SSRG International Journal of Mechanical Engineering
ISSN: 2348-8360/ https://doi.org/10.14445/23488360/IJME-V13I8P111

Volume 13 Issue 8, 131-138, August 2026

Original Article

Design and Fabrication of Bioinspired Turtle Wall Climbing Robot (TWCR) using Coppeliasim

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Received: 12 March 2026 Revised: 14 April 2026 Accepted: 16 May 2026 Published: 27 August 2026

Abstract *- Though there are various wall-climbing robot designs proposed so far. There are only a few wall-climbing robots that are based on biomimetic developed mimicking the movement or features of any living organism. There is always a great demand for such a biomimetic robot that climbs wall which is to be light weighted compact in size, that can perform various industrial application tasks. That too, especially to perform any precise task where the navigation time is given the least priority, there is a scope for slow moving robot that climbs walls. In this article, one such biomimetic robot that climbs walls is designed inspiring the shape and movement of a turtle. The mathematical modelling of this turtle bot is done using free body diagram. Then, this Turtle Wall Climbing Robot (TWCR) is modeled in FEMM in order to justify its design with respect to the flow of magnetic field strength and intensity. The design of this turtle bot was first made in the simulation environment named Coppeliasim. In this Simulation environment, the turtle WCR is allowed to ascend and descend, so that the compatibility and feasibility check is made, and the time taken is also noted. These simulation readings are then cross-verified with the readings taken from the fabricated real-time testing made on the wall inside the lab.*

Keywords *- TWCR, Bio Inspired Wall Climbing Robot, Femm, Coppeliasim, Free body diagram.*

1. Introduction

There is a huge role of the wall climbing robot in the maintenance, repairing and also performing testing in the industrial environment. A bio-inspired wall-climbing robot is one that mimics the way some animals, such as geckos, insects, or spiders, stick to and move along walls in order to climb vertical surfaces. Though many researchers have contributed in design and fabrication of these bio-inspired wall climbing robots, there is no bio-inspired wall climbing robot that mimics the turtle movement that moves slowly, hence there is a need for surveying these research papers considering the weight and speed of those wall climbing robots as key features of comparison. Lam et al. [1] proposed a biomimetic robot that climbs a wall weighing 4.6kg, having the capability to move at a speed of 3.7mm/s. Bartsch et al [2] designed a biomimetic robot that climbs a wall that weighs around 23 kg and moves at a speed of 0.31m/s. Jodah et al. [3] proposed gecko inspired robot weighing 2.5kg and moving speed of 0.03m/s. Aihong Ji et al. [4] proposed a biomimetic robot that climbs a wall weighing 800 g and 400 g, each moves with a speed of 0.08 m/s. Mohammed K. Jodah et al. [5], which weighs around 400 g, climbs at a speed of 0.046m/s. Linsen Xu et al. [6] presented a biomimetic robot that climbs a wall that weighs around 128 g, and moves with a speed of 0.01m/s. Daltorio et al. [7] presented a bioinspired wall-climbing robot that weighs around 130 g, and information about its speed is not available. Funatsu et al. [8] designed a biomimetic robot that climbs a wall that weighs 13.5g, but the information about its speed is not available. The biomimetic robot that climbs walls proposed by Hernando et al. [9] weighs 3.8 kg, and it moves with a speed of 0.04m/s Tzu-Hsuan Lin et al. [10] designed another bioinspired wall climbing robot, which weighs 7 kg and the speed of these robots is not mentioned. Kotay and Rus [11] designed a biomimetic robot that climbs a wall that weighs 566 g climbs at a speed of 0.0125m/s. Carlo and Metin [12] weigh around 80g and 10 g, the speed of this robot is0.02mm/s. Ozgur Unver et al. [13] proposed a bioinspired wall-climbing robot that weighs 85 g and moves with a speed of 60mm/s. BirkMeyerer et al. [14] designed a bioinspired wall climbing robot that weighs 15g and has a speed of 0.10 m/s for the wall inclined at 70 °. Gaowei Liu et al. [15] proposed a robot that climbs the wall, weighing around 2 kg and moves with speed of 2-5 cm/s. Jinfu Liu et al. [16] proposed a wall-climbing robot that weighs 922 g and has a speed of 0.15 m/s.

Table 1. Bio inspired wall climbing robot

Author	Payload	Weight	Speed	Reference
Lam et al.	1.75 kg	4.6 kg	3.7 mm/s	1
Bartsch et al.	20 kg	23kg	0.31m/s	2
Jodah et al.	1.0kg	2.5kg	0.03m/s	3
Aihong Ji et al.	250g	400g	0.08m/s	4
Mohammed K. Jodah et al.	250 g	400 g	0.046m/s	5
Linsen Xu et al.	30g	128 g	0.01m/s	6
Daltorio et al.	26g	130g	INA	7
Funatsu et al.	4g	13.5g	INA	8
Hemendo et al.	1.5kg	3.2 kg	0.05m/s	9
Tzu-Hsuan Lin et al.	510g	7kg	INA	10
Kotay and Rus et al.	116g	566g	0.0125 m/s	11
Carlo and Metin et al.	80g,10g	80g,10g	0.02mm/s	12
Ozgur Unver et al.	100 g	85g	60 mm/s	13
BirkMeyer et al.	100g	15g	0.10 m/s (<70o)	14
Gaowei Liu et al.	20-30g	120-150g	~0.01–0.02 m/s	15
Jinfu Liu et al.	922g	<2kg	0.15m/s	16
Bian et al.	0.3 kg	0.8kg	0.02 m/s	17
Hongkai Li et al.	0.81kg	4.9kg	INA	18
Chung et al.	3-4kg	6-7kg	0.03-0.05m/s	19
Zhang et al.	50-100g	500 g	0.02-0.03 m/s	20
Shen et al.	5-6kg	12-15kg	0.05-0.08m/s	21
Jilin Liu et al.	200-300 g	1.2kg	0.08-0.1m/s	22

Bian et al. [17] proposed a robot that climbs the wall, which weighs 360g, and climbs with a speed of 0.12m/s. Hongkai Li et al. [18] proposed another boinspred wall climbing robot with a weight of 4.9 kg; the speed of this bot is missing in this article.

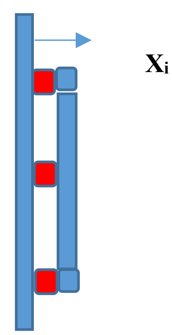
Chung et al. [19] discussed a truss climbing robot with a movable gripper with a weight of 6-7 kg and a speed of 0.03-0.05m/s.

Zhang et al. [20] proposed caterpillar type bioinspired wall climbing robot with a weight of 500 g, which moves with a speed of 0/02-0/03m/s. Shen et al. [21] introduced a robot that climbs the wall with a weight of 12-15kg and has a speed of 0.05-0.08m/s. Jilin Liu et al. [22] introduced the gecko inspired robot that climbs the wall with weigh of 1.2 kg Moreover, moves with a speed of 0.08-0.1m/s.

2. Mathematical Analysis - TWCR in Static

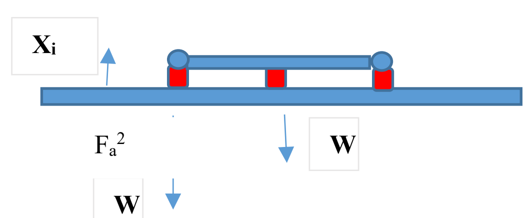
Although turtles do not naturally climb walls, turtles' slow motion stands unique characteristics that could serve as an inspiration for a different type of climbing robot, such as a robust, stable body structure with a low centre of gravity Broad, sturdy limbs for stable motion Capacity to lift large objects action that is slow but extremely controlled.

In case 1, the turtle robot that climbs the wall is on a vertical wall. In case 2, the turtle robot that climbs the wall is considered to be on the horizontal surface. In case 3, the turtle wall climbing robot is on upside down inverted position,



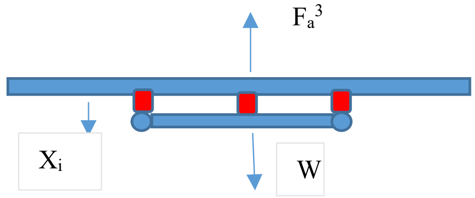
$$F_a^{\,1} = \sum_{i=1}^{4} X_i \tag{1}$$

Fig. 1 Turtle WCR (TWCR) on vertical wall



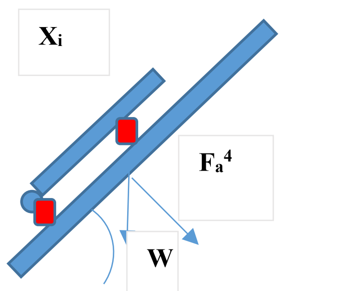
$$F_a^{\,2} = \sum_{i=1}^{4} X_i - W \tag{2}$$

Fig. 2 Turtle WCR (TWCR) on horizontal wall



$$F_a^3 = W + \sum_{i=1}^{4} X_i \quad (3)$$

Fig. 3 Turtle WCR (TWCR) –upside down



$$F_a^4 = \sum_{i=1}^{4} X_i - W\cos\theta \quad (4)$$

Fig. 4 Turtle WCR (TWCR) on inclined position

In case 4, the turtle wall climbing robot is considered to b climbing on an inclined surface which is having the angle of inclination of around 45 °.

The suction force exerted by each solenoid is denoted by Xi, and the value here is considered as 2kg or 19.6 N. Substituting these values of Yi and W in all Equations from (1) to (4), the expected or needed adhesive force value Fa^1 ,Fa^2 ,Fa^3 and Fa^4 are calculated as given in Table 2 below. The maximum adhesive force required is 8.5 kgf (as shown in Figure 3).

Table 2. Comparison of required adhesive force

Case num	Denotion	Required adhesive force (kgf)
Case-1	Fa^1	8
Case-2	Fa^2	7.5
Case-3	Fa^3	8.5
Case-4	Fa^4	7.65

3. FEMM Analysis

The Turtle wall climbing robot is modeled in a simulation platform named FEMM, as shown in Figure 5. This FEMM software is used to analyze the distribution and flow of the magnetic flux line. The flow of magnetic flux intensity is also visualized using the same tool. The design is first built in the FEMM platform by joining nodes and inter-nodes, and the flow of density lines of magnetic flux is as shown in Figure 6. Next, suitable materials and channel media are selected, leading to the creation of a mesh, and lastly, the analysis is completed.

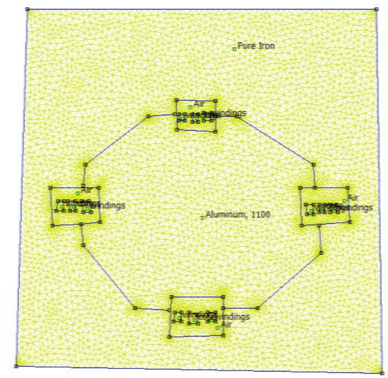


Fig. 5 TWCR design FEMM mesh created

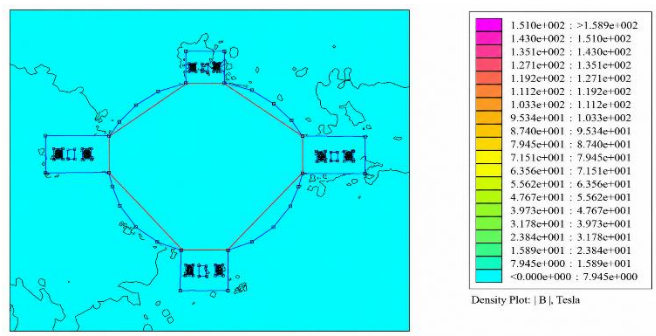


Fig. 6 TWCR- magnetic flux lines flow with the value of filed strength

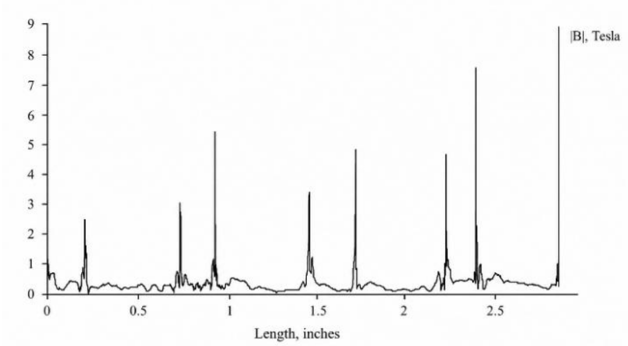


Fig. 7 Magnitude of flux density |B|

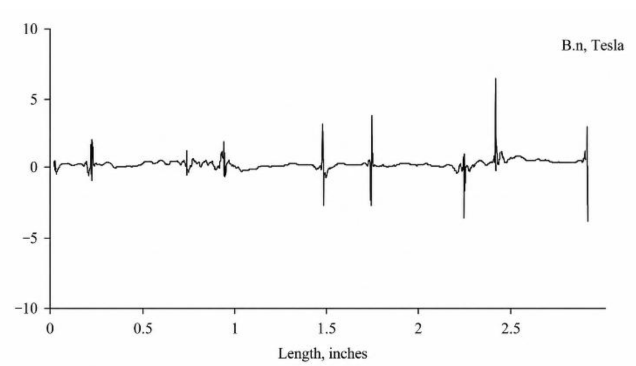


Fig. 8 Normal flux density B.n

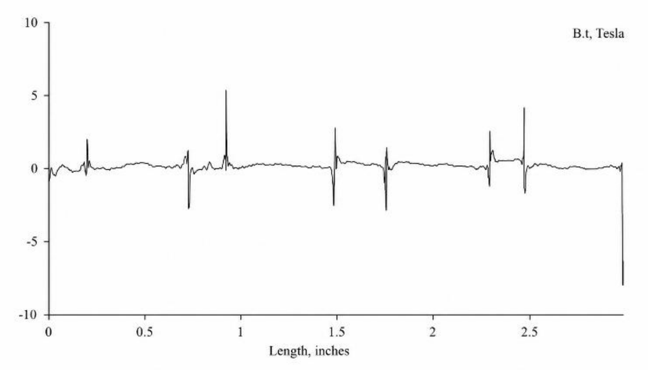


Fig. 9 Tangential flux density B.t

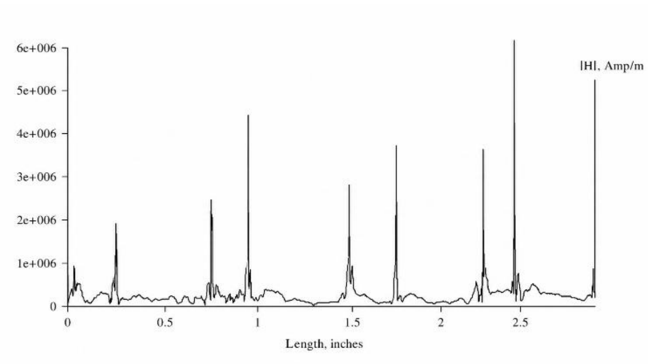


Fig. 10 Magnitude of field intensity |H|

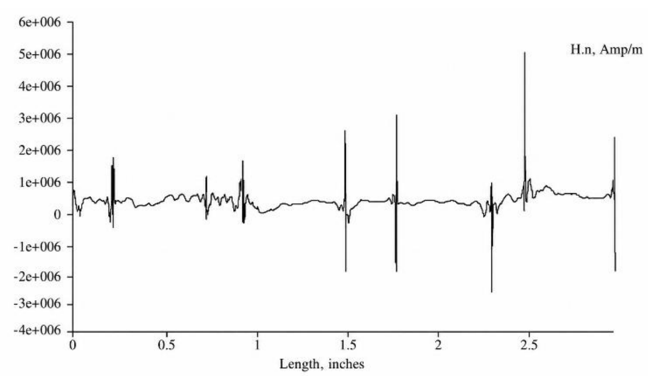


Fig. 11 Normal field intensity H.n

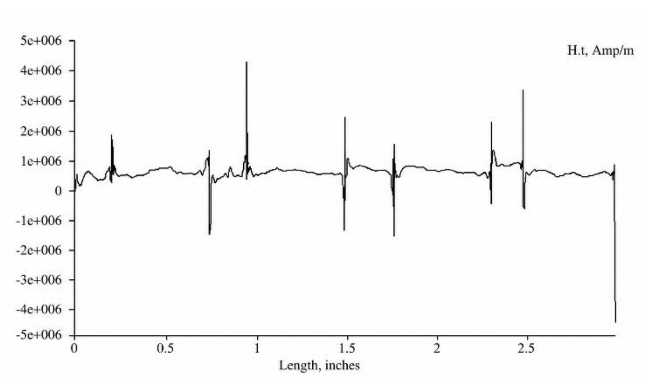


Fig. 12 Tangential field intensity H.t

Figure 7 shows the Magnitude of flux density, while analyzing the graph its clear that there are 4 peak value which indicates that the flux density line exists only at the place where the solenoid is fixed. Figure 8 displays the normal flux density exerted by TWCR in the FEMM simulation. Figure 9 shows the tangential flux density of TWCR in the FEMM simulation. Figure 10 shows the Magnitude of field intensity with a peak value of $6e^{+006}$. Figure 11 indicates the normal field intensity of TWCR in FEMM software. Figure 12 shows the tangential field intensity of TWCR in FEMM software.

4. Simulation Analysis - CoppeliaSim

The TWCR proposed designed is modeled in a simulation environment named Coppeliasim. In this simulation model, there are four prismatic joints that act as linear actuators in the simulation environment. The proximity sensor is fixed at the tip of the prismatic joint. The proximity sensor is the one that replaces the purpose of the solenoid in real-time testing. The force exerted from the proximity sensor is considered to be 2kg or 19.6N, and this value is fed to the simulation via lua script.

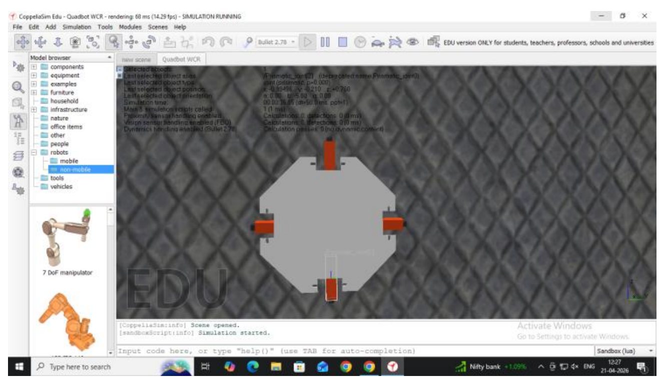


Fig. 13 TWCR design in Coppeliasim

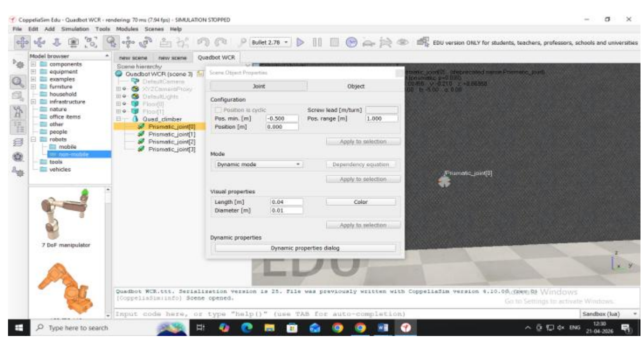


Fig. 14 Feeding value in Coppeliasim

Figure 13 shows the TWCR design in Coppeliasim environment. Figure 14 shows how the value is to be fed into Coppeliasim. lua script.. The TWCR is allowed to ascend and descend the metal wall in a simulation environment, and the readings are tabulated in the Tables 2 and 3, respectively. Later, this reading is used for plotting the graph as shown in Figures 18 and 19, respectively. Figure 15 shows the collective image of the TWCR climbing metal wall in a simulation environment. The simulation time taken during each trial can be easily noted as the value is displayed on the screen, as shown in Figure 15.

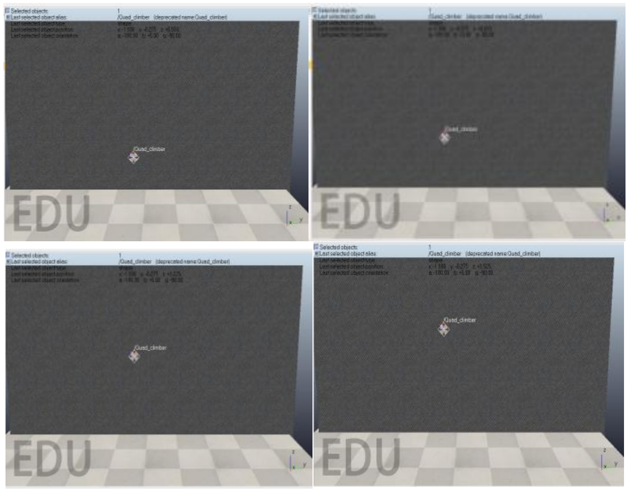


Fig. 15 The TWCR is climbing the metal wall in a simulation environment

5. Experimental Analysis - Hardware Testing

The simulated design of TWCR is fabricated in real time environment, with its chassis 3D printed and having 4 servo motors, which are connected with a linear actuator that in turn is connected with solenoids. The solenoid used at the end of the linear actuator exerts a force of 2kg or 19.6 N. The Arduino controller is used in which the program is loaded to operate the servo motors and activate the solenoids accordingly in a sequential way for both the easy climb and descend. The total weight of the TWCR is 500 grams. There are 4 servo motors which are connected with solenoids (S1, S2, S3, S4).

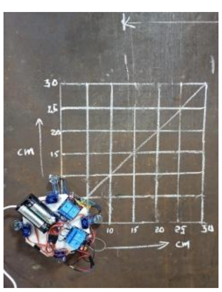


Fig. 16 TWCR on the metal wall located at the starting point

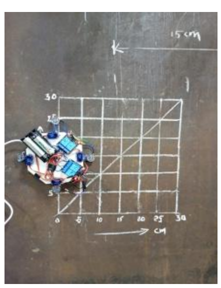


Fig. 17 TWCR climbing metal wall at mid-way

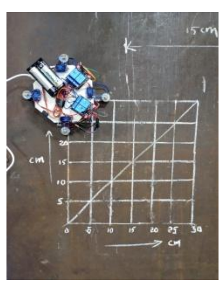


Fig. 18 TWCR is climbing the metal wall and reaching the destination

Figure 16 shows that TWCR is at the starting point on the metal wall, and from this point, it is allowed to climb the metal, and the time taken to reach the destination point is noted and tabulated as shown in the Table 2 . Similarly, the time taken by the TWCR to descend the metal wall is also noted and tabulated as shown in Table 3. Figure 17 shows the TWCR climbing the metal wall in the middle way. Figure 18 shows the TWCR reaching the destination point on the metal wall. Table 2 has been tabulated with both the simulation time taken value and real time experiment time taken value by allowing the TWCR to climb. The time taken by TWCR in both the simulation and real-time experiment is plotted as shown in Figure 19. It shows that both are in line with each other. The time taken is in seconds, and the height climbed is in cm.

Table 2. TWCR climbing upward

Height reached (cm)	Simulation	Real-time testing
	Time taken in seconds	Time taken in seconds
0	0	0
2	34	46
4	65	77
6	100	105
8	128	130
10	148	167

Table 3 has been tabulated with both the simulation time taken value and real time experiment time taken value by allowing the TWCR to descend. The time taken by TWCR in both the simulation and real-time experiment is plotted as shown in Figure 20. It shows that both are in line with each other. The time taken is in seconds, and the height descended is in cm.

Table 3.TWCR descending downward

Height reached (cm)	Simulation	Real-time testing
	Time taken in seconds	Time taken in seconds
10	0	0
8	26	35
6	59	67
4	80	93
2	102	110
0	125	138

Figure 19 shows how the simulation and real-time data are in line with each other in the case where the TWCR is allowed to Climb on the metal wall. The difference in the time taken compared with simulation and real-time testing happens because of the various other external factors in the real-time environment, like the friction of the metal wall, temperature, noise, and humidity of the lab environment, which may affect the functionality of the control unit. The sliding friction of the solenoid plays a vital role in reducing the speed of the TWCR in real time environment compared with that of a simulation environment, since in the simulation environment, all the external factors or parameters are ignored while selecting the physical engine in the simulation environment. The physical engine chosen in the simulation environment in this case is Newton.

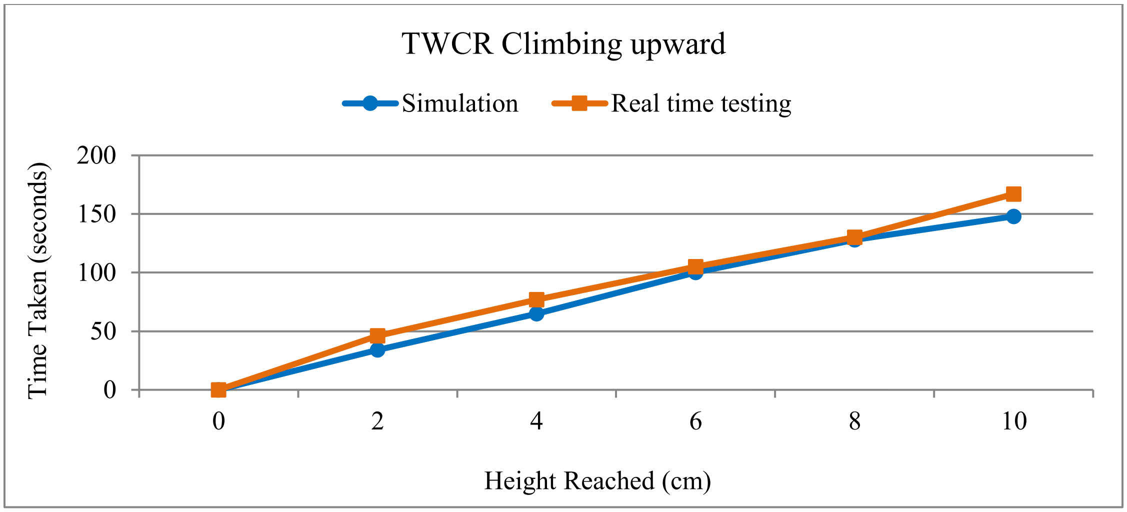


Fig. 19 Simulation Vs Real time Experiment- TWCR Climbing upward

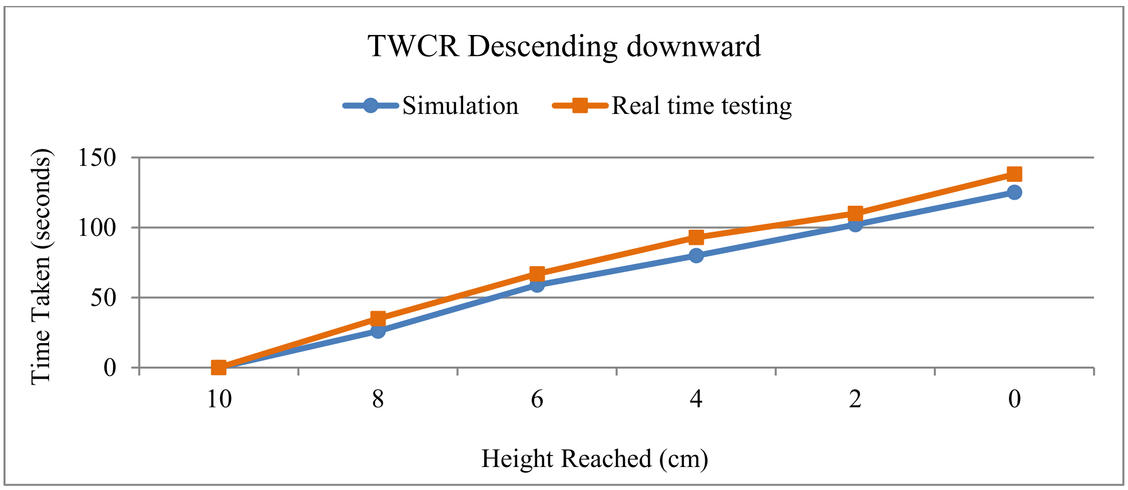


Fig. 20 Simulation Vs Real time Experiment- TWCR Descending downward

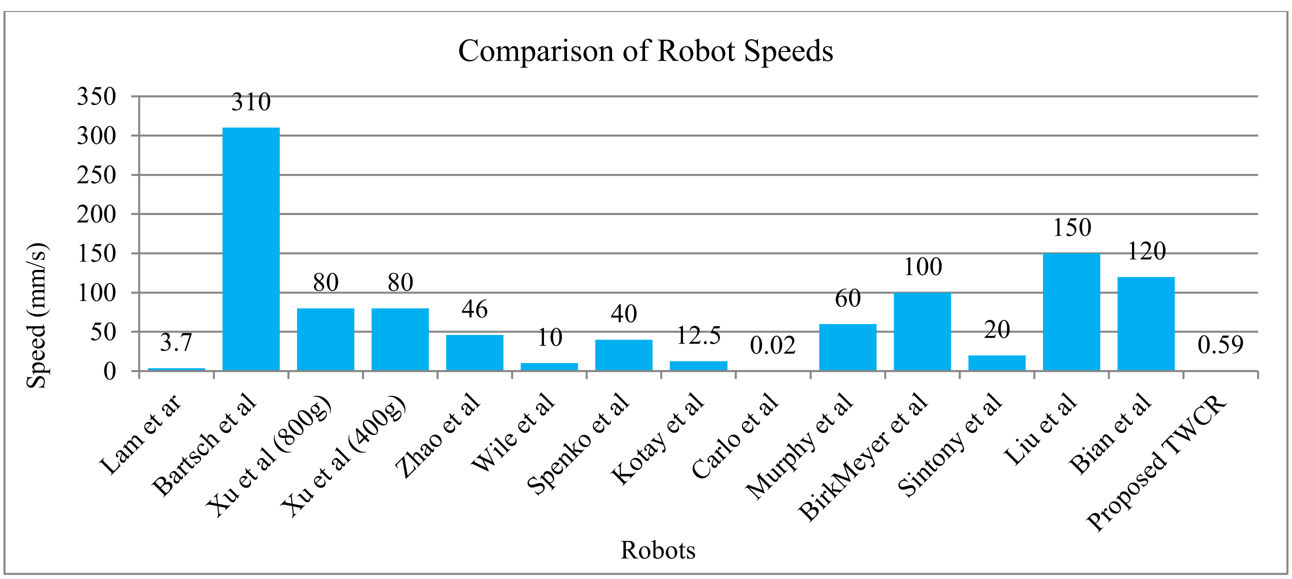


Fig. 21 Comparison of speed of existing bio-inspired wall climbing robot with proposed Turtle Wall Climbing Robot) TWCR

It seems the speed of the proposed TWCR is 0.059 cm/s or 0.59mm/s. As shown in Figure 21, the speed of the existing bio-inspired robot that climbs the wall is compared with that of the speed of the proposed turtle robot that climbs the wall (TWCR). It is clear that the speed of the proposed TWCR is the second slowest, standing next to that of the one designed by Carlo and Metin. However, the proposed design in this research article is unique and was designed before compared to the other existing bio-inspired wall climbing robots. Figure 20 shows how the simulation and real-time data are in line with each other in the case where the TWCR is allowed to descend from the destination point to the starting point.

6. Discussion

An intensive literature survey, as proposed by Palanivel et al. [23] on existing bioinspired wall climbing robots, has paved the way for the indigenous design and identified the way to convert the proposed simulated design to an actual, real-time product. The required adhesive force calculated in mathematical modeling is justified in both simulation modeling using Coppeliasim and real-time testing. The speed attained by the proposed WCR is the second slowest one compared to the existing bioinspired wall climbing robot. The research article stands out in the sense of 4 headed turtle shaped wall climbing robot. The Figure 7 to 12 show the Magnitude of flux density |B|, Normal flux density B.n, Tangential flux density B.t, Magnitude of field intensity |H|, Normal field intensity H.n, of the proposed turtle wall climbing robot design in the FEMM environment, justifying the feasibility and reliability of the design in terms of magnetic field interference, field strength, flow of flux lines, etc.

7. Results

Figures 19 and 20 show that coppeliasim can be considered as an effective modeling tool for wall-climbing robots by exhibiting the simulation result more or less similar to the real-time practical testing. Thus, by utilizing this kind of modeling software, the cost of real-time fabrication can be drastically reduced by reducing the failure cost or unnecessary scrap cost incurred by the trial and error. Thus an bioinspired wall climbing robot, which is lighted weight, weighing around 500 grams, compact in size with its chassis base dimension (13 x 13 cm), moving at a slow speed of 0.59mm/s which was modeled in a simulation environment, is fabricated and tested in real time environment.

8. Conclusion

Thus, the proposed bioinspired 4-headed Turtle Wall climbing robot seems to be unique in its design and speed obtained for navigation (both climbing up and descending down), which can be utilized for various précised operation of wall climbing robots where slow speed of navigation matters a lot. The study is refrained for bi direction (climbing up and descending down) and not considered for left and right movement. This study can be further expanded to determine the payload capacity of the TWCR both in static and dynamic modes.

Conflict of interest

There is no conflict of interest, both in terms of financial interest and personal relationships.

Funding Statement

The authors declare that there is no funding to be acknowledged.

Acknowledgment

The authors acknowledge the open source simulation platform named FEMM and Coppeliasim used in this research work.

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