need to acknowledge the Edge impulse software for providing this platform to do this project and also need to thank the Coppelia Sim software for enhancing the simulation design and testing of the quadruple bioinspired mesh climbing robot
- **Author contributions:** The authors declare that they have equal right on this paper.
- **Funding information:** The authors declare that there is no funding to be acknowledged.
- **Data availability statement:** The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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