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Design of Omnidirectional Wall Climbing Robot with Its Payload Analysis

Rakesh Rajendran[1]*, Shivakumar N[2], Rajanandhini C[3], Saravanakumar U[3]

[1]Centre for Excellence in Training and Research in Automation Technology (CETAT), Periyar Maniammai Institute of Science and Technology, Thanjavur, Tamil Nadu, India, [2]Department of Mechanical Engineering, Periyar Maniammai Institute of Science and Technology, Thanjavur, Tamil Nadu, India, [3]Department of Electronics and Communication Engineering, Periyar Maniammai Institute of Science and Technology, Thanjavur, Tamil Nadu, India. *Corresponding Author's Email: rak2win@gmail.com

Abstract

Robotics has emerged as an inevitable technology playing a vital role meeting lots of applications, especially when the industrial application is considered it contributes more towards the sustainable development goal number 9. To be more précised the wall climbing robots plays major role in industrial application meeting the demands of the industry such as performing nondestructive testing on vertical walls, vessels etc. There are two major features which has to be considered while designing Wall Climbing Robots. One is payload and the other one is self-weight. It is important to consider these parameters for the efficient performance of Wall climbing Robots. These wall climbing robots should be able compact and able to travel any direction for industrial applications like testing, cleaning, painting and for any other industrial applications. In this paper, an attempt is made to design and fabricate an omnidirectional Bi-Wheeled Wall Climbing Robot (BWWCR). A mathematical calculation using free body diagram is also presented to validate the theoretical required adhesive force. The simulation software named Coppelia Sim is used for designing the bot and the static and dynamic payload testing done with fabricated hardware is compared with that of simulated software. Software named Finite Element Magnetic Methods (FEMM) is used to study the flow of magnetic flux density throughout the surface and the stability of the bot while climbing with change in direction is also studied through the software named Edge impulse.

Keywords: Bi-Wheeled Wall Climbing Robot (BWWCR), Coppelia Sim, Edge Impulse Software, FEMM, Free Body Diagram.

Introduction

Though there are many parameters affecting the design feature of the wall climbing bot, the major two features will be payload and self-weight. Wall climbing robots with its capability to access in omni direction saves the time taken for scanning the area particularly while performing NDT testing in industries hence there is always a great scope for the design and application of these omni directional wall climbing robots. A method of using simulation software named Coppelia Sim for determining the payload capacity of a bidirectional bot (climbs up and descend down) for the given specification like self-weight, velocity of the motor and adhesive force of the magnetic wheel is documented in the literature (1). The same work is extended here in this paper for an omni directional wall climbing bot. The desired adhesive force for a wall climbing robot can be determined using mathematical modeling (i.e Free Body diagram) and a simulation software named FEMM to check the flow of magnetic flux density lines throughout the length of the bot (2). In this paper, these two methods are again used for this omni directional wall climbing bot in order to determine the desired adhesive force and also the flow of magnetic flux density lines. In addition to that, the stability of the proposed BWWCR is also justified with the help of the Edge impulse software in terms of X, Y and Z axis during the dynamic test. The design of wall climbing bot is studied using free body diagram and finite element analysis (3). FEMM can be used for analyzing the performance of proposed cylindrical magnet enhanced by electromagnetic vibration energy harvesting method (4). The Halbach array performance was comparatively measured between AB method and FEM method (5). The free body diagram method and usage of Ansys software for FEA is documented in the literature (6). The performance of proposed bot

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can be analyzed using FEMM and Ansys Maxwell (7). The construction of free body diagram is discussed in detail for suction mechanism wall climbing robot (8). The FEM analysis can be used to justify the design of electromagnetic suction type wall climbing robot (9). The FEMM software is used for studying the effect of magnetic field (10). The simulation software used to study the behavior of electro permanent magnetic wheel is documented in the literature. (11). The FEMM analysis can be used to determine the variation in magnetic flux density for the proposed bot (12). The Ansys FEM software can be used to validate the proposed design of magnetic adhesive wall climbing robot (13). The performance of magneto rheological valve is determined using FEMM software (14).

Methodology

The research starts with theoretical calculation of desired adhesive force using mathematical equation. The FEMM software is used to analyze the flow of magnetic flux lines throughout the length of the proposed WCR. The Coppelia Sim software is used to model the proposed WCR and test its performance to read the time taken in dynamic mode to reach the particular height with particular payload, the same procedure is then repeated with hardware testing in real time experiment. Free body diagram is the method mathematically justifies the proposed design of wall climbing robot. This free body diagram of the proposed BWWCR is subjected to four different cases as shown in Figure 1 to Figure 4.

Case:1: The Figure 1 shows the wall climbing bot on the horizontal surface with various force vectors acting from and towards the body in this case 1, now considering the adhesive force exerted from the magnetic wheel as K_i and the weight of the proposed BWWCR as G, then the required adsorption force (F_1^a) is as given in the equation [1].

$\sum K_i = G + F_1^a (1)$ where i=1,2. -------------[1]

Case:2: The Figure 2 shows the wall climbing bot on the inclined surface (θ is the inclination angle) with various force vectors acting from and towards the body in this case 2, now considering the adhesive force exerted from the magnetic wheel as K_i and the weight of the proposed BWWCR as G, then the adsorption force (F_2^a) as given in the equation [2].

$\sum K_i = G \cos\theta + F_2^a (1)$ where i=1,2 -------[2]

Case:3: The Figure 3 shows the wall climbing bot on the vertical wall surface (θ value as 90^o - perpendicular to the ground surface) with various force vectors acting from and towards the body in this case 3, now considering the adhesive force exerted from the magnetic wheel as K_i and the weight of the proposed BWWCR as G, then the required adsorption force (F_3^a) is as given in the equation [3].

$\sum K_i = F_3^a (1)$ where i=1,2-----------------[3]

Case:4: The Figure 4 shows the wall climbing bot on the vertical wall surface with upside down tilted position with various force vectors acting from and towards the body in this case 4, now considering the adhesive force exerted from the magnetic wheel as K_i and the weight of the proposed BWWCR as G, then the required adsorption force (F_4^a) is as given in the equation [4].

$\sum K_i + G = F_4^a$ where i=1,2-----------------[4]

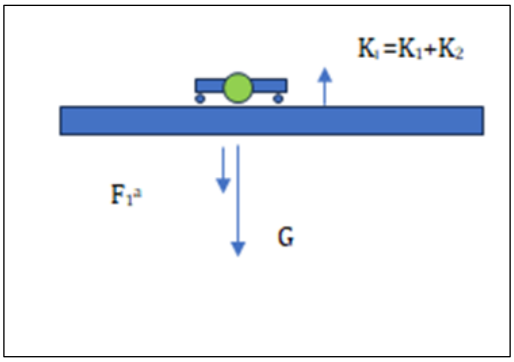

Figure 1: Case 1: The Bot on Horizontal Surface

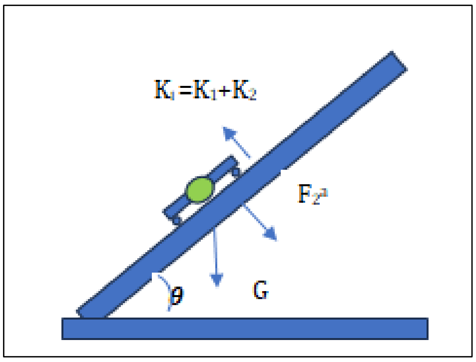

Figure 2: Case 2: The Bot on Inclined Surface

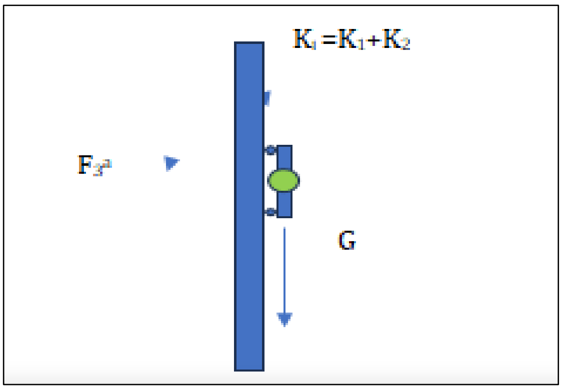

Figure 3: Case 3: The Bot on Vertical Wall

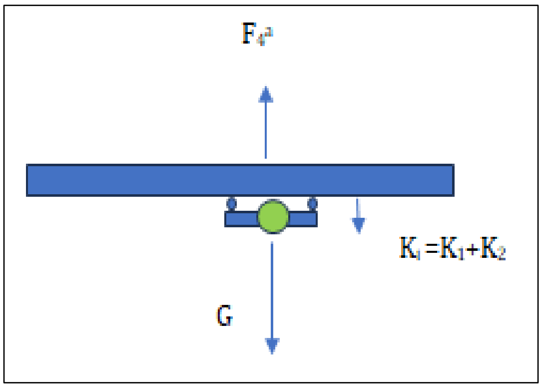

Figure 4: Case 4: Bot-Upside down Inverted Surface

Adhesive Force from Mathematical Modeling

The weight G of the BWWCR is around 1.7 kg. The super strong magnetic wheel made of NdFeB has an adhesive force value of 330N, since there are two magnetic wheels, the total adhesive force exerted should be 660N which is the value of K_i. By applying these values in the equation 1, 2, 3 and 4, the total desired adhesive for each case can be obtained as given in the Table 1.

Table 1: Desired Adhesive Force for Each Cases

	Case1	Case2	`Case3	Case 4
Desired Adhesive force (F_a)	644N	649 N	660 N	676 N

The Table 1 illustrates that in case 4 condition where the bot is at upside down inverted position, the total desired force required is 676 N which is higher when compared to all other three cases, but by considering the application (for vertical wall) and availability of magnetic wheel with proposed dimension, the minimum desired adhesive force is fixed to be 660 N. (i.e. 330 N from each wheel) which is higher than the desired adhesive force value in case 1 and case2.

FEMM Software

The performance of Halbach magnet array can be verified by analyzing magnetic flux density using FEM software (15). Software simulation for Finite Element Analysis helps us to study the flow pattern of magnetic flux density and strength of magnetic field intensity of a designed wall climbing robot using permanent magnetic wheel. Inspite of these available software Ansys, STAAD, MATLAB, FEMM software is having more features for finite element magnetic effect analysis. The magnetic wheel is made of NdFeB with standard of N55 which is available in the library of this FEMM software which enables as to declare the material type easily while designing.

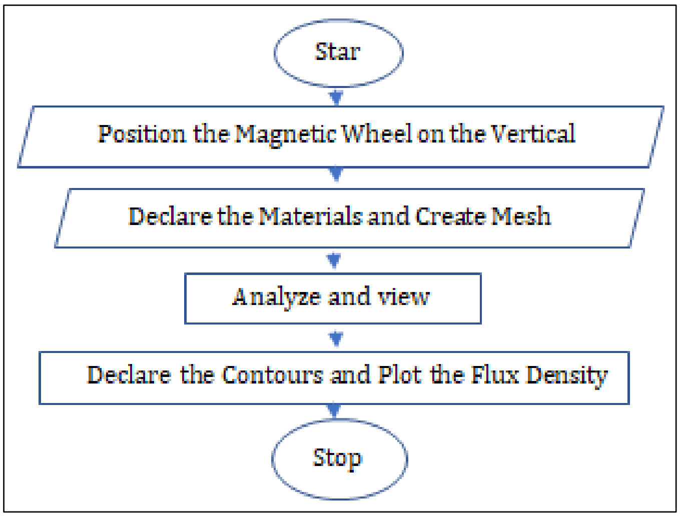

Figure 5: Flowchart for FEMM

The magnetic wheels are positioned on the vertical wall and the appropriate materials are chosen from the library, further those materials are declared with nodes and the mesh is created with declared nodes. Now click the analyze and view result to see the magnetic flux lines plot. Further declaring the contours and choosing the flux density graph, the magnetic flux density analysis can be obtained with the range of flux density in terms of Tesla.

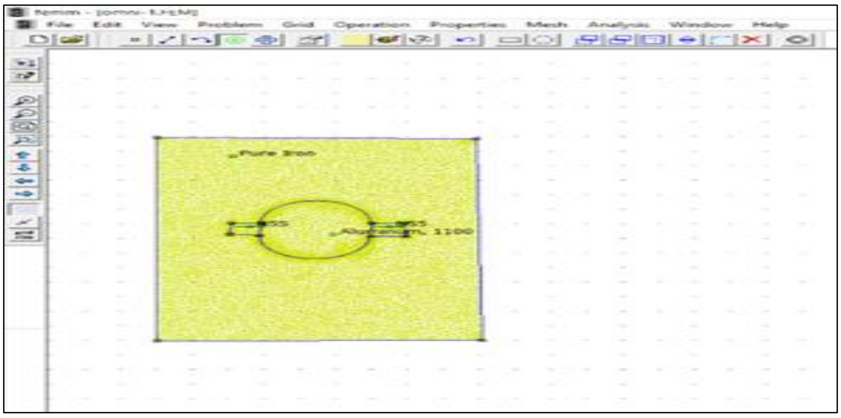

Figure 6: Mesh Constructed in FEMM

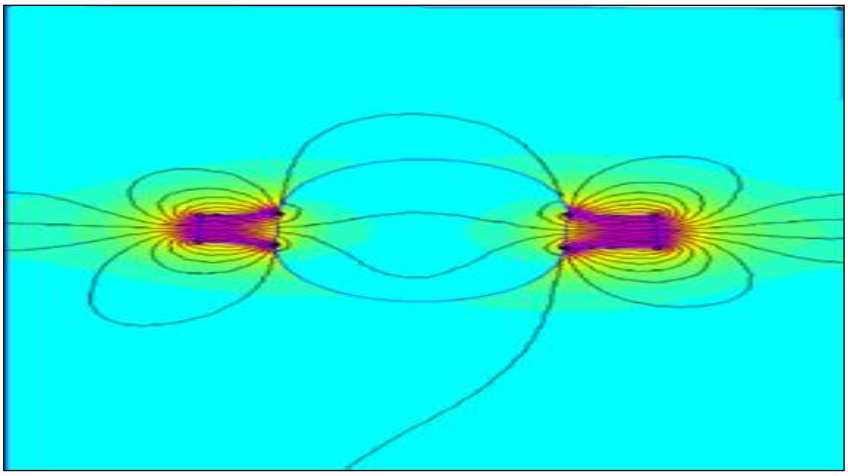

Figure 7: Flow of Magnetic Flux Density

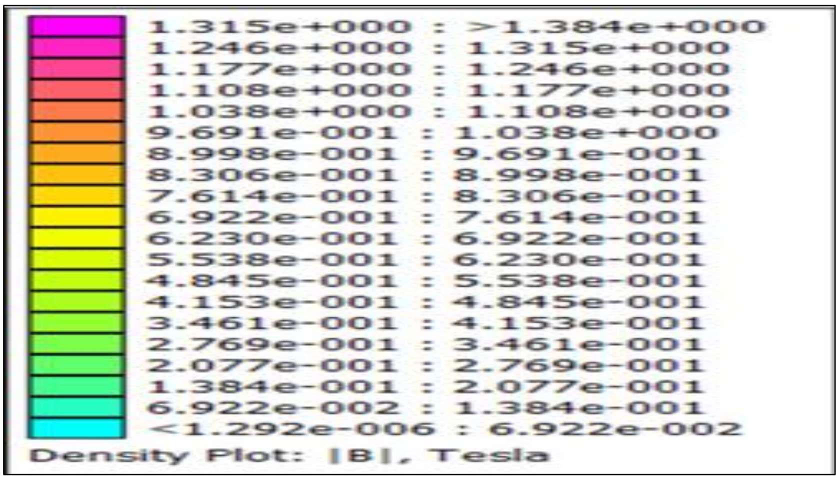

Figure 8: Range - Magnetic Flux Intensity

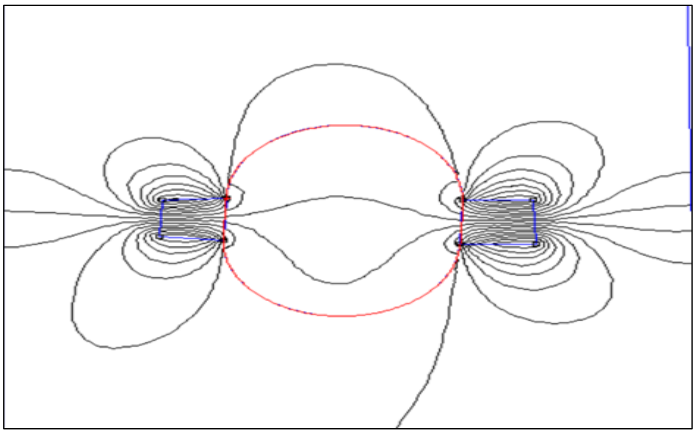

Figure 9: Contour Defined along the Circumference of the Bot

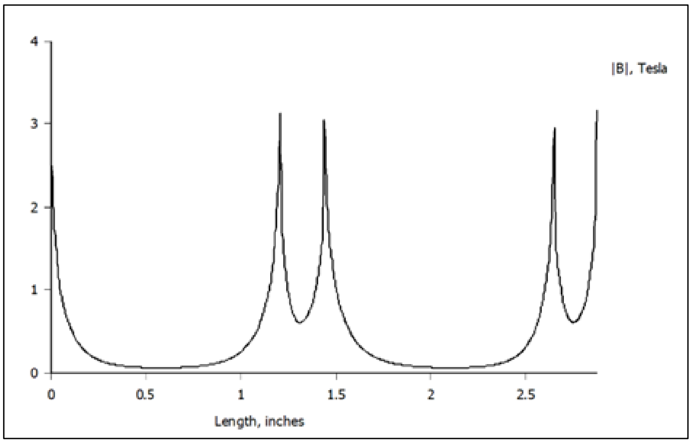

Figure 10: Magnetic Flex Intensity along the Circumference of the Bot

The overall methodology for the design and analysis is as shown in flowchart Figure 5. The magnetic flux density exerted from one wheel is not influenced with that of another wheel as shown in Figure 6 to Figure 8. This value of magnetic flux density for the proposed BWWCR design is found to be 1.4 Tesla. The Figure 9 shows the contour path which reads the flow of magnetic flux intensity along the circumference of the proposed omni bot. The two-peak value of magnetic flux intensity shown in Figure 10 indicates that maximum flux density falls on the place near to the magnetic wheel and since there are two wheels, it indicates two peak shoot value of the magnetic flux intensity.

Software and Hardware Modeling

Before the actual fabrication, the proposed BWWCR design is modelled with the software named Coppelia Sim as shown in Figure 11. The parameters like velocity of the motor, weight, adhesive force of the magnetic wheel can be fed as input via lua script to the software before simulation. The payload to weight ratio can be obtained as tabulated in Table 4 by allowing the bot to climb on the metal wall. The payload capacity of the proposed BWWCR is varied as 2.5 kg,4.5 kg,5 kg ,10kg,12 kg and 15 kg based on the availability of weight disc for actual experimental testing. For each payload trial in simulation, the respective time taken to climb the defined height 40 cm is noted and tabulated as shown in table. The height climbed by the bot is measured with help of distance check option tool available with CoppeliaSim. The CAD software is used to design the proposed model as shown in Figure 12. The Figure 13 shows the actual fabricated omni bot (upside down inverted position) with two superstrong magnetic wheels made of NdFeB. There are two castor wheels at the front and back of the disc which is provided for balance support and have no adhesive for exerted from this wheel. During the actual experimental test, the omni bot is allowed to carry the payload of 2.5 kg, 4.5 kg,5 kg ,10kg,12 kg and 15 kg and the respective time duration taken by the bot to cover the 40 cm height is noted and tabulated as shown in Table 3. The Figure 14 shows the BWWCR carrying 15 kg during dynamic mode of the actual experiment.

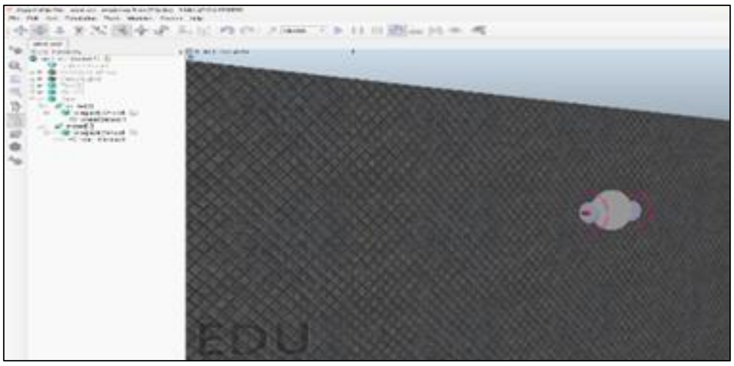

Figure 11: Omni Bot on Metal Wall-Side View

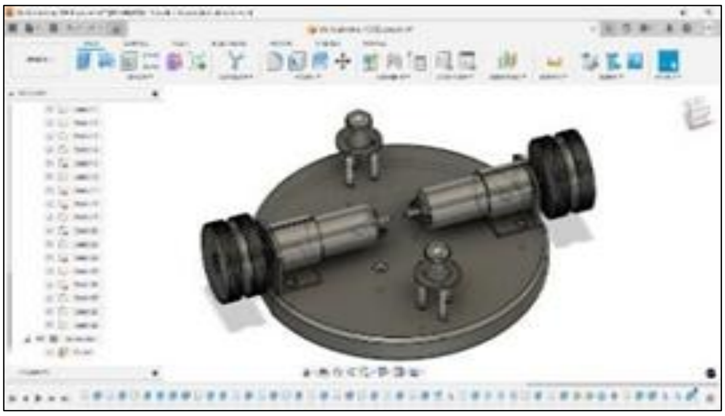

Figure 12: CAD Design of the Proposed Omni Bot

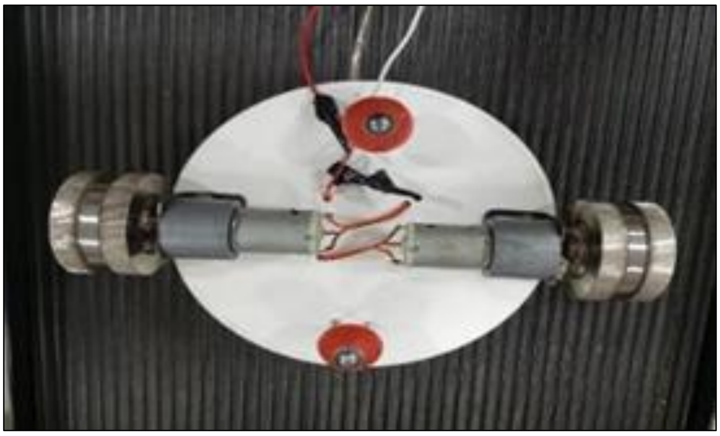

Figure 13: Actual Fabrication of Omni Bot

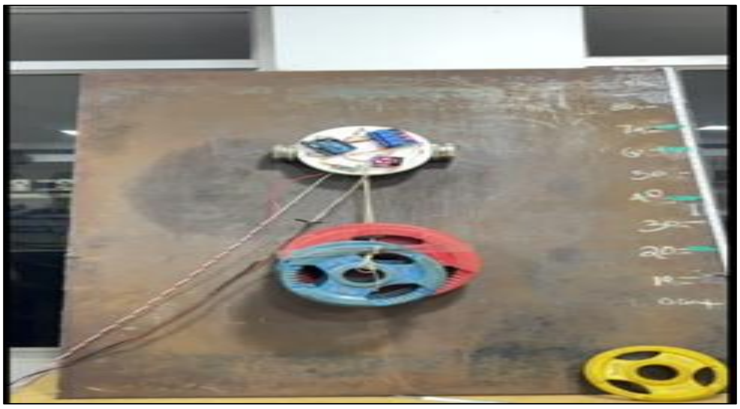

Figure 14: BWWCR Carrying 15kg in Dynamic

Table 2: Desired Adhesive Force for Each Cases

	Simulation Testing	Hardware Testing
Payload capacity (kg)	20kg	15 kg

Results and Discussion

Though there are many researchers who proposed the design of wall climbing robots, considering the design having bi wheel, the comparison is made with the existing one as shown in Table 4. The highest p:w value for one of the existing wall climbing robot is 10 (16). The Analysis of the payload to weight ratio (p: w value) of all existing magnetic adhesive wall climbing robot is documented in the literature (17), the payload to weight ratio value of the proposed omni bot is 9 and it is compared with the existing one as shown in Table 4. This omni direction bot having a weight of 1.7 kg is able to have payload capacity of 15 kg and hence the payload to weight ratio value is 9. Table 2 shows the value of payload capacity of the proposed BWWCR both in case of simulation and actual experiment and the result is more or less same for climbing the defined height of 40 cm. This justifies the purpose of using simulation software for fixing the better design parameters before moving to actual fabrication, this in turn saves the time, effort and reduce the cost and scrap. The Table 3 compares the time taken for carrying a specific payload in both simulation and actual experiment and it is found that the result in experiment is in line with that of the simulation as shown in Figure 15. The stability of BWWCR while climbing the metal wall in dynamic mode is also determined with respect to X,Y and Z axis as shown in Figure 16 in Edge impulse software as documented in the literature (18). The graph shows there is less fluctuation and the stability of the BWWCR is good in time series scale.

Table 3: Simulation Time Taken Vs Actual Time Taken

S. No:	Payload Capacity(kg)	Simulation Time(s)	Experimental Time (s)
1	2.5	4	5
2	4.5	5	5.5
3	5	5.5	6
4	10	6	7
5	12	7	8
6	15	9	11

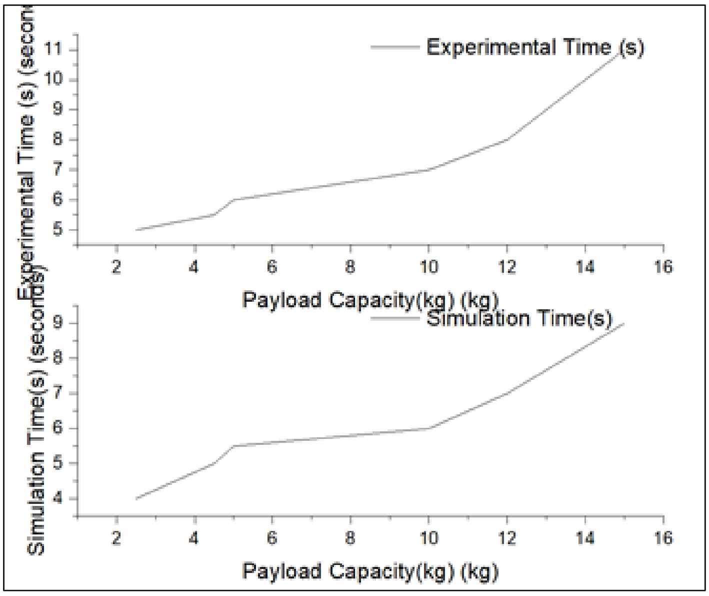

Figure 15: Simulation Vs Experimental-Time

Table 4: Comparison of P: W

S. No:	Authors	Payload (P)	Self-weight (W)	P: W
1	Tavakoli et al (17)	12 kg	1.2 kg	10
2	Proposed BWWCR	15 kg	1.7 kg	9

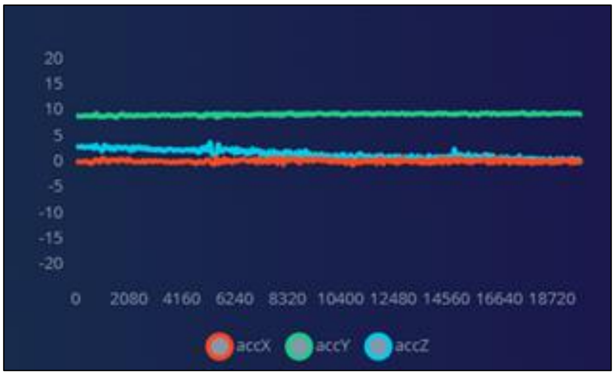

Figure 16: Stability of BWWCR in Dynamic -Edge Impulse

Conclusion

The proposed BWWCR having the payload to weight ratio value as 9 is successfully designed using software modelling like FEMM and Coppelia Sim. The theoretical calculation of desired adhesive force using free body diagram has minimized the practical trial and error study. The usage of modelling design using software has enabled the precision of the fabricated hardware design of BWWCR which has led to reducing the scrap cost.

The stability of the proposed BWWCR is also justified with the help of Edge impulse software. In future this study can be further expanded by replacing normal wheels with omni wheels, so that the diagonal movement of the BWWCR could be simpler and faster which reduces the time taken for scanning the given wall surface area.

Abbreviations

BWWCR: Bi Wheeled Wall climbing Robot, FEMM: Finite Element Magnetic Method, kg: kilogram, s: seconds.

Acknowledgement

Need to acknowledge the FEMM open-source 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 this BWWCR bi wheeled wall climbing robot on metal wall. Also need to thank the Edge impulse platform for providing the support to perform IoT based stability analysis for the proposed BWWCR.

Author Contributions

R. Rakesh: Concept developer and Contributed in Simulation, C. Rajanandhini: Contributed towards literature review, U. Saravanakumar: Contributed in fabrication of bot, N, Shivakumar: Contributed in drafting the work.

Conflict of Interest

The authors declare that there is no conflict of interest.

Ethics Approval

There is no specific data with required ethics approval.

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