Structural Analysis of Biomimetic Metal Net Climbing Robot (Mncr) and Dead Reckoning Using Imu for Analysing its Stability Under Triple and Double Step Signal

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Abstract. In the growing era of technology in construction industries, field robotics has evolved with many significant advancements that enhance construction processes. Specifically, Mesh Net Climbing Robots (MNCRs) have undergone technological updates in terms of locomotion and adhesion mechanisms. Mobile climbing robots can be categorized into legged, wheeled, and crawling types. Many researchers have studied the design features of these robots, particularly GAIT mechanisms. Not all GAIT strategies are equally suitable for ensuring stability, especially when robots climb vertical mesh surfaces against gravity. This paper presents a detailed structural analysis of an MNCR using ANSYS software and explores possible gait mechanisms for legged robots using two- and three-step signals to complete one cycle of motion. The dead reckoning method with an Inertial Measurement Unit (IMU) is used to evaluate stability factors for each GAIT and the results are compared to determine the most suitable option. An IoT-based approach via Edge Impulse software is also applied to measure stability across different GAIT. The design of this MNCR provides insights into developing wall-climbing robots capable of performing NDT tests on high-rise buildings or bridge pillars.

Keywords: Dead reckoning, three and two step signals, Metal Net Climbing Robot (MNCR), Gait, ANSYS.

1 Introduction

The possible Gait mechanism of wall climbing robot classified based on the number of step cycle is as given in Fig 1. For a wall climbing robot to be stable while climbing, the gait mechanism places a vital role especially when legged robot is considered. Hence in this paper, an experimental study is further made with the fabricated biomimetic metal net climbing robot (MNCR) undergoing various gait mechanism with neither two step duty cycle or three step duty cycle. The performance on the MNCR is analyzed in each case with respect to its stability factor while climbing measured through one of the dead reckoning methods named inertial measurement unit. The proposed MNCR is able to with stand certain load capacity without any

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structural deformation as discussed by Chen et al [1]. Rajendran et al [2] has proposed an electro pneumatic and electromagnetic based adhesive wall climbing robot. Wei et al [3] worked gait analysis and stability analysis of a quadruped robot. Wang et al [4] developed a bioinspired beetle shaped robot which could effectively move on mesh surface. As an example, Xu et al [5] introduced a surface coefficient and base height-based spot stability margin for a multilegged robot. Uckert et al [6] developed lemur a amphibious robot that can also walk offering astro biological capabilities to access the extra-terrestrial. Shahriari et al [7] developed an approach to gait generation in a six-legged robot, which utilized Q-learning. The 4-leg WCR proposed here is 3D printed, as shown in Fig 6 & 7. Each limb is driven by 3 servo motors. It is named A0, A1, A2 and B0, B1 B2 and C0, C1, C2 and D0, D1 D2 servo motors. So, all in all, there are 12 such servo motors, and the activated one is determined by the step duty cycle. Here, in this paper, the gait analysis has done with double and triple duty cycle

2 Related Works

Zi et al [8] proposed a novel adaptive and multimodal rock-climbing robot. Poonja et al [9] studied gait analysis on human walking pattern with 17 degrees of freedom bipedal that walks in uncomfortable environment. Akhtaruzzaman et al [10] proposed train wall climbing robot that can walk on smooth vertical surface overcoming barrier which if of height about 1cm. Huang et al [11] studied the moving mode, controlling mode and necessary conditions required for different adsorption of wall climbing robot. Bilal et al [12] introduced gait analysis for a 4-legged wall climbing robot with suction cup as adhesive medium. Menon et al [13] proposed gecko inspired wall climbing robot with synthetic dry adhesive. Bell et al [14] proposed a cyclic gait through which it can climbing the wall with peg configuration. Linder et al [15] proposed an automatic detection of random placed handholds for a wall climbing robot using computer vision. Parness et al [16] proposed LEMUR-3 which is capable enough to climb cliff surface and smooth glass. It uses micro spine grippers for climbing the rocky surface. Maempal et al [17] introduced a pipe climbing robot for which different gaits are proposed based on the speed of climbing. Nadan et al [18] proposed a passive gripper where the forces are distributed based on optimized control strategy for avoiding the detachment of the robot. Rajendran et al [19] introduced a wall climbing robot with high payload to weight ratio justified through a software named Coppelia Sim. Owaki et al [20] discussed about the coordination between the gait transition for a quadruped robot using central pattern generator model. Wang et al [21] developed a new palm design with micro spine structure for human scale climbing robot. Gong et al [22] proposed gait parameter extraction model through which many features like gait duty cycle, gait sequence, gait frequency and gait trajectory. Xu et al [23] developed a suction-based mechanism with hook like claws that enables climbing the wall.

3 Methodology

The designed concept has been modelled and analyzed with the help of SOLID WORKS design package. This SOLID WORKS yields stress, strain, displacement model of the design proposed. The implemented 3D model is designed as shown in Fig 1 and its displacement model is shown in Fig 2. Wang et al [24] were analyzing caterpillar-type wall climbing robot using SOLID WORKS. Another software design and analysis model for a tracked wall climbing robot for ship inspection in ship building was introduced by Huang et al [25]. Bisht et al [26] developed an inchworm inspired biped wall climbing robot, for that the design analysis was carried out using SOLIDWORKS software. Zulkifli et al [27] developed a hybrid adhesive mechanism wall climbing robot design analysis method with the help of the SOLID WORKS. The minimum and maximum stress at the proposed wall developed during the analysis is 4.824e+00N/m^2, 3.364e+08N/m^2 respectively as depicted in the Fig 3. The maximum and minimum strain on the proposed wall is calculated during analysis and it is 3.272e-09 and 1.143e-01 as represented in Fig 4.

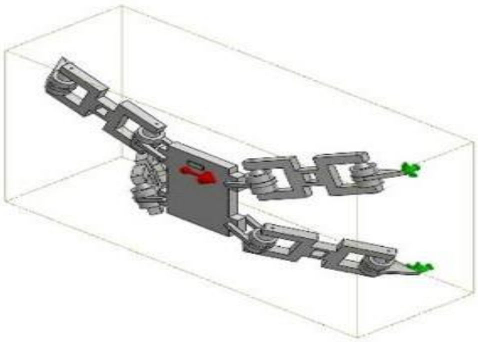


Fig. 1. Solid work model.

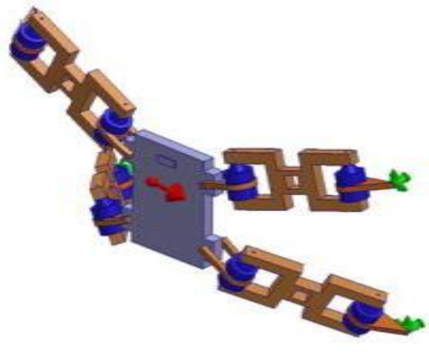


Fig.2. MNCR-displacement model.

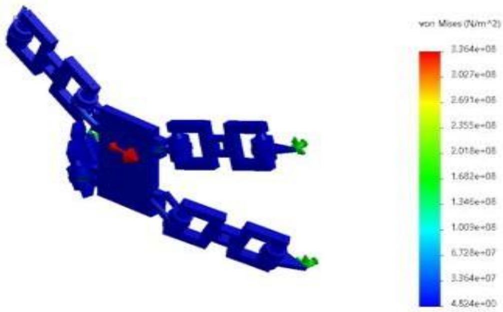


Fig.3. Stress analysis- MNCR.

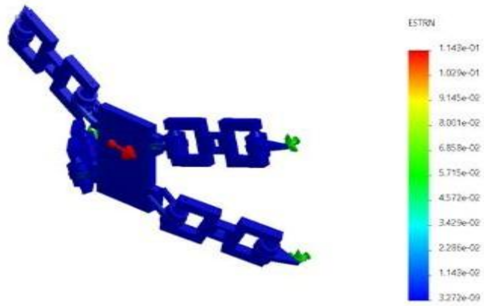


Fig.4. strain analysis – MNCR.

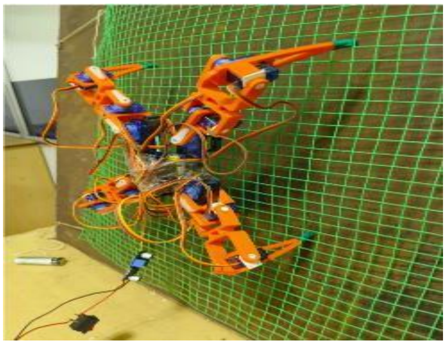


Fig. 5. Side view of MNCR -dynamic state in lab.

Fig .6. Front view of MNCR -dynamic state in lab.

3.1 Gait analysis

As mentioned in Fig 5 and 6, there are various possible Gait mechanism for this proposed MNCR classified based on the step cycle .Front hopping Anticlockwise, Front hopping clockwise, Rear hopping anticlockwise, Rear hopping clockwise, front first and rear next hopping, Rear first and front next hopping are the common possible GAITS of which this front first and rear next ,Rear first and front next hopping Gait will work with two step signals and rest of the Gaits work with three step signals for completing one cycle.

3.2 Front Hopping Anticlockwise GAIT

The Fig 7 depicts the front hopping anticlockwise Gait, in this Gait, the front leg A and B hops together (AB+) and then rear left leg C hops (C+) followed by rear right leg D (D+) as shown in equation 1. The hopping is represented by ‘+’symbol. It needs three step signals for completing one cycle. The table 1 shows the mode of activation of servo motors for each step signals

$$\boldsymbol{AB+ \longrightarrow C+ \longrightarrow D+} \qquad (1)$$

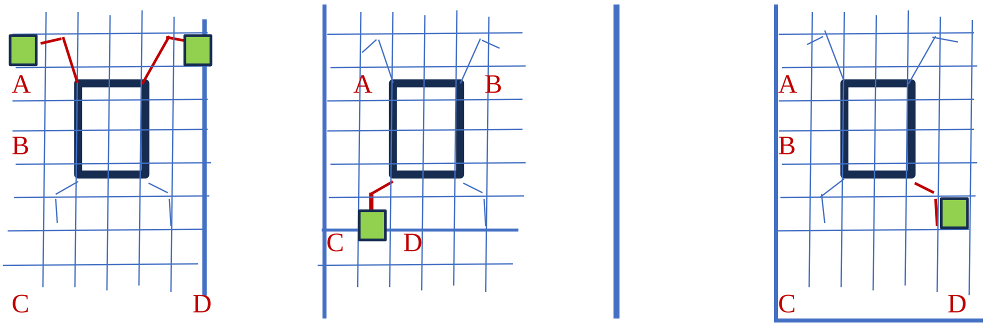


Fig. 7. Front Hopping Anticlockwise GAIT.

Table 1. Servo motor activation- Front Hopping Anticlockwise GAIT.

Step signal	A1	A2	A3	B1	B2	B2	C1	C2	C3	D1	D2	D3
Signal 1												
Signal 2												
Signal 3												

3.3 Front Hopping Clockwise GAIT

The Fig 8 depicts the front hopping clockwise Gait, In this Gait, the front leg A and B hops together (AB+) and then rear right leg D hops (D+) followed by rear left leg C (C+) as shown in equation 2. The hopping is represented by ‘+’symbol. It needs three step signals for completing one cycle. The table 2 shows the mode of activation of servo motors for each step signals.

AB+ → **D+** → **C+** (2)

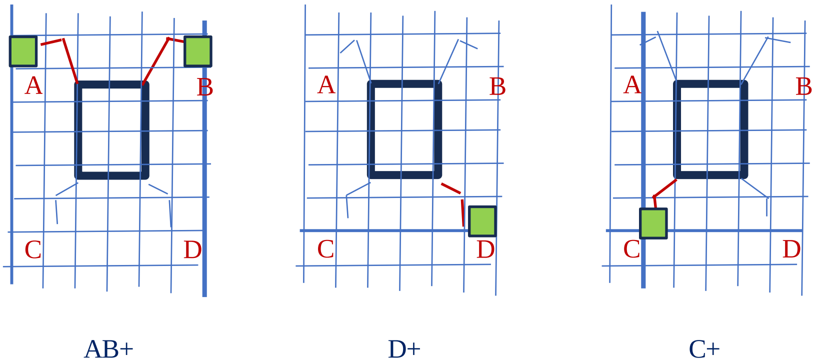


Fig. 8. Front Hopping clockwise GAIT.

Table 2. Servo motor activation- Front Hopping Clockwise GAIT.

Step signal	A1	A2	A3	B1	B2	B2	C1	C2	C3	D1	D2	D3
Signal 1												
Signal 2												
Signal 3												

3.4 Rear Hopping Anti Clockwise GAIT

The Fig 9 depicts the rear hopping anticlockwise Gait, In this Gait, the rear leg C and D hops together (CD+) and then front right leg B hops (B+) followed by front left leg A (A+) as shown in equation 3. The hopping is represented by '+'symbol. It needs three step signals for completing one cycle. The table 3 shows the mode of activation of servo motors for each step signals

CD+ → **B+** → **A+** ....(3)

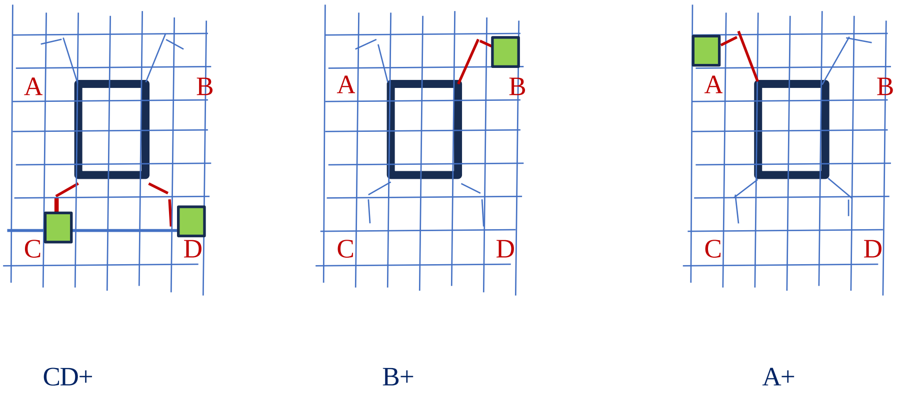


Fig. 9. Rear Hopping Anti clockwise GAIT.

Table 3: Servo motor activation- Rear Hopping Anti Clockwise GAIT.

Step signal	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	D3
Signal 1												
Signal 2												
Signal 3												

3.5 Rear Hopping Clockwise GAIT

The Fig 10 depicts the rear hopping clockwise Gait, In this Gait, the rear leg C and D hops together (CD+) and then front left leg A hops (A+) followed by front right leg B (B+) as shown in equation 4. The hopping is represented by '+'symbol. It needs three step signals for completing one cycle. The table 4 shows the mode of activation of servo motors for each step signals

$$\textbf{CD+} \longrightarrow \textbf{A+} \longrightarrow \textbf{B+} \tag{4}$$

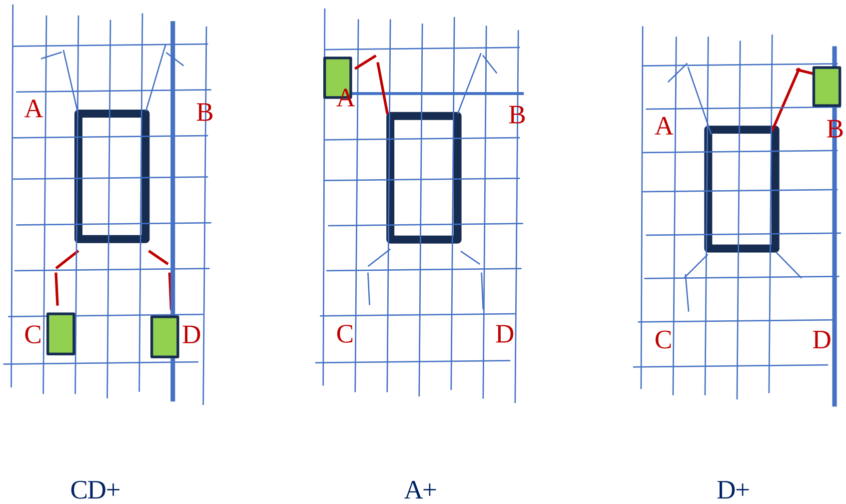


Fig.10. Rear Hopping Anti clockwise GAIT.

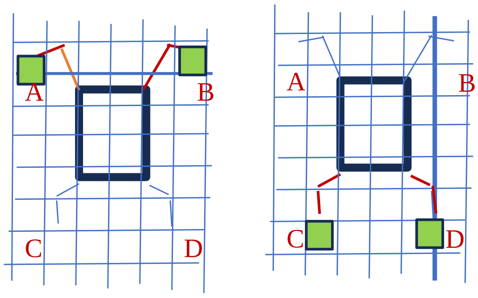
Table 4: Servo motor activation- Rear Hopping Clockwise GAIT.

Step signal	A1	A2	A3	B1	B2	B2	C1	C2	C3	D1	D2	D3
Signal 1							/					
Signal 2	/											\
Signal 3				\ /		\						

3.6 Front First Hopping & Rear Next Hopping GAIT

The Fig 11 depicts the front first and rear next hopping Gait, In this Gait, the front leg A and B hops together (AB+) for first step signal and rear leg C and D hops together (CD+) for the second step signal as shown in equation 5. The hopping is represented by '+'symbol. It needs two step signals for completing one cycle. The table 5 shows the mode of activation of servo motors for each step signals

$$\textbf{\textit{Case 5: AB+}} \longrightarrow \textbf{\textit{CD+}} \qquad (5)$$



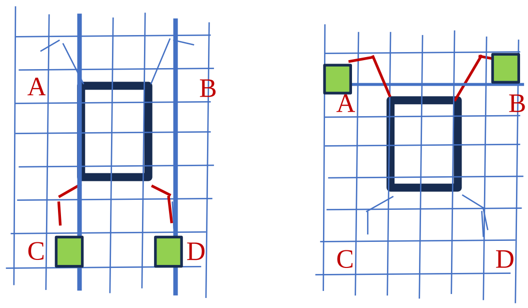
AB+ ***CD+***

Fig. 11. Front First Hopping & Rear Next Hopping GAIT.

3.7 Rear First Hopping & Front Next Hopping GAIT

The Fig 12 depicts the rear first and front next hopping Gait, In this Gait, the rear leg C and D hops together (CD+) for first step signal and front leg A and B hops together (AB+) for the second step signal as shown in equation 6. The hopping is represented by '+'symbol. It needs two step signals for completing one cycle. The table 6 shows the mode of activation of servo motors for each step signals

Case 6 : CD+ $\longrightarrow$ ***AB+*** 6)



CD+ AB+

Fig.12. Rear First Hopping & Front Next Hopping GAIT.

Table 5: Servo motor activation- Rear Hopping Clockwise GAIT.

Step signal	A1	A2	A3	B1	B2	B2	C1	C2	C3	D1	D2	D3
Signal 1												
Signal 2												

Table 6: Servo motor activation- Rear Hopping Clockwise GAIT.

Step signal	A1	A2	A3	B1	B2	B2	C1	C2	C3	D1	D2	D3
Signal 1												
Signal 2												

4 Result and Evaluation

The dead reckoning method named Inertial Measurement Unit (IMU) is considered for stability analysis of the proposed MNCR for various GAIT analysis. The stability analysis for front hopping anticlock wise is represented in Fig 13, it shows that there is less deviation in X and Y axis but more deviation in Z axis. The stability analysis for front hopping clock wise is represented in Fig 14, it shows that there is less deviation in X and Y axis but more deviation in Z axis. The stability analysis for rear hopping anticlock wise is represented in Fig 15, it shows that there is less deviation in Y axis but more deviation in X and Z axis. The stability analysis for rear hopping clock wise is represented in Fig 16, it shows that there is less deviation in Y axis but more deviation in X and Z axis. The stability analysis for front first and rear next hopping is represented in Fig 17, it shows that there is less deviation in X axis but more deviation in Y and Z axis. . The stability analysis for rear first and front next hopping is represented in Fig 18, it shows that there is less deviation in X axis but more deviation in Y and Z axis.

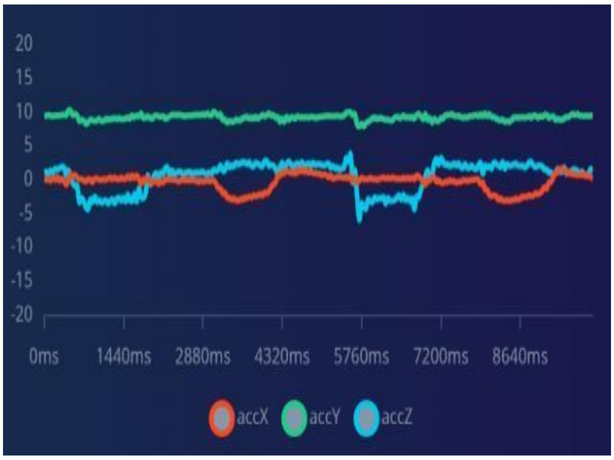


Fig.13. Front Hopping Anticlockwise GAIT.

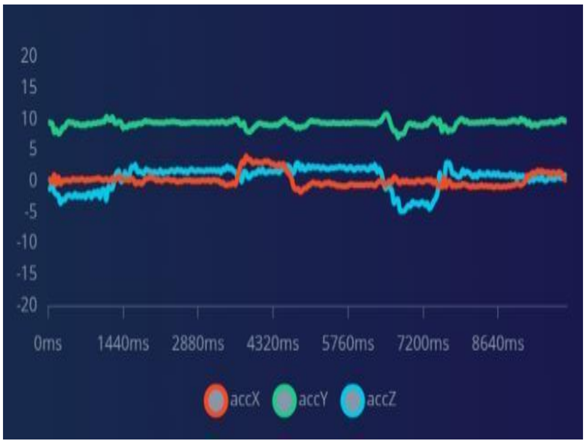


Fig.14. Front Hopping Clockwise GAIT.

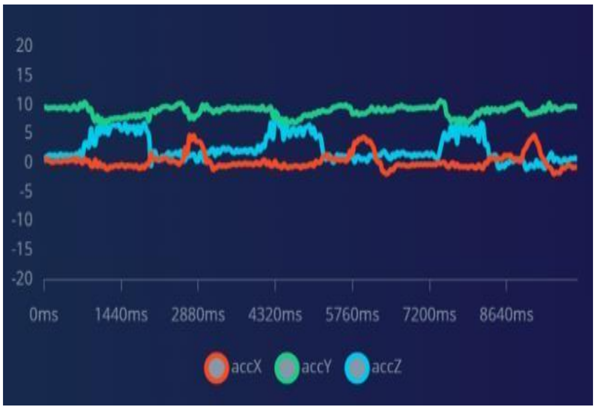


Fig.15. Rear Hopping Anti Clockwise GAIT.

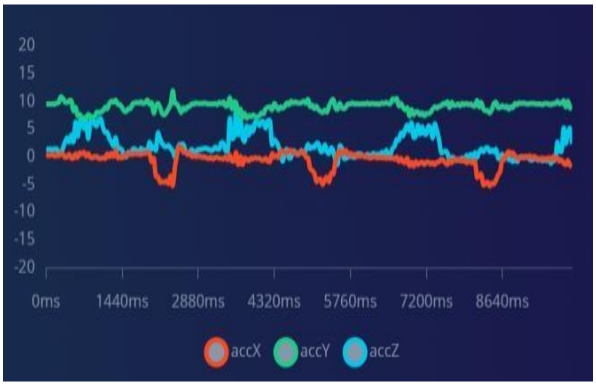


Fig.16. Rear Hopping Clockwise GAIT.

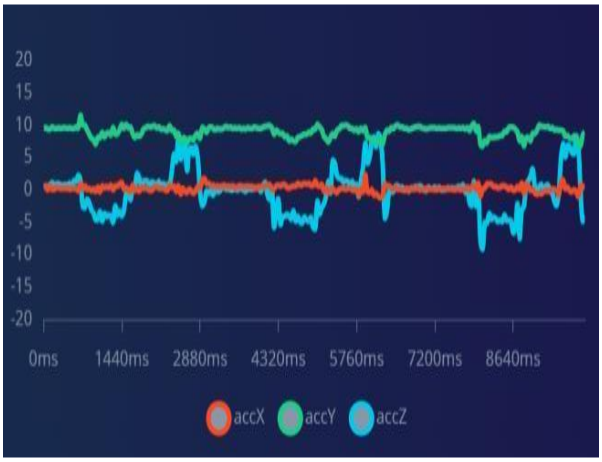


Fig.17. Front First and Rear Next Hopping.

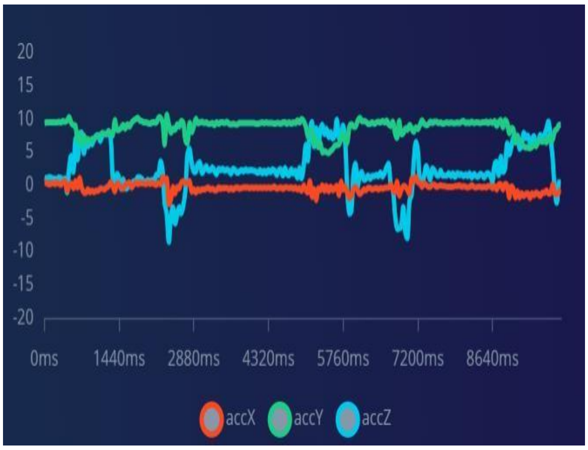


Fig.18. Rear First and Front Next Hopping GAIT.

5 Conclusion

The structural analysis pf the proposed MNCR model designed and analyzed in SolidWorks have proven practically with the 3D printed model in lab test as shown in Fig 5 and 6.Comparing the stability graph obtained in Edge Impulse software as shown in Fig 13 to 18 for each different GAITS working with three and two step signals, it is clear that the stability graph obtained in Front hopping anticlockwise (as shown in Fig 13) and clockwise (as shown in Fig 15) is found to be more stable when compared with stability graphs of other GAITS (ie Fig 15 to 18) , as more deviation is found only in one axis (ie Z axis).

Acknowledgement

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