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DESIGN AND DEVELOPMENT OF MOBILE STAIR CLIMBING ROBOT

SUSHANT PATE and JATIN DAVE
Mechanical Engineering Department, Nirma University
Ahmedabad, Gujarat, 382481, India
Email: 15BME119@nirmauni.ac.in, jatin.dave@nirmauni.ac.in
www.nirmauni.ac.in

DARSHITA SHAH, ASHISH MAJITHIYA
Mechanical Engineering Department, Nirma University
Ahmedabad, Gujarat, 382481, India
Email: darshita.shah@nirmauni.ac.in, ashishrmajithiya@gmail.com

High mobility and maneuverability are the most desirable features for a rough terrain locomotion system. In the recent scenario, energy conservation need to be considered while selecting a desired mobility of the system. Wheeled robots can give desired mobility with fewer energy requirements than legged robots. Limitation of wheeled mobile robots is to pass obstacles height more than half of the wheel diameter. This paper presents a novel design that can pass obstacles of the same height as its own wheel and imparts viable solution to the current limitations. A robot is designed and Analyzed with basic mathematical considerations. The results of analytical solutions are compared with the actual prototype model.The control of the robot from the far location is required. The presented autonomous stair climber robot is controlled by a Raspberry pi controller to trigger the circuits of the robot. This robust design increases the mobility of the wheeled robot and reduces energy requirement along with smooth stair climbing motion. This work can also be extended to ha {}ve locomotion on uneven terrain.

Keywords: Mobile robot, uneven terrain, High mobility, Design, Control, Raspberry Pi

1. Introduction

Over the past decade, there have been growing interest among researchers to develop robots that can go anywhere over rough terrain. As high mobility and maneuverability is desired for uneven terrain locomotion [1]. In the early days, so many researchers have developed a legged robot that can easily pass the obstacle and go on rough terrain comfortably. But it’s a fact that the energy required in a legged robot for locomotion was much more than a wheeled robot[2,3]. There are certain limitations with a wheeled robot that they can pass obstacles only half of the wheel diameter. It is found that tracked locomotion may give better results but maneuverability is very less [4,5]. In order to improve the locomotion capabilities of the wheeled robots to climb obstacles, a novel design is developed. The proposed design is capable of climbing stairs of the height same as the wheel diameter of the robot. Design of the components of the robot is done and its finite element analysis is carried out in ANSYS. The results of the analysis shows that stress and deformations were within the allowable limits and design is safe. A prototype is also developed and tested experimentally that gives satisfactory motion for climbing a stair. The robot’s capabilities in traveling along obstacles can extend to certain specific and important applications like Surveillance during the war, Exploring mines, Space exploration, and Archaeology [6,7]. Section 2 of the paper includes the Conceptual design of the robot. The robot is to be designed in such a way it can pass obstacles height equal to the height of its wheel. The robot is controlled with the raspberry pi controller which can be operated remotely. Section 3 presents the kinematic analysis of the robot at three stages as approaching step, climbing advanced on the step, and climbing up on the step. Finite element analysis of all the components of the robot is included in section 4. Developed prototype and experimental results were presented in section 5 and finally concluding remarks in section 6.

2. Conceptual Design

Conceptual design of a robot is done to overcome limitation of wheeled locomotion that it can climb the step height half than that of the its wheel diameter [8,9,10]. The proposed design is capable of climbing steps of the height same as its wheel diameter with satisfactory locomotion. Figure 1 shows the design of a wheeled stair climbing robot. Certain sealant features of the design are as follows.

- Separate bogie is to be provided for each pair of wheels to avoid restriction of the bogie movement.
- Complete rotation of bogie around its axis won't result in climbing up the obstacle as it is free. Apply stoppers to avoid rotation.
- Design such a way that the elastic property of material itself acts as suspension system.
- Frame is to be designed to accommodate control circuit.
- Middle link is to be designed to keep enough ground clearance. The wheels must not touch each other. It is a crucial point to design.
- According to manufacturing limitations the cover is to be designed to bare loads without affecting function.

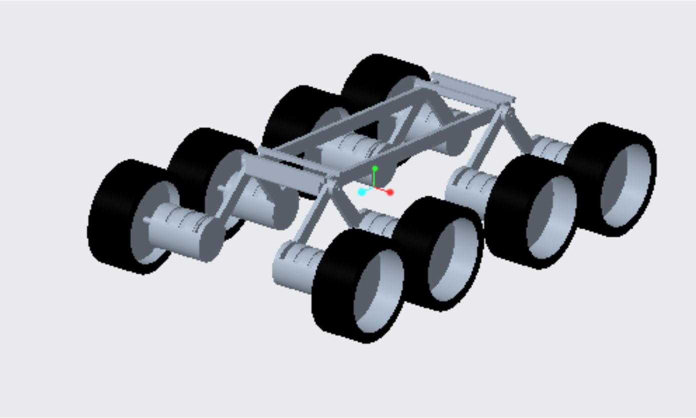

Figure 1. Concept design model.

3. Kinematic Modelling of Robot

In this three different situations are considered for kinematic modeling. First is when robot approaches the step. Second is when it starts advancing climbing on the step. The third is when it is climbed the step. Different forces acting on the robot are shown. With help of the moment calculation the torque required to climb the step is found.

3.1. *Robot Approaches the step*

The Figure 2 shows the situation when robot approaches the step. Here, N_1, N_2, N_3, N_4 and N_5 are the normal force from the ground. While F_1, F_2, F_3, F_4 and F_5 are the traction force generated by the wheel.

Based on classical mechanics analysis robotic dynamic model is set up. From robot's force equilibrium and moment equilibrium we get Eq. (1) to (3)

$$F_1 + F_2 + F_3 - N_4 = mx\ddot{a} \tag{1}$$

$$N_1 + N_2 + N_3 - F_4 = my\ddot{a} \tag{2}$$

$$\begin{aligned} -mg\rho\cos(\varphi - \alpha) + (xcos\beta + R)(F_1 + F_2 + F_3) + (Lcos\alpha + x + R)F_4 \\ + (Lsin\alpha)N_4 + (Lcos\alpha)N_3 + (xcos\beta)N_2 - N_1(xsin\beta) \\ - mx\ddot{a}(y_g) - my\ddot{a}(x_g) = I\ddot{a} \end{aligned} \tag{3}$$

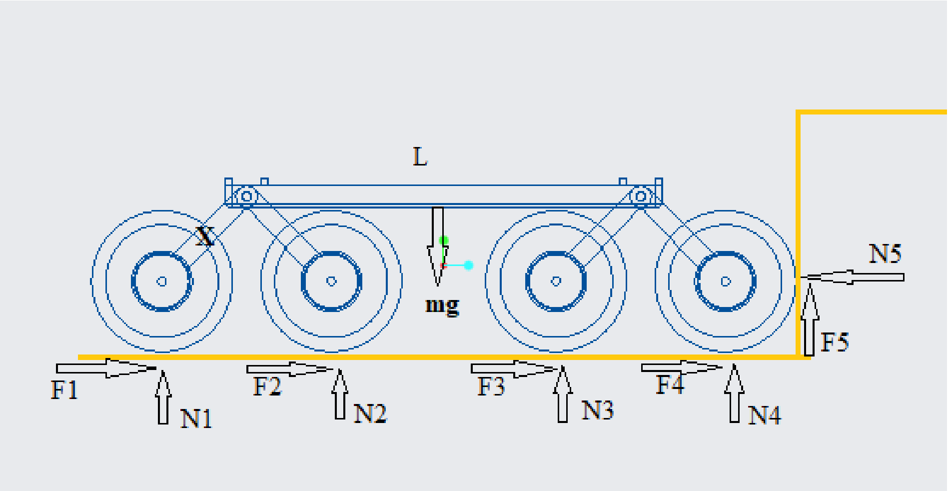

Figure 2. Robot touching the step

To find traction force, following procedure is followed. High frication is advisable for climbing the steps. μ_i is coefficient of friction and the advisable range for it is 0.1 to 0.3 for comfortable climbing.

$$F_i = \mu_1 N_i \tag{4}$$

The traction force is found out using the Eq. (1) and (3). The driving torque can be found out using following equation.

$$F_i = {}^{M_i - M_{fi}}/_{R} \tag{5}$$

The resisting torque is generated due to frictional forces. The resisting torque changes for different surfaces and different conditions.

3.2. *Climbing up the step*

The Figure 3 shows the situation when robot starts climbing up the step. N1, N2, N3 and N4 are the normal force from the ground. While F1, F2, F3 and F4 are the traction force generated by the wheel. In this step, the rear wheels are pushing forward while front wheels try to go up on the surface of the step. The resultant force will be helpful for successful climbing.

$$F_1 + F_2 + F_3 - N_4 = mx\ddot{a} \tag{6}$$

$$N_1 + N_2 + N_3 - F_4 = my\ddot{a} \tag{7}$$

$$\begin{aligned} -mg\rho\cos(\varphi - \alpha) + (xcos\beta + R)(F_1 + F_2) + ((L + x)cos\alpha + x + R)F_4 \\ + ((L + x)sin\alpha)N_4 + N_2(xsin\beta) - N_1(xsin\beta) - mx\ddot{a}(y_g) \\ - my\ddot{a}(x_g) = I\ddot{\alpha} \end{aligned} \tag{8}$$

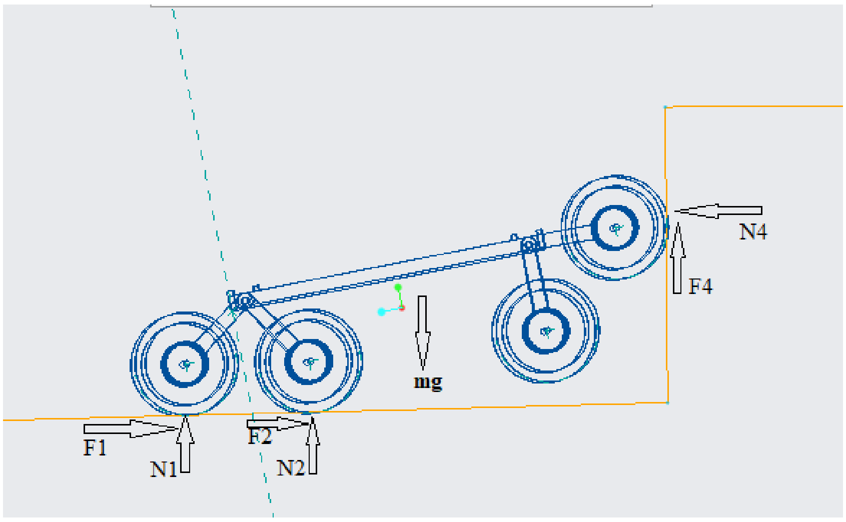

Figure 3. Robot climbing up the step

3.3. *Climbing the step*

The Figure 4 shows the situation when robot starts climbing up the step. N_2 $N_3$and $N_4$are the normal force from the ground. While F_2F_3 and F_4 are the traction force generated by the wheel. In this stage the robot has almost passed the obstacle and final part is left. Front wheelspull rest of the body forward while rear wheels pushes the body upward.

$$-N_2 + F_3 + F_4 = mx\ddot{a} \tag{9}$$

$$F_2 + N_3 + N_4 = my\ddot{a} \tag{10}$$

$$\begin{aligned} (Lcos\alpha + xsin\beta)N - (F + F)\left(cos\alpha\left(L - x - {}^{R}/_{cos\beta}\right)\right) - m\ddot{x}(y) - m\ddot{y}(x) \\ = I\ddot{\alpha} \end{aligned} \tag{11}$$

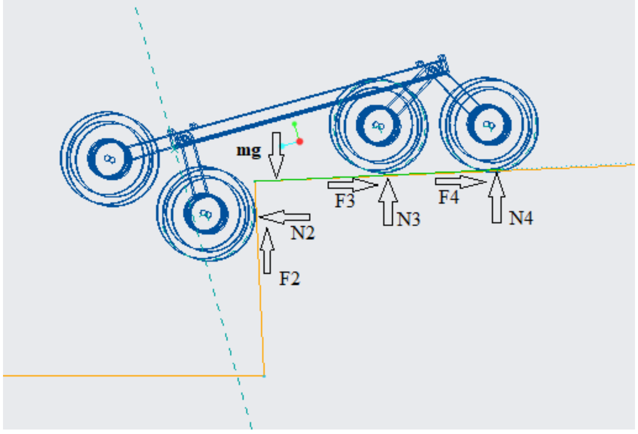

Figure 4. Robot Climbing the Step

4. Analysis of the Components of the Robot

Each component of robot is analyzed and maximum forces that a robot can withstand and the maximum stress are found. Finite element analysis is done in ANSYS.

4.1. *Frame*

It is a main structure on which all components are mounted. The strength of this component must be high. There are two different cases in which manner force can act on the frame.

Case 1: Robot is in still position

In this case forces acting on the body will be due to its own component weight which are mounted on the frame. This weight consists of the control circuit and power supply. In this case force acting on the frame is 3.95 N.

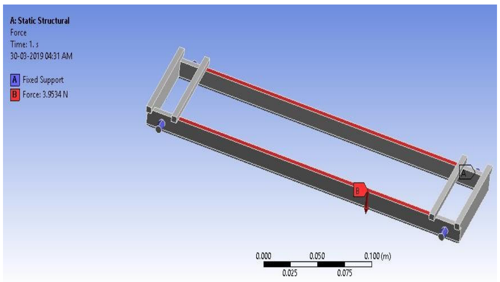

Figure 5. Forces on frame case 1

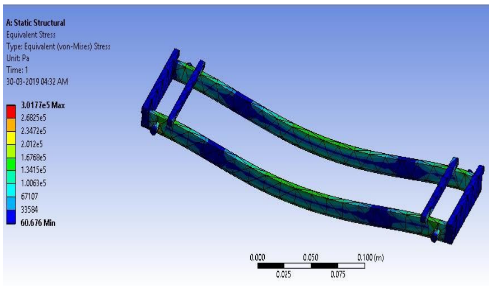

Figure 6. Total Deformation of frame case 1

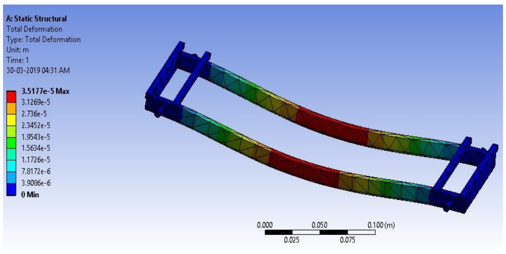

Figure 7. Stress on frame case 1

The value of stress found is in the allowable limit. The deformation is also in the allowable range (Figure 5,6,7). As the results are in the allowable range no further modification is required.

Case 2: Robot is climbing on an obstacle

In this case forces acting on the body will be due to its own component weight which are mounted on the frame and the forces acting on the stopper. The force acting due to component weight on the frame is 3.95 N. Force due to restricting motion of middle link is 28.8N. The total force on the frame will be of 33.56N.

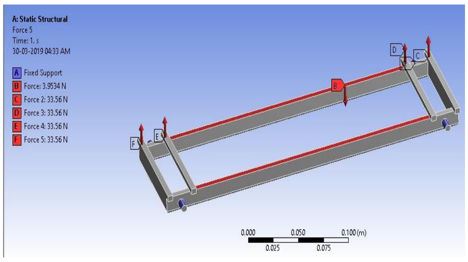

Figure 8. Forces on frame case 2

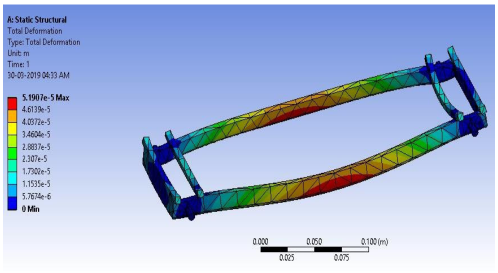

Figure 9. Total deformation of frame case 2

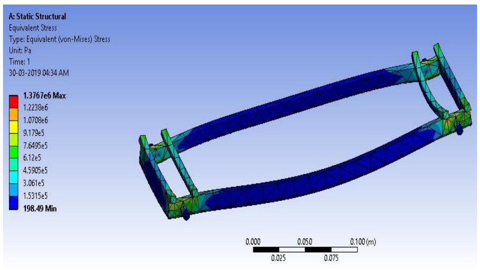

Figure 10. Stress on frame case 2

The value of stress found is in the allowable limit. (Figure 8,9,10) The deformation is also in the allowable range. As the results are in the allowable range no further modification is required.

4.2. *Middle Link*

Design of this link is very important. This link connects the wheels and the frame. Actuators are mounted in the structure of middle link. Centre of the link is connected with the frame. The revolute joint allows the link to rotate. The stoppers are provided to restrict the motion. It is subjected to impact loads. This structure must be rigid. If the robot collides with obstacle or if it falls from certain height, then this component is subjected to high stress. The forces acting on the middle link will be twice of its weight force. The force acting on the link is 67.12N. Following figure shows the deformation and stress generated in the link.

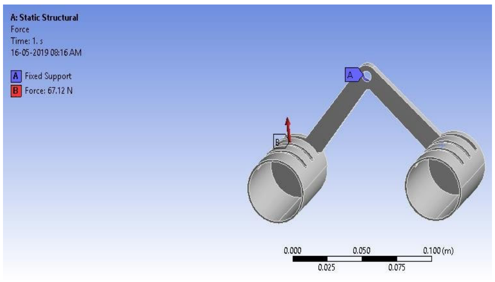

Figure 11. Forces on middle link

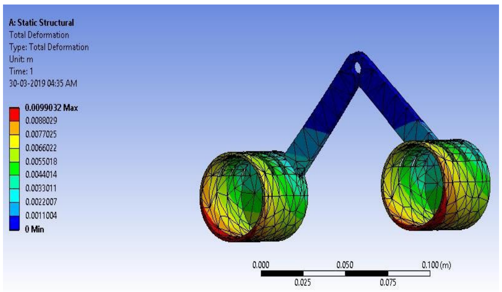

Figure 12. Total deformation of middle link

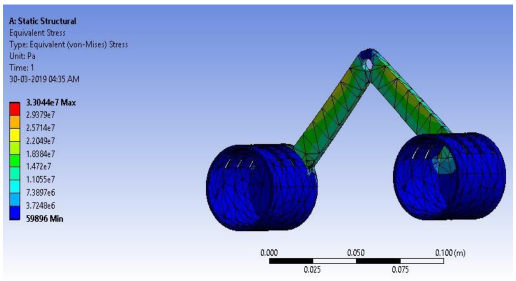

Figure 13. Stress on middle link

The value of stress found is in the allowable limit. (Figure 11,12,13) The deformation is also in the allowable range. As the results are in the allowable range no further modification is required.

4.3. *Cover*

It is a crucial component of this robot. The reliability of robot is highly dependent on the cover. This is going to take maximum force in the worst conditions. This is going to hold the assembly properly. If this component is not properly attached, then there will be wavy motion in the side direction. Considering a case that robot is hanging on two wheels from side. In this case maximum force will be exerted on the cover. The force applied is 26.36N.

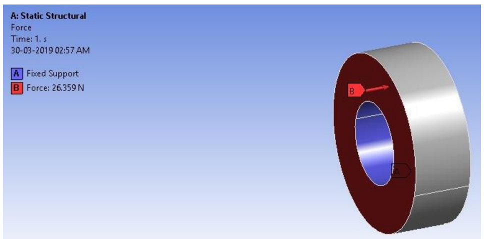

Figure 14. Force on cover

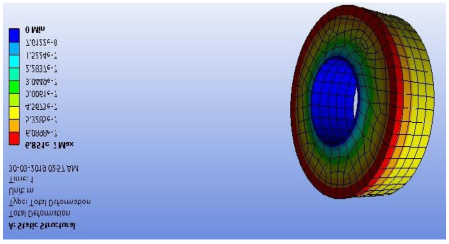

Figure 15. Deformation of cover

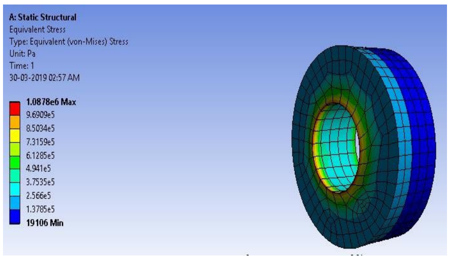

Figure 16. Stress on cover

The value of stress found is in the allowable limit (Figure 14,15,16). The deformation is also in the allowable range. As the results are in the allowable range no further modification is required. All the values of results are shown in the results and discussion chapter.

5. Prototype Developed

5.1. *Control System Design*

Control system is designed to control the robot. One of the best way to communicate with robot to control using Wi-Fi. In this project Wi-Fi based control of the robot is done. It allows us to control the robot from remote location. The control must be in a closed loop. In this project camera is mounted on the robot for visual inspection [11]. Using that video stream, decision is taken by human about which controlling action must be taken.

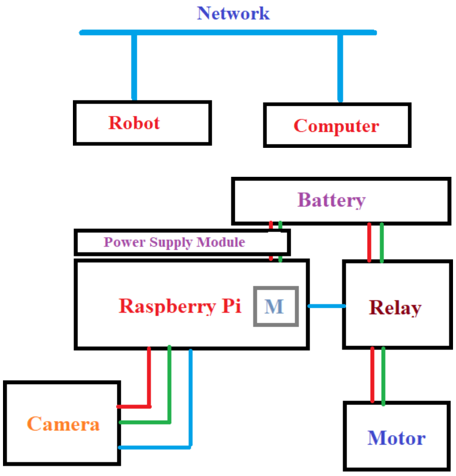

Figure 17. Control System

With use computer controlling signal is sent. The signal channels through Wi-Fi network and reaches to Raspberry pi. What action is to be done is already written in the code [A1]. It will trigger relay module. According to requirement different pins are activated for control. As relays are there to activate actuators the movement of robot is done.

This control action is still not in a loop. The camera module on robot records the videoand stream it on our computer. By analyzing that video record further decision is taken about what controlling action is to be done next.

All components are given power supply from common battery. As operating voltage range of raspberry pi is different, voltage regulator is provided for that supply.

Figure 18. Raspberry pi

Figure 19. Memory card

Figure 20. camera module

Figure 21. Battery

Figure 22. Voltage regulator

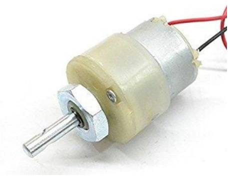

Figure 23. Motor

5.2. *Prototype*

For assembly of components super glue was used. As there are limitations with some fabrication processes the design was done accordingly. Super glue was the option to overcomeall those limitations. As strength of super glue is high it helps components to act as a single body. Following figure shows complete assembly of robot.

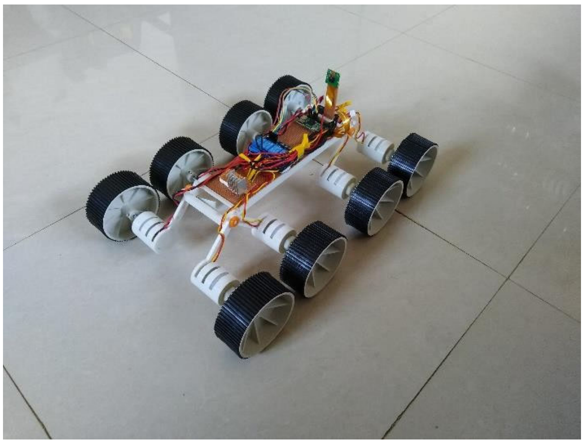

Figure 24. Final Assembly

5.2.1 Experiment to climb steps

It is the final phase of the project. The test runs are done to check the experimental results. The experimental results must satisfy the designed conditions. There may be slight variation in the results.

An obstacle of same height as robot was used for the test run. It successfully completedthe task with desired results.

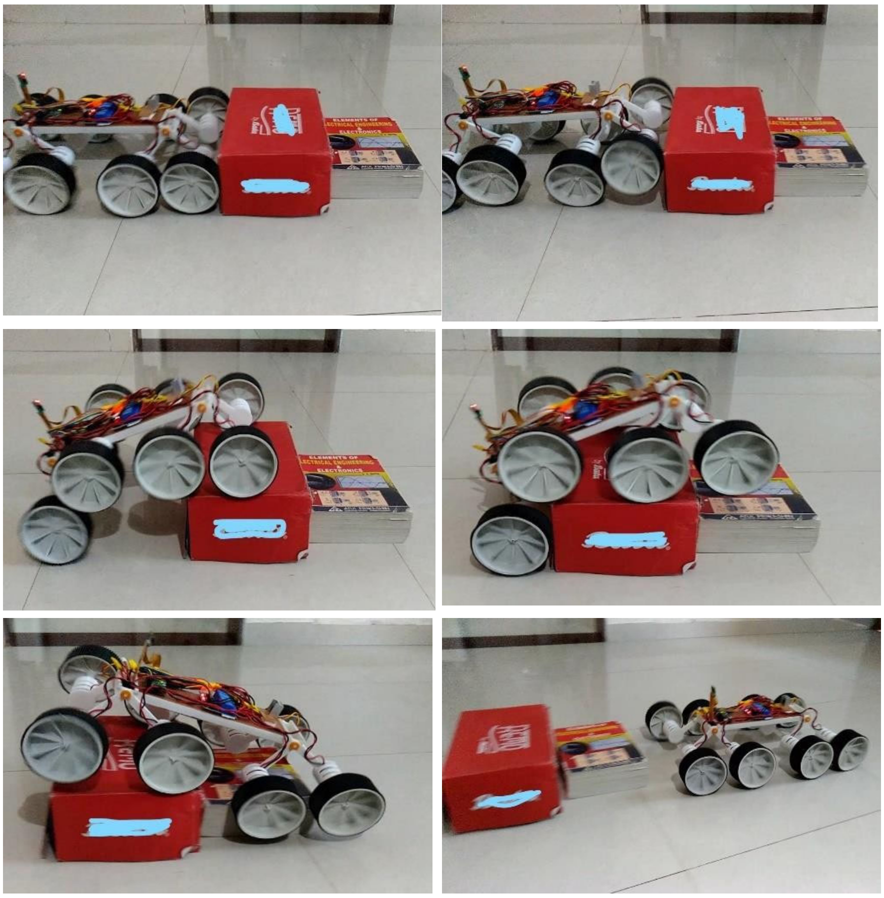

Figure 25. Test Run

Following results are achieved from analysis of components. Which are in the permissible limits. By results we can say that components are safe in working conditions. Theultimate tensile strength of PLA material is 5.4E+7 while our values are below that value so they are in safe region. The FOS was considered 1.5 for critical component. It is satisfactorilydesigned and it is in safe region.

- Frame
  Case 1
  Max. Deformation = 0.035177 mm
  Max. Stress = 3.01E+05 Pa

  Case 2
  Max. Deformation = 0.051907 mm
  Max. Stress = 1.37E+06 Pa

- Middle Link
  Max. Deformation = 9.9032 mm
  Max. Stress = 3.3E+07 Pa

- Cover
  Max. Deformation = 0.006851 mm
  Max. Stress = 1.08E+06 Pa

The test run of robot was successful. The robot can cross obstacle heighted same as its own. Itwas designed condition and it is satisfied. The capacity of robot is more than it is designed. Till 21cm height it can successfully complete the task. Up to 28cm height it can work but the probability of complete climbing the step reduces as we go above 21cm.

6. Conclusion

The limitations with robots having wheels in mobility in uneven terrain is that it can pass steps of half the height of the wheel diameter. This limitation was overcome by a novel design that can climb obstacles up to the height of a wheel diameter. This design imparts high mobility and maneuverability and can give satisfactory stair climbing motion of the step height greater than the diameter of the wheel of the robot. As wheeled robots uses less energy it is an efficient way for stair climbing and uneven terrain locomotion. Control of robot from a remote location is achieved which can further be extended for surveillance also.

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