DESIGN, ANALYSIS and FABRICATION OF A RECONFIGURABLE STAIR CLIMBING ROBOT

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by

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DECLARATION

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another pers on nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university or other institute of higher learning, except where due acknowledgement has been made in the text.

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CERTIFICATE

This is to certify that the thesis entitled "**Design, Analysis and Fabrication of a Reconfigurable Stair Climbing Robot**" submitted by Ashish Singh (Roll No. 710ME4089) to National Institute of Technology Rourkela, is a record of bonafide research work under my supervision and I consider it worthy of consideration for the degree of Dual Degree-Bachelors and Master of Technology of this Institute.

To the best of my knowledge, this work or a part has not been submitted to any University/Institution for the award of any Degree or Diploma.

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Ashish Singh

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Dedicated

To

My beloved Parents

ABSTRACT

Over the past few years, the scientists have tried to develop robots that can move on rough terrains. However, there are few robots that are suitable for use in rough terrains. A number of new technologies have evolved for reliable localization, obstacle avoidance and even autonomous map building in dynamically changing environment. However, mobility in very rough terrain is often very limited due to the absence of adequate locomotion concepts. The aim of this project is to introduce a new class of locomotive concept that will have excellent off-road capabilities. As a first prototype of this class, this four-wheeled robot will have the capability of climbing the stairs of height equal to its diameter. It will possess maximum gripping capacity and stability during motion in rough terrain owing to the 4 differential driven wheel configurations.

The long-term goal of our research is to develop a robust outdoor platform which is suitable to be included in disaster mitigation as well as in security and surveillance missions. The platform should be able to transport application sensors to areas that are dangerous for humans to access, e.g. a collapse-endangered building or an industrial compound after a chemical accident. In those cases, before they enter, the rescue personnel might need some information about the air contamination or the whereabouts of people inside an area. The robot should be upgradeable with a variety of application sensors, e.g. cameras, thermal vision, or chemical sensors. To be usable in any search and rescue or security application, the robot has to be operational without changing batteries for at least two hours.

As the first step into these future goals, our work has wireless control of the robot, which will steer the robot in the target area from remote. The robot will be wirelessly controlled through PC using ZigBee technology. In the future work, sensors, cameras, manipulators can be added to the robot frame. The robot can then serve complex tasks in dangerous areas remotely.

CHAPTER 1

INTRODUCTION

1.1. Introduction to Stair Climbing robot

Stairways are omnipresent in man-made environments. These were designed to easily bridge large vertical distances for humans. However, stairs represent a serious challenge to vehicles and robots during the time of disaster such as fire, earthquakes. There is a strong demand for mobile robots that can climb the stairs, for example, to aid people who have difficulty in walking, in urban search and rescue or urban reconnaissance. However, there are few robots that are suitable for use in rough terrains. Most of the existing surface locomotion concepts are based on wheels, caterpillars or legs and have not much evolved lately [1].

Each classification of mobile robot possesses their unique advantages and suffers from certain disadvantages. For the legged robots, they have the capability to adapt to many kinds of unstructured environment and in doing so they can stabilize themselves as different legs can orient themselves with independent configuration[2]. Nonetheless, these robots are instinctively complex and are comparatively slow. The wheeled robot can relate for the slow locomotive speeds of legged robots as they can move faster because of their rolling motion. However in unstructured conditions, their mobility is often very inadequate and highly depends on the type of surroundings and the typical size of encounter obstacle [3].

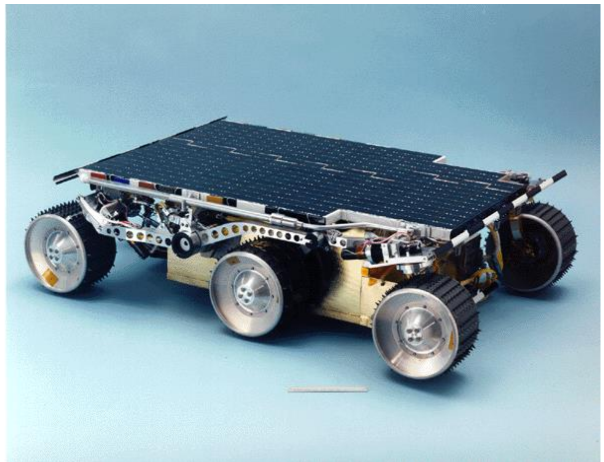
Caterpillars reveal splendid rough terrain capacity due to their steadiness and good friction coefficient whilst moving. The points of interest are simplicity and robustness, however the friction losses between the surface and the robot when the robot's turning are high [4].

To have a platform with legs that are able to strategically choose contact points on the ground is a vast advantage over wheels in many ways. Not only because of the previously mentioned reason that it can step over obstacles, but also for the fact that it can move smoothly over terrain [5]. Consider a statically stable robot that moves one leg at the time and gently places it at a new stable position, the main body of such a robot would move forward smoothly like a boat, even on really rough terrain like in a forest [6].

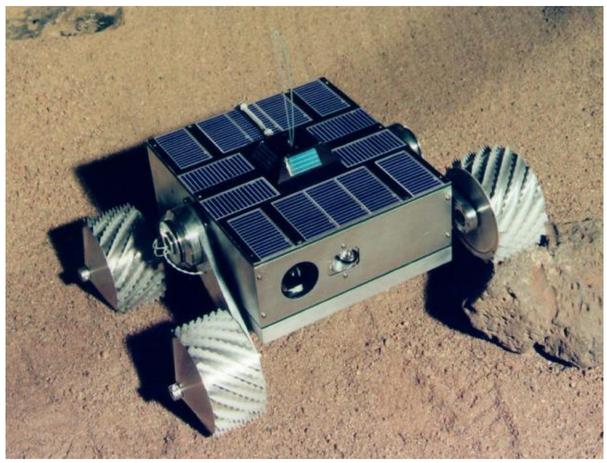
The tracked mobile robots have high off-road capability yet ordinarily have overwhelming weight. However, the tracked mobile robots have low energy efficiency in turning motions. On the other hand, the legged mobile robots have great adaptability in rough terrain but usually involves a complex locomotive mechanisms which needs complicated control algorithms [7].

The wheel has always been the easiest way to implement mobility in a vehicle, and also the fastest method of travel. Relative to speed it is also the most energy efficient way to travel. The implementation is often very simple, and does not require any advanced techniques such as vector controllers or additional joints to get the robot moving [8].

The locomotion of all wheeled robots can be primarily categorized as active and passive locomotion [9]. Passive locomotion is a concept based on passive suspensions which involves no sensors or any additional actuators and at the same time guarantees stable movement. Whereas, an active robot generally has an entrenched closed loop control this maintain the solidity of the system during motion [10]. Under this definition, Sojourner, and Micro5 are passive robots; walking machines, Nanorover and SpaceCat are active robots; Marsokhod [11,12] and Hybtor [13] are hybrid robots based on their locomotion mode.



(a) “Sojourner” with passive suspension



(b) “Nanorover3” with active stability unit

(c) “Hybtor” with hybrid locomotion mode

Figure 1.1 Robots with Active, Passive and Hybrid Locomotion modes

It is clear that active locomotion extends the mobility of a robot but simultaneously increases the complexity. It also needs extended control and power resources. However, in many fields of application, power consumption, complexity and reliability are predominant criteria. This is especially the case for planetary rovers. Therefore this work is devoted towards the development of a passive locomotive concept. The robot will combine the advantages of wheeled and leg robots, i.e., it will have the capability of moving fast on smooth surface as well as adapting itself to unstructured terrains owing to its flexible frame design, which allows independent roll of the front and rear wheels.

1.2. Objective

Adding real climbing abilities to a wheeled rover requires the use of a special strategy and often implies dedicated actuators like for the Marsokhod and Hybtor or complex control procedure like for the SpaceCat or for the Nanorover. But to simply the complexity and to exclude dedicated actuators, my work includes design of a new paradigm, which is combing the pros of wheeled and legged robots.

The objective of this work is to first develop a wheeled-leg robot with the capability of climbing stairs with a large variation of height. The high- torque of the motors driving the wheels provide a fast climbing ability of the robot with a robust mechanical design which is capable of enduring high stresses on the uneven ground. The structure of the robot is based on a legged-wheels concept, which has small leg attached to the circumference of the wheel. These legs serves the same purpose as that of the gear, i.e., mating with the next stair step while climbing and pushing the robot to climb to the next step as the wheel rotates. The use of rubber treads on the contact surface of the wheel provide additional grip between the tire and the ground. The rubber layering also provides a mild damping effect. The independent roll of the front and rear wheels adds the much needed capability of overcoming obstacles of the four wheels independently. Such a design enables mobility over a considerable variation in terrains, including hills, rocks and sand.

The long term objective of this research is to add a vigorous outdoor platform which is suitable to be incorporated in disaster fighting missions and in security and observation missions. The stage ought to have the capacity to transport application sensors to zones that are perilous for humans to get to, e.g. a jeopardized building or an industry after a chemical accident. In those cases, before they enter, the salvage team may require some data about the air pollution or the whereabouts of individuals inside that region. The robot ought to be upgradeable with a mixed bag of utilization sensors, e.g. cameras, thermal vision, or chemical sensors. To be used in any search or security application, the robot must be operational without changing batteries for no less than two hours.

As the first step into these future goals, our work has wireless control of the robot, which will steer the robot in the target area from remote. The robot will be wirelessly controlled through PC using ZigBee technology. In the future work, sensors, cameras, manipulators can be added to the robot frame. The robot can then serve complex tasks in dangerous areas remotely.

1.3. Organization of the report

The outline of the thesis is as follows.

Chapter 2 discusses literature review of the mobile robots. A survey work of the most popular robots is briefly described.

Chapter 3 discusses the design methodology of the stair climbing robot. The CAD modeling of the proposed design is described along with the design of the wheel. All possible embodiment of the proposed design approach is also discussed.

Chapter 4 discusses the dynamic simulation of the proposed robot architecture. Multi-Body Dynamic simulation is discussed in detail, with emphasis on the wheel torques, traction forces and the wheel slip. A finite element analysis of the robot is discussed with emphasis on Impact Analysis and implicit dynamics of the robot.

Chapter 5 reports fabrication and assembly of the robot. All the information about the hardware is furnished in this section.

Chapter 6 The testing of the robot in different conditions is recorded. The robot is tested on stairs of varying stair heights by adjusting the frame. The experiments performed demonstrate the robot’s superior mobility, functionality and durability characteristics.

Chapter 7 contains a summary of important conclusions and scope for future work in the proposed stair-climbing robot.

CHAPTER 2
BACKGROUND

Over the decades, the science community have focused on the development of mobile robots that can move in uneven and irregular terrains. The prime goal of making such robot was to deploy them in hazardous areas and control them remotely. To make these machines intelligent, several technologies have been developed and implemented in these robots. Technologies like localization, odometry, Global navigation units, Artificial intelligence and mapping has been developed and tested in dynamically changing environment. However, mobility in very rough terrain has remain limited because the locomotion concepts have not evolved much. The wheels, tracks or legs are the most common existing locomotion. These are discussed in the next sections.

2.1 Classification of Robots

Stair climbing has been carried out with robots using different types of locomotion. One can roughly distinguish wheeled, legged, and tracked robots.

A. Wheeled Robots

Wheeled robots typically have to resort to mechanic extension to conquer stairs. One application of such a technique is in-patient treatment, where stair climbing could greatly improve mobility, and thus eminence of life, of people confined to wheelchairs. Lawn and Ishimatsu [14] present a stairclimbing wheelchair using two (forward and rear) articulated wheel clusters attached to movable appendages. The robot is equipped with step-contact sensors, but relies on user steering and is thus only *semi-autonomous*.

i. Scouts

The Scouts[15] are specialized robots that carry out low-level, usually parallel tasks aimed to meet the mission objectives. Scouts in Fig. 2.1a can include simple sensory units or units with locomotion, tools or other specializations. This body fits snugly inside a protective covering called a Sabot that absorbs much of the impact during the launch, and allows the Scout to even break through a glass window and land safely and ready to begin its mission.

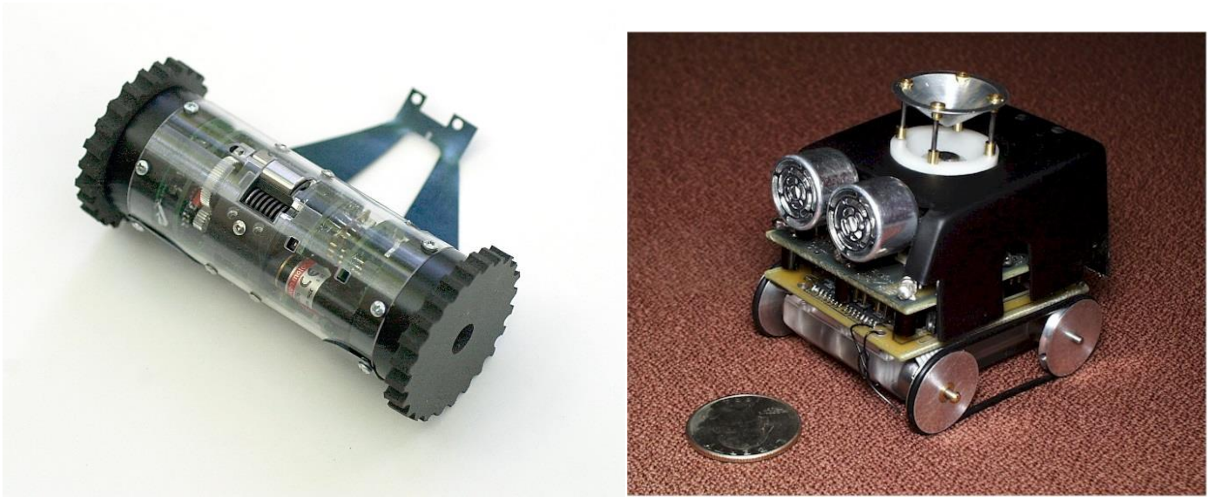


Figure 2.1 Wheeled Robots (a) Scouts (b) Millibots

ii. Millibots

Millibots [16] are small semi-autonomous and autonomous robots to be installed by a larger robot or field agent. We envisage a cluster of robots: that are capable of relocation themselves for supreme sensor efficiency & that form a group of mixed robots supplementing each other for comprehensive mission capability with segmental payloads.

The wheel in Fig. 2.1b has always been the tranquil way to contrivance mobility in a vehicle, and also the fastest method of travel. Relative to speed it is also the most energy efficient way to travel. The application is often very modest, and does not need any advanced methods such as vector controllers or additional linkages to get the robot moving.

It should be renowned that wheeled vehicles request paved exteriors (or at least regular) in order to travel, being tremendously fast and operational in these surfaces. At the same time these mechanisms can be simple and have a light weight. However, more than 50% of the Earth surface is unreachable to customary vehicles (with wheels and tracks) (Anon, 1967) being difficult, or even impossible, that wheeled vehicles surpass large obstacles and surface unevenness. Even all-terrain vehicles can only surpass small obstacles and surface unevenness but at the cost of high energy consumption (Bekker, 1960).

B. Legged Robots

To have a platform with legs that are able to deliberately choose contact points on the ground is a vast advantage over wheels in many ways. Not only because of the previously mentioned reason that it can step over obstacles, but also for the fact that it can move smoothly over terrain. Consider a statically stable robot that moves one leg at the time and gently places it at a new stable position, the main body of such a robot would not forward smoothly like a boat, even on really rough terrain like in a forest.

Another advantage is the ability to change direction of movement without changing the direction the body is facing. This is useful in tight spaces and creates a faster and more natural movement in places with a lot of obstacles. Wheels also have a tendency to slip on the ground when they lose traction. A leg on the other hand is much kinder to the surface it moves over. It can distribute its weight and even move its center of mass without changing the positions of its supports. This advantage is desirable in cases like moving up or down a slope or stairs, or where there is a long distance between supporting objects to step on.

All these possible advantages come at a price though, the design will be more complicated and will have more moving parts. While a robot with wheels could work just ne with only two motors, one for forward trust and one for steering for example, a robot with legs needs at least tree actuators for each leg if one wants it to be more useful than a wheel. The actuators used today are still heavy compared to their power output. This often makes legged robots very heavy or weak, especially if they have many legs.

i. Big Dog

Boston Dynamics Corporation was founded, as a spin-off from the MIT, in 1992 by Marc Raibert and some of his colleagues. The initial company focus was on software for human simulations, such as DI-Guy, which at that time was being used for military applications. In 2005 however they presented the first version of their quadruped robot called Big Dog in Fig 2.2a.The main goal of the project was the development of a mechanical mule with the following properties:

- Autonomous power
- Capability of carrying heavy payloads
- Outdoor operational
- Having static and dynamic mobility
- Fully integrated sensing for mobility
- Able to jump over a 1m ditch, climb 45 (100%) slopes, run at 5m/s, and carry over 50kg payload.

Figure 2.2 Legged Robots (a) “Bigdog” (b) “Scorpion”

ii. “SCORPION”

The SCORPION is an eight-legged walking robot for hazardous outdoor-terrain. It uses a biomimetic control concept which allows a very flexible, robust walking behavior in various terrains. The walking gaits of the SCORPION in Fig. 2.2b robot are based on research on walking patterns of real scorpions. The SCORPION can be controlled in an intuitive way with an HMD, an optional voice control, and a data glove. Possible future fields of application include exploration of hazardous environments, e.g. in extraterrestrial or SAR missions.

The developed models of the biological motor systems enable the robot to adapt autonomously to a multitude of different terrains and obstacles. Possible future fields of application include exploration of hazardous environments, e.g. in SAR missions. Currently an amphibious version of the SCORPION is under development. A copy of the SCORPION is in use at the NASA Ames Research Center to evaluate the advantages of legged systems for extraterrestrial missions.

C. Tracked Robots

An alternative consists on tracked vehicles in Fig 2.3. Although they present increased mobility in difficult terrains they are not able to surpass many of the found difficulties and its energy consumption is relatively high.

Figure 2.3 Examples of Tracked Robots

2.2 Advantages of Wheeled Robot and Legged Robot

For the purpose of developing a mobile robot which has a simple structure, light weight, and good energy efficiency, we have elaborately analyzed the features of the three types of locomotive mechanism – wheeled, tracked, and legged. The tracked mobile robots have high off-road capability but usually have heavy weight; the tracked mobile robots have low energy efficiency in turning motions; and the legged mobile robots have extensive adaptability to rough terrain but usually have complex locomotive mechanisms that need complicated control algorithms. Moreover, the legged mobile robots have humble mobility on the plane surfaces. On the other hand, the wheeled mobile robots have simple structure, good mobility on the plain surfaces, and good energy efficiency in turning, but have poor adaptability to the rough terrain. Therefore, considering the indoor applications, we opted to develop a wheeled mobile robot. Our wheeled mobile robot, however, has a locomotive mechanism which enables it to adapt to rough terrain, such as the stair like the legged mobile robot.

The generally cheapest, and also the most stable system considering its class with good terrain qualities is the four wheeled platform with constant drive to all wheels, with Knobby tires and dynamic suspension and a dynamic chassis. This method is often used where the terrain and the environment require a very high level of mobility.

The benefits of robotic arrangements whose mobility platform is built on three wheels is primarily that it is a easy to use device, easy to program and is easy to manoeuvre. It is also one of the cheapest statically stable mobile robot platforms, and it does not require many motors or parts. The disadvantages of having contact to the ground at only three locations is that it does not allow the user of the device to have same options for the placement of heavy components or equipment, and will not provide the same stability as a robot with a four-wheeled base. This can cause the robot to become unstable and risks tipping over because of, for example, centrifugal forces when turning.

The weaknesses of a three-wheeled configuration are the four-wheeled designs' strengths. A four-wheeled configuration provides an optimal surface area for useful equipment like batteries, motors and controller boards. Weight balancing is easily done and it is not nearly as sensitive to tipping as a platform with fewer than four wheels. The benefits of the continuous track is that it smoothers out the path and divides the terrain and the obstacles in to aatten road, and this eases obstacles that could otherwise prevent the vehicle's movement. The track does also have a much larger active surface to the ground, which generates more grip compared to what a wheel or leg does. This platform configuration is easy to navigate and turn, but does not have a comparable mobility in speed compared to wheels, and it generally uses more power when it has more internal friction, and also weighs more.

A wheeled robot can be built in such way that its chassis is lower than the top of the wheels, which means that if it falls upside down it can still drive the same way it does upright.

2.3 Challenges of a Stair Climbing Robot

There are five fundamental issues involved in climbing steep natural terrain: hardware design, control, sensing, grasping, and planning. A substantial amount of work needs to be done in each of these areas in order to develop a real climbing robot.

2.3.1 Hardware Design

An efficient hardware design can enhance the performance of the robot, and often can make all other fundamental issues easier to deal with. Though, the past uses of hardware solutions has helped in maintaining equilibrium which consequently resulted in a limitation on the terrain that could be navigated.

Wheeled robotic systems have been used for a long time to ascend and traverse natural slants of up to 50 degrees, to descend slopes of up to 75 degrees, and to climb over small hurdles in rough terrain. These systems uses some form of active or paasive suspension as in [17], or use rappelling as in [18]. Similar results have been obtained using legged rappelling robots [19] and a snake-like robot [20].

The territory that these wanderers can navigate heartily is great, however none of the current frameworks has been indicated to be equipped for climbing common slants of 90 degrees or higher. A wide mixture of robots fit for climbing vertical counterfeit surfaces is accessible. The vast majority of these robots abuse some property of the surface for simple getting a handle on. For instance, some of these robots utilization suction glasses or changeless magnets to abstain from slipping [21]. Others exploit elements, for example, gallery handrails [22] or posts [23]. Be that as it may, the surface properties that are misused by these robots for the most part are not accessible in characteristic landscape.

Future studies could address the utilization of different sorts of instruments for getting a handle on vertical normal surfaces, for example, devices for boring jolts or setting different sorts of apparatus in rock. The utilization of these instruments would permit all the more difficult trips to be finished, in the same way that "guide" helps human climbers [24]. Be that as it may, these apparatuses get an expand weight and intricacy, moderating development and constraining potential applications.

2.3.2 Control

There are three essential segments of the control issue for a climbing robot: support of balance, endpoint slip control, and endpoint power control. These three segments are firmly related. Keeping in mind the end goal to look after offset, both the area of the focal point of mass of the robot and the strengths from contacts with normal components must be controlled. Control of slip at these contacts is straightforwardly identified with the course and greatness of the contact strengths.

Existing control methods, for example, those in view of the operational space plan [25] could shape a pattern way to deal with the configuration of a control structural planning for a climbing robot. However these systems could be stretched out in various diverse approaches to accomplish better execution. Case in point, future examination may address the configuration of an endpoint slip controller that is stable concerning the arch of a contact surface, as opposed to regarding a point contact just.

2.3.3 Sensing

For control and getting a handle on, the robot must be fit for detecting the introduction of its body regarding the gravity vector, the area of its focal point of mass, the relative area of contact surfaces from its appendage endpoints, and the strengths that it is applying at contacts with common elements. For arranging, the robot should furthermore have the capacity to find new holds and produce a portrayal of their properties, potentially obliging an estimation of levels of slip at contact focuses. Sensor coordination, keeping in mind the end goal to obtain and utilize this data with calculations for control, getting a handle on, and arranging, is a testing issue.

Existing building arrangements are accessible which can prompt the advancement of a standard approach for every situation. For instance, sensors, for example, those portrayed in [26] can give essential endpoint constrain and slip estimations, an inertial unit and attractive compass can give position data, an on-board vision framework can give an unpleasant portrayal of hold areas and properties, and encoders can give the area of the focal point of mass. On the other hand, the change of each of these sensors regarding execution, mass diminishment, or expense decrease presents an open territory for exploration.

2.3.4 Grasping

The execution of a climbing robot is subject to its capacity to handle "holds," or elements on a lofty regular surface. It has as of now been noticed that particular getting a handle on plans, depending on particular properties of the surface, for example, exceptionally smooth surfaces, pegs, or handles, can't be utilized for getting a handle on discretionary normal elements. The issues included in getting a handle on common holds will be inspected further in this area.

Customarily handle examination has been keen on either getting an article or holding it fixed (additionally called "fixturing") Research in this subject dates as far back as 1876 it was demonstrated that a planar item could be immobilized utilizing at least four frictionless point limitations [27]. Great diagrams of later work can be found in [28]. In this field a critical idea is "power conclusion," characterized as a grip that "can oppose all article movements gave that the end effector can apply adequately huge powers at the one-sided contacts." [29] Nearly all examination on handles has concentrated on selecting, describing, and improving handles that have the property of power conclusion. Be that as it may, for the assignment of climbing a grip require not accomplish power conclusion to be a valuable handle. For instance, a robot may discover a rack like hold exceptionally successful for pulling itself up, despite the fact that this grip would be totally not able to oppose powers applied in different bearings. Consequently, the methods for selecting, portraying, and advancing handles must be extended essentially to apply to climbing robots.

A subjective order of diverse sorts of handles as of now exists in the writing for human climbers [30,31]. In this order, handles are first broken into two classifications, those implied for pockets, edges, and different defects on generally unbroken vertical rock appearances, and those implied for supported vertical splits. A few illustrations of distinctive face and split handles are indicated in Figure 2. The writing gives an unpleasant thought of the quality and utilization of every sort of handle regarding criteria, for example, an apparent level of security, the measure of torque that can be applied on a hold, and the measure of erosion at the "force point." Not just is this master instinct subjective, additionally it is clear that human climbers need to perform extra handle getting ready for particular cases. As put by Long, "There are the same number of various types of holds as there are approaches to snatch them [32]." However, this instinct can be utilized as a beginning stage for deciding important quantitative criteria for handle choice and streamlining.

An examination of the climbing writing with past chip away at automated handle arranging uncovers a few other crucial contrasts between the two applications that may get to be essential in future exploration. Case in point, numerous climbing holds are little, so the fingers utilized as a part of a climbing handle regularly have expansive measurements in respect to the article to be gotten a handle on. Writing on mechanical getting a handle on basically considers the situation where the fingers have little measurements with respect to the item. What's more, some climbing handles, are in light of sticking fingers in a split. This procedure is altogether different from one a robot may use to get an article, and obliges a high level of adaptability and little degrees-of-opportunity with a specific end goal to "un-jam" the fingers. Plainly, proceeded with take a shot at climbing robots in the long run will prompt the thought of an abundance of new issues in getting a handle on.

CHAPTER 3
MECHANICAL DESIGN PARADIGM

The design of the robot includes this salient points as discussed in the following.

1) A leg-wheel robot is utilized as an essential robot to examine a suitable mechanism for harsh landscapes on the grounds that both wheel and leg are crucial for roughterrain mobile robots. This kind of robot, which has been examined by Hirose, and different scientists, has both rapid and high versatility for unstructured territories.

2) The proposed robot has four wheels to keep up its stability when the center of gravity changes because of any additional load.

3) Each wheel is joined to the tip of a leg on the grounds that by and large, adequate space is not accessible to set the leg and wheel independently on the body of the robot.

Just like animals and insects living in different conditions have different shapes, there must be specific locomotion mechanisms that are suitable for movement on each rough terrain. Therefore, the proposed mechanism is not the best for all terrains. This robot is specifically designed for climbing the stairs of varying height and in uneven terrains.

3.1 Design of the Multi-Legged Wheel

The most crucial part of this project is the development of a legged-wheel. As stated in Chapter 1, the objective of the wheel in our robot is combining the advantages of both the wheeled robot and the legged robot. The wheeled structure will give the robot a qualifying ability of traversing fast in smooth regular terrain. And the legs will play an important part when the robot tries to climb a step. Keeping these as the requirements, it is necessary that the legs do not interfere when the wheel rolls on the surface. This can be obtained by a smart wheel design which makes the legs an integral part of the wheel roll. This means that the legs are attached to the wheels such that they touch the ground and rolls onto it. This rolling will fulfill the phenomenon of the wheel, i.e., moving fast in plain surface. The advantages of legs will come into play as the robot is in front of an obstacle which the wheel protruding will help in gripping the surface and thus climbing.

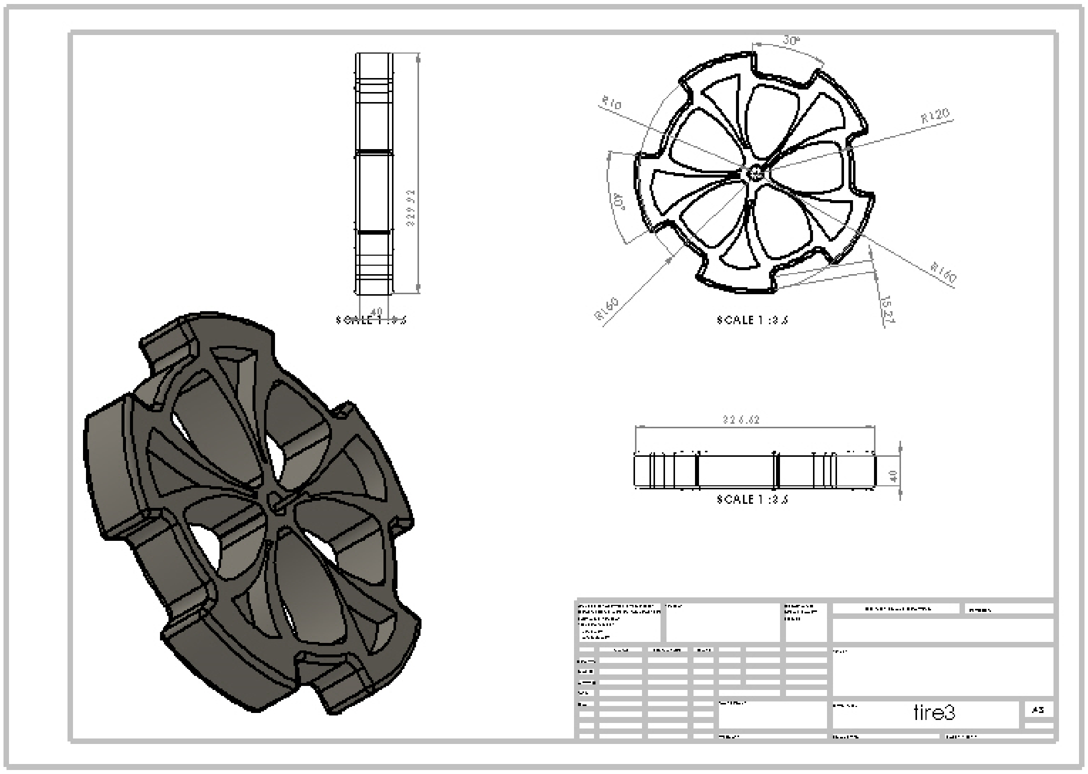


Figure 3.1: Solidworks design of the wheel

The wheel was designed in Solidworks shown in Fig. 3.1. To reduce the weight of the wheels, the rims was assigned a light density material, PTFE. In order to decrease the physical shock during locomotion, rubber pads where applied at leg tips. The specifications are enlisted in Table 1.

TABLE 1: Legged Wheel Specifications

S. No.	**Specification**	**Dimension**
1.	Outer diameter	160 mm
2.	Core diameter	120 mm
3.	Hub diameter	12 mm
4.	Leg height	40 mm
5.	Leg width	100 mm
6.	Leg Angle	40^o

In contrast a wheeled robot would only be able to go on a plateau of a height which is much less than the height of the wheel shaft. While driving with high velocities, the leg tips have direct contact to the ground. In this case, this robot behaves like a wheeled system, reaching velocities of around 5 kmph, which is equivalent to two body lengths per second. The inclusion of the legs on the wheels allows the robot to climb a step up to a height equal to the outer radius of the wheel, which is a significant improvement. The added advantage is that, the addition of this functionality do not affect its performance in plain surfaces. It is still capable of moving relatively fast on an even terrain and climbing the stairs or obstacles.

3.2 Frame design

To ensure light weight of the robot, the frame design is optimized by FEA topological optimization and a design is concluded as shown in fig 3.2. A static analysis of the frame was carried out and the stresses in the different critical parts were checked. It was crucial that the maximum stress in these parts ae less than the maximum allowable stresses. Some amount of material was removed to reduce the overall weight of the frame. It was iterated and checked every time to ensure that it complies with the maximum allowable stresses.

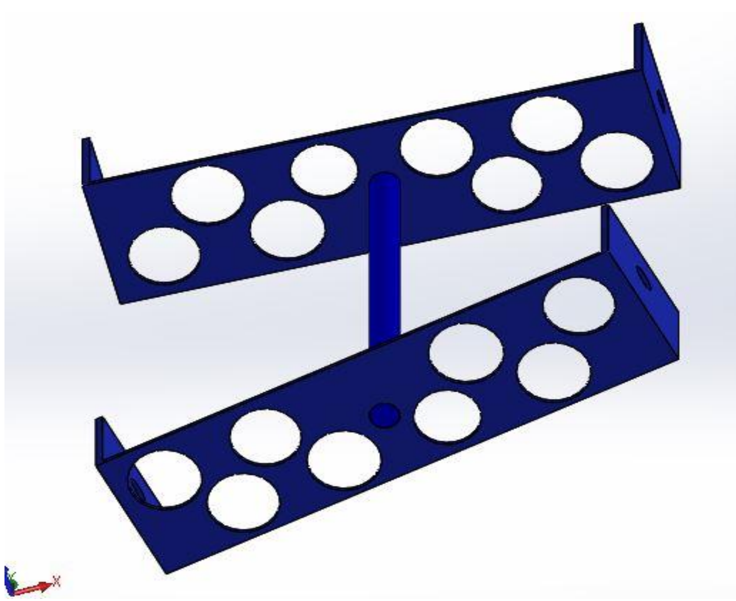


Figure 3.2. Leg like axle on the front and rear connected by the roll shaft

The frame will have two leg-like axle, one in front and one in rear connected by a roll shaft in the center. The roll shaft allow the axle to raise any of the right or left wheel when an obstacle is encountered. Fig. 3.2 shows the two leg like axle which are connected by a central roll shaft. The roll shaft will allow the two axel to roll independently and thus respond to the incoming obstacle individually.

3.3 Robot Mechanism

WMRs usually have been utilized in the indoor environment due to their advantages on the indoor applications. To extend the WMR's application area to the outdoor environment, the WMR must have good adaptability to the environment. In order to improve this adaptability, we proposed a simple locomotive mechanism shown in Fig. 3.3 that makes it possible for the driving wheels to move relative to the robot body and for the wheels to change its orientation with the robot body, according to the shape of terrain.

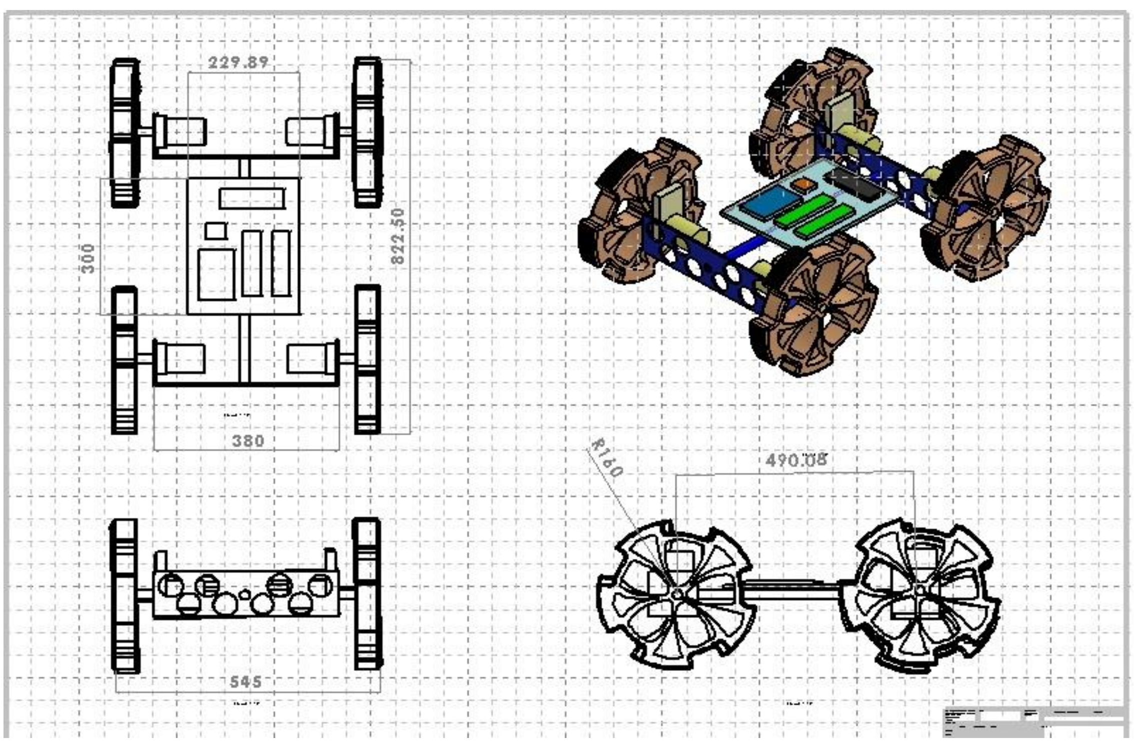


Figure 3.3 Drafted View of the Proposed Robot

TABLE 2: Robot Specifications

S. No.	Parameter	Dimension
1.	Length	82.5 cm
2.	Width	54.5 cm
3.	Height	32 cm
4.	Wheelbase	49 cm
5.	Motors	4
6.	Motor Power	102 kg-cm
7.	Motor Weight	0.5 kg
8.	Battery	11.1V Li Po battery
9.	Battery Weight	0.43 kg

Fig. 3.4 shows the adaptability of the WMR with the proposed locomotive mechanism according to the two different types of terrains. This mechanism is hereafter referred to as *leg-like axle*. Moreover, in order to enable every leg to raise its wheel. The robot is equipped with a leg-like axle at both the front and rear. This allows the axle to roll about the robot body and maintain contact with the ground or obstacle and ensure loss of contact.

Another important point to note out is that when the robot encounters an obstacle first, it has a momentary stop. At this moment, the wheels only rotate without any translation. This continues until the legs at the front wheels grips the obstacle and propels the robot forward. A detailed study if this mechanism will be studied in the next chapter.

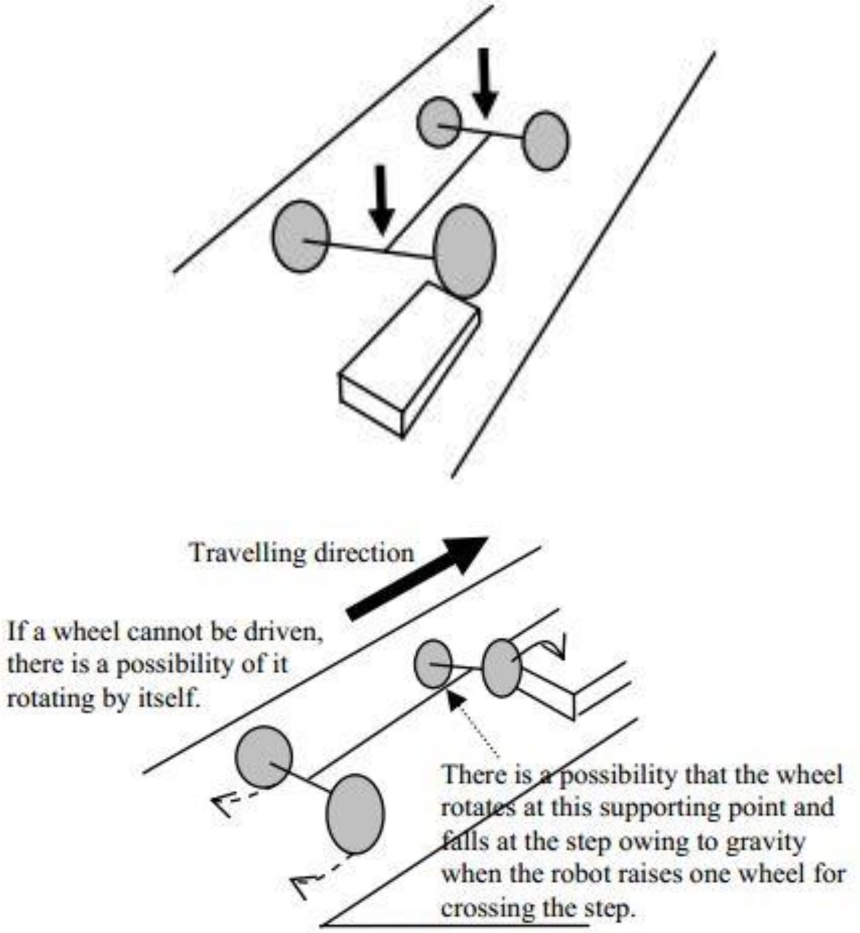


Figure 3.4 Roll Shaft- Wheel axles can orient themselves according to the terrain

To be usable for a variety of missions, the robot has to be able to carry sensors to areas which are normally not accessible to wheeled and tracked robots. The blue colored board in Fig. 3.3 shows the platform at which the electronic control unit along with camera, sensors, battery, microcontrollers etc. are assembled. The board is attached to the central roll shaft which rotates with the roll shaft. On this robot we can also employs the robot body to carry the payload,e.g., as in the case of urban disasters or hostage situations where in these robots are designed to rescue workers.

CHAPTER 4

MODELING AND DYNAMIC SIMULATION

4.1 Introduction

This chapter will be discussing about the Multibody Dynamics (MBD) simulation and Finite Element Analysis (FEA) of the stair-climbing robot. This simulation chapter will test the robot maneuverability in different terrains. The full body dynamic simulation will study the torque requirements, power consumption, reaction forces, frictional forces and wheel slip of the robot. For multibody simulation, **MSC Adams** Multibody Dynamics software platform has been used which is integrated to **Solidworks**. The simulation steps for the MBD analysis are as following:

Step 1- First an assembly imitating the physical world dimensions of the robot with the assigned material properties and joints of the mechanism (Revolute, Prismatic etc.) is modeled in Solidworks. The model dimension is same as the actual robot and kinematic analysis is based the geometry of the actual robot. All the conditions (mass length, boundary condition, friction, coefficient of restitution) are near to real value in order to have an accurate simulation results which will correspond to the real robot.

Step 2-The robot is first simulated in a stair-climbing effort. The chief objective is determine the minimum coefficient of friction required between the wheel and the stairs to climb. Another important result necessary for selecting the motor, is the torque requirement.

Step 3- We will extract some crucial results such as reaction forces of the ground on the wheels, and on the robot as a whole. This forces will be used in the impact analysis and the explicit dynamics of the robot in the later stages of FEA.

Step 4- Finite Element Analysis of the robot will be studied to ensure that the robot possesses the endurance strength of sustaining the cyclic stresses from the uneven terrace and while climbing the stairs.

4.2 Dynamic Modeling

The free-body diagram of forces and velocities is shown in Fig. 4.1, with the vehicle having instantaneous positive velocity components $\dot{x}$ and $\dot{\theta}$ and negative velocity $\dot{y}$. Wheels develop tractive forces F_{xi} and are subject to longitudinal resistance forces R_{xi}, for i= 1,….,4. We assume that wheel actuation is equal on each side so as to reduce longitudinal slip. Thus, it will always be F_{x4}= $F_{x1}$and F_{x3}= F_{x2}. Lateral forces F_{yi} act on the wheels as a consequence of lateral skidding. Also, a resistive moment M_r around the center of mass is induced in general by the $F_{yi}$and R_{xi}forces.

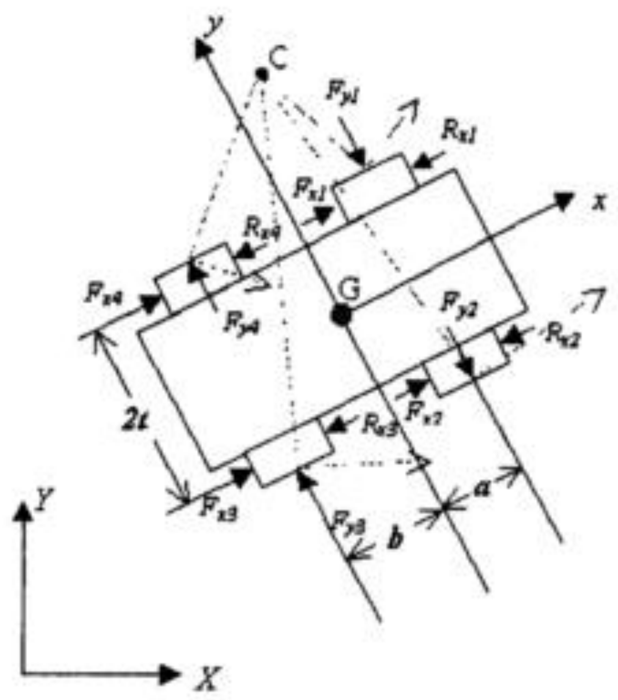


Fig. 4.1 Free Body Diagram of the Robot

For a vehicle of mass m and inertia I about its center of mass, the equations of motion can be written in frame *f* as:

$$ma_x = 2F_{x1} + 2F_{x2} - R_x \quad (1)$$

$$ma_y = -F_y \quad (2)$$

$$I\ddot{\theta} = 2t(F_{x1} - F_{x2}) - M_r \quad (3)$$

To express the longitudinal resistive force R_x, the lateral resistive force F_y, and the resistive moment M_r, we should consider how the vehicle gravitational loading is shared among the wheels and introduce a Coulomb friction model for the wheel-ground contact. We have

$$F_{x1} = F_{x2} = \frac{b}{a+b}.\frac{mg}{2} \quad (4)$$

$$F_{x3} = F_{x4} = \frac{a}{a+b}.\frac{mg}{2} \quad (5)$$

At low speed, the lateral load transfer due to centrifugal forces on curved paths can be neglected. In case of hard ground, we can assume that the contact patch between wheel and ground is rectangular and that the tire vertical load produces an uniform pressure distribution. In this condition, where is the coefficient of rolling resistance, assumed independent from velocity. The total longitudinal resistive force is then

$$R_x = \sum_{i=1}^{4} R_{xi} = f_r.\frac{mg}{2}.(sgn(\dot{x}_1) + sgn(\dot{x}_2)) \quad (6)$$

Introducing a lateral friction coefficient, the coefficient, the lateral force acting on each wheel will be $F_{yi} = \mu F_{xi}\ sgn(\dot{y}_i)$. The total lateral force is thus

$$F_y = \sum_{i=1}^{4} F_{yi} = \mu.\frac{mg}{a+b}.(bsgn(\dot{y}_1) + sgn(\dot{y}_3)) \quad (7)$$

while the resistive moment is

$$M_r = a(F_{y1} + F_{y2}) - b(F_{y3} + F_{y4}) + t[(R_{x2} + R_{x3}) - (R_{x1} + R_{x4}] \quad (8)$$

$$= \mu.\frac{abmg}{a+b}(sgn(\dot{y}_1) - sgn(\dot{y}_3)) + f_r.\frac{tmg}{2}(sgn(\dot{x}_2) - sgn(\dot{x}_1)) \quad (9)$$

4.3 MBD simulation of the robot- Animation Results

The robot with four wheels is assembled in Solidworks with the robot frame. The Solidworks include a tool called MOTION ANALYSIS which will help in conducting detailed motion analysis and evaluate the mechanical performance of our design. SOLIDWORKS motion analysis uses the assembly mates along with part contacts and a robust physics-based solver to accurately determine the physical movements of an assembly under load. With the assembly motion and forces calculated, a structural analysis of the components can be performed to ensure product performance. There are two types of motion analysis, kinematic and dynamic:

i. Kinematic analysis is used to determine how the design moves under forces and motion drivers which are applied to the assembly. The important results in interest are the range of part motions and also in calculating part displacements, velocities, and accelerations.

ii. Dynamic motion analysis calculates the forces generated by the movement of the parts, and also the movement itself.

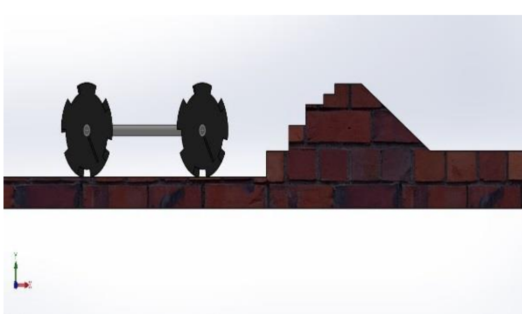
Both kinds of motion analysis has been carried out to study the motion kinematics of the frame mechanism and dynamic forces acting between the tire and the ground. Fig. 4.2 shows the animation result of the robot climbing a modelled stairs in different frames. The simulation is a time bases analysis, which means it solves the governing physics between the robot and the stairs. Fig. shows the motion of the robot at different time steps of the simulation. We have included the gravity in our simulation. The 3D contact between the four wheels and the ground is modelled with a kinetic and dynamic coefficient of friction as 0.15 and 0.30 respectively.

Figure 4.2.Dynamic Motion Analysis of the robot climbing a stair
in MSC ADAMS View Software

As can be seen the legs of our new wheel design is able to grip the stairs at frame iii. It is imperative that all the four wheels are in contact with ground at all times, specifically when the robot climb the stairs as the torque needed is high to avoid the condition of slippage due to a loss of area of contact while climbing. Taking the important idea about the necessary condition of an all-time contact of all the four wheels with the ground, we have incorporated a functionality in our robot to have an adjustable wheel base, which can be adjusted corresponding to the steepest step the robot will climb.

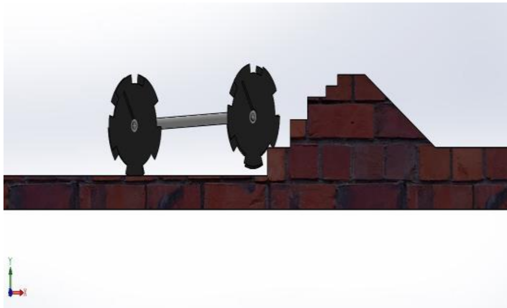
Another important observation that can be seen in frame 6 of Fig 4.3 is the possibility of the robot main body to touch the ground. Therefore the ground clearance of the robot becomes a crucial factor to limit the domain of unstructured environment, i.e., the maximum step height our root is able to ascent. After a continuous test of varying step height, it is concluded that the robot can climb a step of a height equal to the outer radius of the wheel.

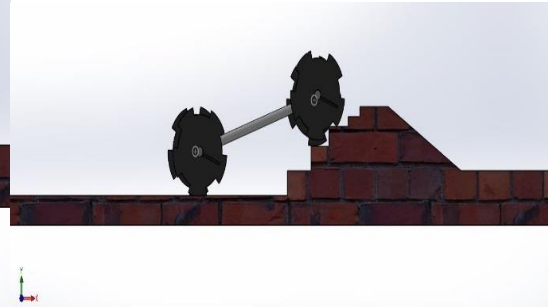
In the event that a vehicle is moving forward on a plane and the same speed is applied to all wheels, no slip happens under perfect conditions. Under real conditions, slip is uunavoidable, however the slip level stays low on a plane because the ideal speeds of all wheels are equal. In rough terrain, nonetheless, kinematic constraints oblige each wheel to rotate at individual speeds in this way, deviation from the perfect speed is more regular and the slip level increases.



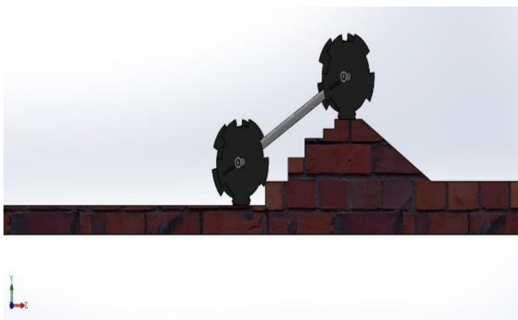
State 1

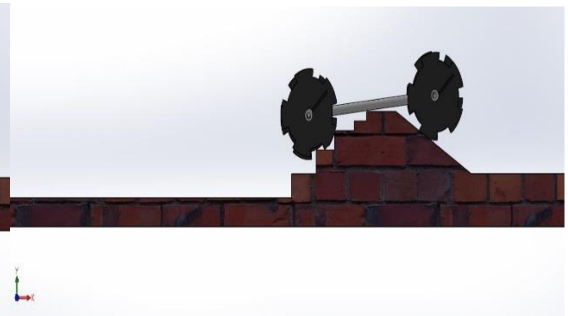
State 2





State 3 State 4





State 5 State 6

State 7 State 8

Figure 4.3 Different States of the robot while climbing the modelled stairs

To encounter the slip, the legs of the robot wheels should be able to grip the uneven terrain independent to each other depending on the surface profile. To solve this important physics constraint, we introduced a flexible suspension mechanism in the form of roll shaft. The roll of the shaft enable the front and rear legs to roll about the central main frame body. It will focus on the sheet’s roll and both front and rear roll adjustment shafts for the movement from point A to point B.

TABLE 3: Parameters of the ADAMS Solver for Dynamic Study in Motion Analysis

S. No.	Options/Parameters	Type/ Setting
1.	Integrator Type	GSTIFF
2.	Maximum Iterations	25
3.	Initial Integrator Step Size	1e-4
4.	Minimum Integrator Step Size	1e-7
5.	Maximum Integrator Step Size	1e-2
6.	Jacobian re-evaluation	Every evaluation
7.	3D Contact Resolution	30%
8.	Accuracy	1e-4
9.	Static Friction Coefficient	0.15
10.	Dynamic Friction Coefficient	0.3

Table 3 shows the parameter settings for the dynamic simulation in the ADAMS Solver.

4.4 Study of Step Climbing

Figure 4.4 Simulation of a Robot climbing a step of 16 cm

Our Leg-Wheeled robot is first simulated in a test environment with a step of a height equal to the outer radius of the wheel. It is as shown in Fig 4.4. The motors are given a speed of 10 RPM. A 3D contact is established with a kinetic and dynamic coefficient of friction as 0.15 and 0.3 respectively to imitate real world conditions. ADAMS Solver in Solid Works converts all the inputs into set of governing equations of physics and solves for other Forces and moments acting on the body.

i. Stair Climbing Speed

The sequential rising of the Center of Gravity of the robot provides the consecutive action of the wheels influencing the climbing ability. Fig. shows the trajectory of CoG for a step climbing of 16 cm. For about 4.4 s of the simulation, the robot is in the bottom plane surface. From 4.4 s < t < 5.8 s, the CoG climbs the stair with the support of the legs pulling the robot on the step. At t=5.8 s, the front wheels reaches the step completely and starts rolling forward. They roll forward for about 2.4 s until the rear wheels touches the step.

As mentioned in the last section, it is necessary that all the four wheel maintain a contact with the ground, because these frictional torques on the wheel contact will help in pushing the weight of the robot upwards. From 9 s< t < 10.5 s, the rear wheels continues climbing the step. The trajectory clearly demonstrates that the mechanical structure transforms the sharp underground structures with steep slopes to a smooth movement of the CoG. This is the key idea, which makes the system much better than other concepts.

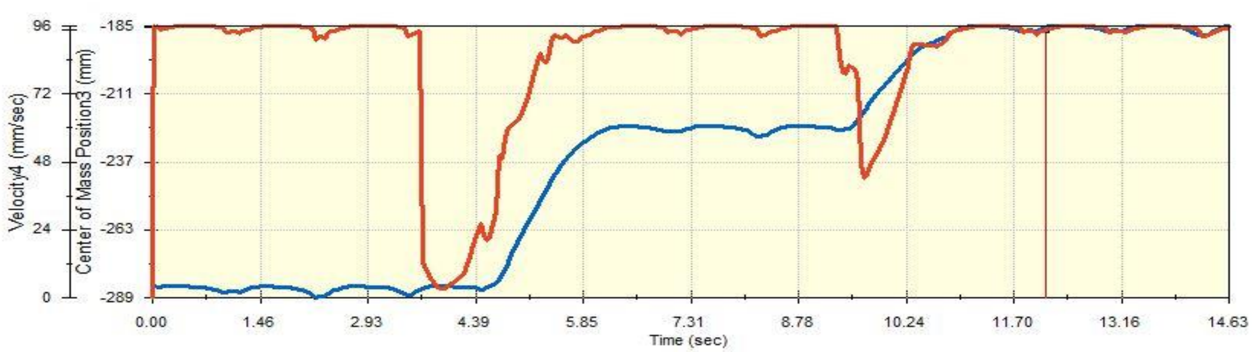


Figure 4.5 CoG Trajectory (in Blue) and velocity (in Red) of the robot climbing a step of 16 cm height.

The red curve in Fig. 4.5 shows the velocity of the robot. It is quite intuitive to understand the uniform velocity of the robot at the beginning and end of the step-climbing maneuverability. The constant velocity in the middle of the curve corresponds to the robot's front wheel rolling on the step with the rear wheels still on the ground. The sharp fall of the robot at t = 4s is when the robot is stopped by the step in front. After this the robot slowly rotates till the next leg of the front wheel grips the step and starts climbing. Similarly the sudden velocity drop at the later stage is during the transfer of the rear wheels onto the step.

ii. Motor Torque requirement

This section outlines the results of additional dynamic simulations performed in order to calculate the torque required in front and rear wheels to propel the robot to climb the step. Once the maximum torque requirement for each wheel was evaluated, proper gear ratios and motors were selected.

Practically, the harshest operating conditions for each motor will dictate the motor's selection criteria. An analysis is performed for each motor in the system by generating torque plots for the step-climbing mobility scenario. Based on those torque plots, the maximum peak torque and its occurrence in a given range of motion are identified. The peak torque values define the maximum torque capacity necessary for each wheel.

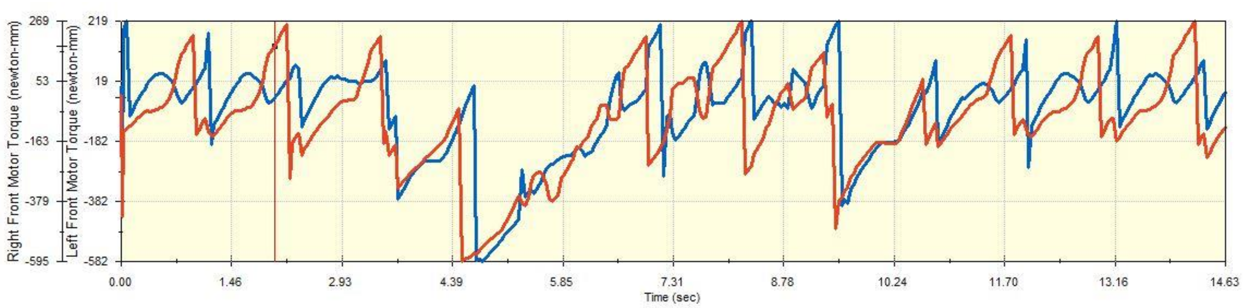


Figure 4.6. Motor torque requirement for Front wheel—step obstacle climbing. (Blue: Left, Red: Right)

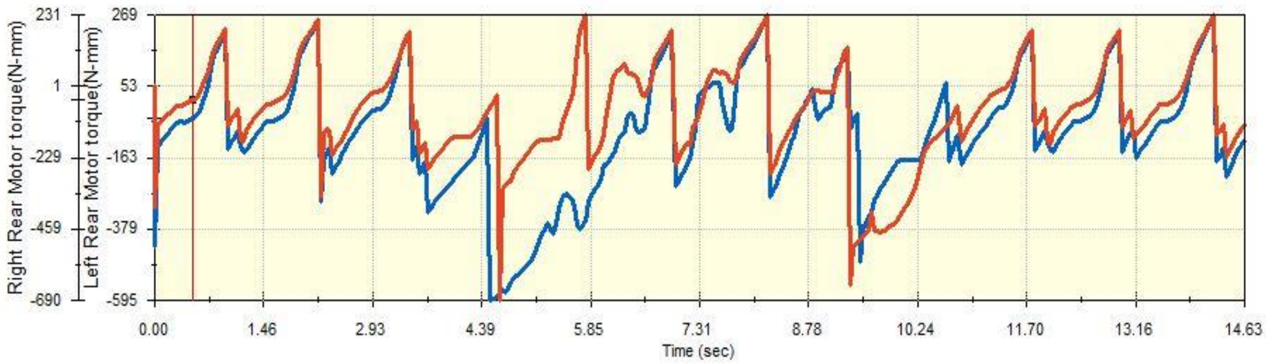


Figure 4.7. Motor torque requirement for Rear wheel—step obstacle climbing. (Blue: Left, Red: Right)

Fig 4.6 shows the motor torque requirement of the front wheels. It can be seen that the torque requirement for both right and left wheels are almost same particularly because both are moving on a plane surface with similar ground conditions. The range of torque required for the left and right wheels (indicated by Blue and Red curve respectively) is between -580 to 220 N-mm and -590 to 270 N-mm respectively. Similarly Fig 4.7 shows the motor torque requirement of the rear wheels. As can be seen by the torque range on the Y-axis, maximum torque requirement is 690 N-mm for the right rear motor m at t=4.4 s which is corresponds to the front wheels climbing the step as in Figure .

A maximum torque value of 690 N mm is required for climbing a step of 16 cm. We will choose Lithium-ion batteries with high drain current capabilities as well as proper gearheads and brushless DC motors were incorporated in the design.

iii. Power Consumption

The robot as a whole needs power to overcome resisting forces like aerodynamic drag, frictional drag etc. while moving. The power consumption curve of Fig. 4.8 gives the total power requirement of the robot which is provided by the four motors. It is very evident that at time t=4.4 s of the simulation, the robot has the peak power requirement. This corresponds to the motion when the front wheels of the robot tries to climb the step.

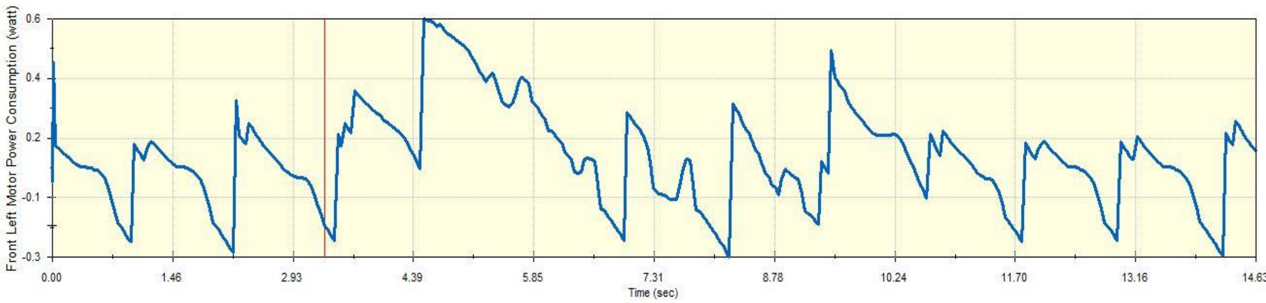


Figure 4.8. Power consumption of the robot in overcoming frictional drag

This power is provided by the combined actuation of all the four frictional torques at the wheel-ground interfaces. However, the power contribution of all the four motors are independent and depends on surface contact and slip at that individual ground-wheel interface. If one of the wheels suffers from slip, then in that condition, the other wheels have to compensate for the lost torque. Therefore, it is important to study the mechanics of slip and try to minimize it. Another essential part of designing a robust locomotive system is introducing wheel torque control which will set independent torques on the four motors.

4.4 Study of slip and coefficient of friction

One of the biggest issues for vehicles moving in rough terrain is the generation of traction. Given that all wheels touch the ground at all times, the load on the wheels changes due to the unevenness of the terrain. If all wheels of the vehicle are powered, the system is over actuated. With the appropriate technique the ideal torques on the wheels can be calculated such that minimum friction is required by the vehicle which reduces the risk of slip. Theoretically, this solution corresponds to the vehicle's best possible performance in terms of slip prevention. Hence, this characteristic is well suited to evaluate the performance of a vehicle. The corresponding metric is called friction requirement.

The calculation of the friction requirement is based on Coulomb's friction law:

$$F_T \leq \mu . F_N \qquad (10)$$

Where F_T : traction force

F_N : normal force

μ : friction coefficient which depends on the materials of the wheel and ground.

The maximum traction force supported by the ground is equal to $\mu.F_N$. If it is exceeded $F_T > \mu.F_N$, slip occurs.

However, it is very difficult to know the exact value of μ in a real environment, and in the case of loose soil, the wheel ground interaction demands for a more complex contact model. Note that it is almost impossible to obtain precise values for the individual translational speed of each wheel in rough terrain. Therefore, slip is calculated only in simulation where all the necessary parameters are available at every time step.

4.5 Finite Element Analysis

Finite element analysis (FEA) offers excellent modeling capabilities for individual components of robot for estimating stresses and strains. Objective of this simulation is to validate the design and find out stresses and strains at failure point which helps to select the material of the robot and parameterize the design in the respect of inertia, loads, and geometry of the robot.

The objective of the static analysis shown in Fig. 4.9 is the investigation of the terrain ability of robot in terms of obstacle climbing. The slow traveling speed of the robot in tough terrains justifies the use of static models for certain types of analyses. These kinds of analyses are mostly of comparative nature rather than absolute, and the results are used for trade-offs during the development of the robot. At this point during a project, time and cost to generate dynamic models of numerous configurations cannot be justified and important parameters required for such models to reach sufficient accuracy with respect to the final design might not yet be defined. Therefore, the static analysis characterized by Table 4. identified as a useful and appropriate means for investigation of locomotion performance to conduct a comparison.

Another key aspect to be highlighted is that the results of the static analysis describe the performance of the pure mechanical structure itself since no controller is needed for simulation.

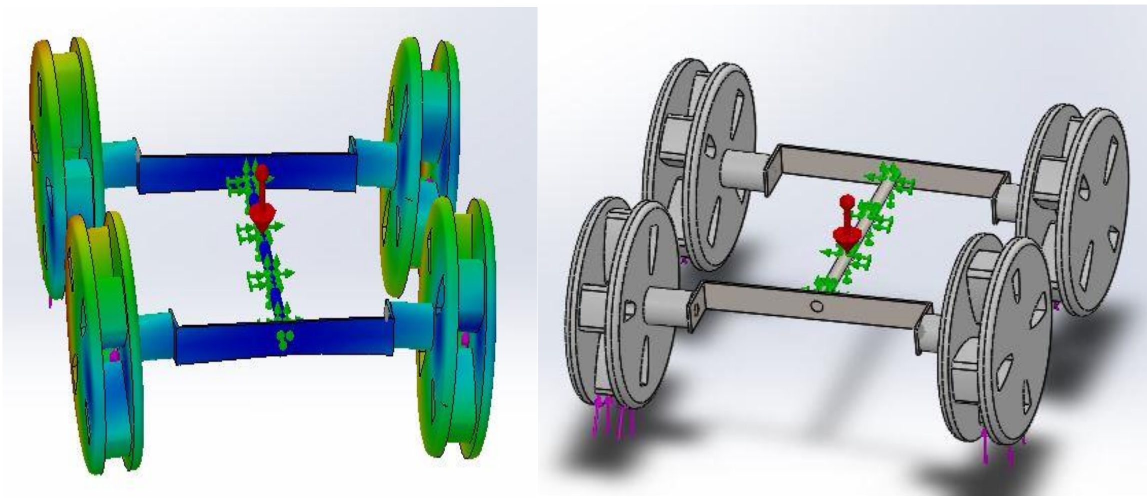


Figure 4.9 .Static Analysis of the robot assembly in Solid works

TABLE 4. Data for forces and moments used for the simulation.

Selection set	**Units**	**Sum X**	**Sum Y**	**Sum Z**	**Resultant**
Entire Model	N	0.50046	261.04	-0.376509	261.04
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

TABLE 5. Reaction Forces and Moments

Stress1	VON: von Mises Stress	10.7447 N/m^2 Node: 374	2.14e+007 N/m^2 Node: 1228

As shown in the study results, the maximum von mises stress is of the order of 7 as shown in Table 5. The frame is made of mild steel plates with a yield strength of 6.20422e+008 N/m^2 . Therefore the robot can bear heavy oscillating loads in rough terrains when moving with a low speed. Fig 4.9 shows the stress distribution on the assembly. The right figure shows the loads acting on the robot. Gravity has been considered for simulating real- time conditions.

CHAPTER 5

FABRICATION AND ASSEMBLY

5.1 Fabrication of Parts

The fabrication of the mechanical structure of the robot involves basically 3 Parts: wheels, leg frame (axles) and the central robot body (hinge). In the design of the robot, body of the robot was divided into two parts, front and rear leg axles.

Material selected for robot body is mild steel which is an on-the-shelf material. The selected material have enough strength to endure the heavy stresses occurred while moving on rough terrains. Mild Steel is a cheap and easily available material. However mild steel is relatively heavy. Therefore to reduce the weights, the design is optimized using FEA to remove any unwanted material, and at the same time ensuring that the components do not fail in cyclic loads.

The central hub is having a key which is attached to the driver motor. The rim and the flanges are made of plastic material which reduces the weight of the wheels significantly. As can be seen, the wheels have five legs which have a rubber contact surface at the circumferential area. The rubber tread has reduced the slippage of the robot considerably as it has a better grip with the stair surface. The overall weight of the wheel is 1.136 kgs. Most of the weight is due to the hub of the wheel which need to be strong to hold the heavy payload of the robot.

Figure shows one of the leg axle of the robot which was fabricated using a mild steel plate of 1cm thickness. The drills on it is in order to reduce the weight. The location of the drills was obtained by optimizing its weight using FEA Material Optimization. Each axle weighs 1.2 kgs. The central hole is for connecting the two axles through the central robot body which has a hinge about which the axles can roll and orient the wheels according to the terrain conditions. The two holes on left and right connects the motor on the internal side and the wheel on the outer side using a spline key.

Fig. 5.2 shows the central body or the robot skeleton. It comprises of a central hinge made of a mild steel. The rod has screw threads of size M12. The white board is the electronic board. It comprises of Microcontroller, Motor drivers, voltage regulators etc.

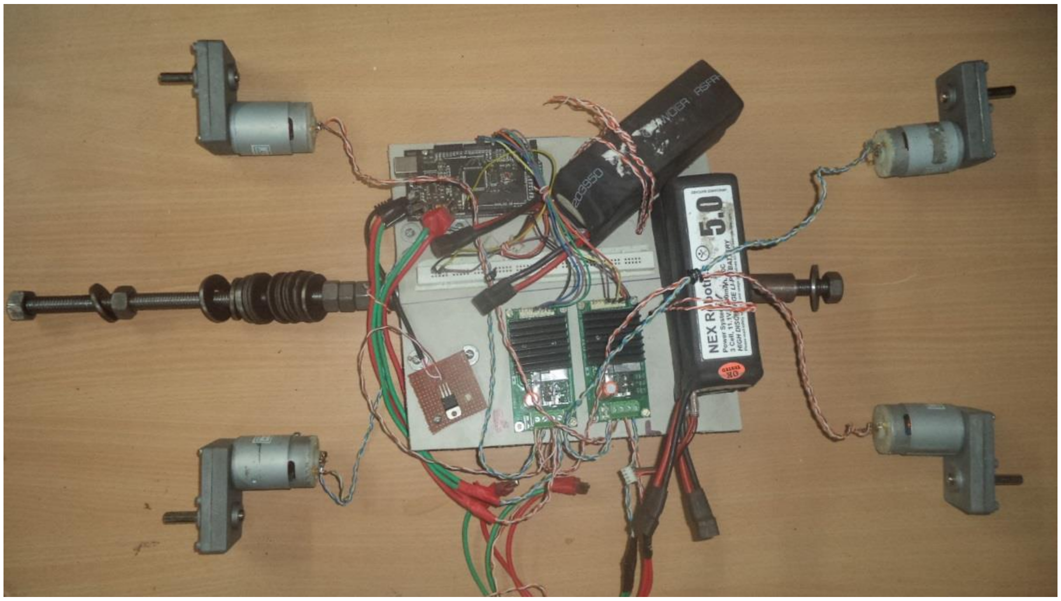


Figure 5.1 Robot Skeleton with the motors

The four motors are attached to the motor drivers on the central electronic board. These motors will be attached to the leg axles, and finally the whole robot frame will be assemble to the four wheels. The weights of the motors is 0.5 kgs each. The hinge with the battery and other boards weigh 5.4 kgs. The heavy weight is primarily because of the heavy weight of the motors.

5.2. Assembly of the Robot

All the three parts, i.e., the robot skeleton, wheels and the leg axles are assembled using screw and nuts. The central hinge is screwed throughout its length, which allows to vary the wheelbase of the robot. This will be helpful for climbing stairs of variable heights. The rolling ability of the axles will provide an added edge of the robot in rough terrains. The wheels legs, which are covered by rubber treads have been given a lot of attention as it was a source of concern for a long time during the testing of the robot.

The robot was facing slip when the wheel legs had a wood base. It was not providing sufficient friction and the robot was slipping over the stair surface. Fig. shows the assemble robot. Table gives the weight distribution of different parts. The overall weight of the robot is 12.15 kgs.

TABLE 6. Weights of different parts of the robot

S. No.	**Part**	**Weight (in kgs)**	**Quantities**
1.	Robot Frame	7.6	1
2.	Leg axle	1.2	2
3.	Motor	0.5	4
4.	Central Hinge & control board	3.2	1
5.	Wheel	1.136	4
	Overall Robot Weight	**12.1**	

As already demonstrated by the simulation in previous section, the required friction coefficient between the wheels and the ground are largely reduced by the proposed locomotion concept. As we expected, the robot was not able to climb the step anymore with all wheels covered by tape. Nevertheless there is a large number of parameters which are not optimized on this first prototype like the weight distribution or the control of the individual motors. This will for sure improve the climbing ability of the robot.

5.3 Hardware Design

A PCB was designed using Fritzing software as shown in Fig. 5.3. It is very good for virtual prototyping and debugging the electrical connections. It has good library support and comprises of a large family of microcontrollers, drivers, capacitors, voltage regulator and other electronic components.

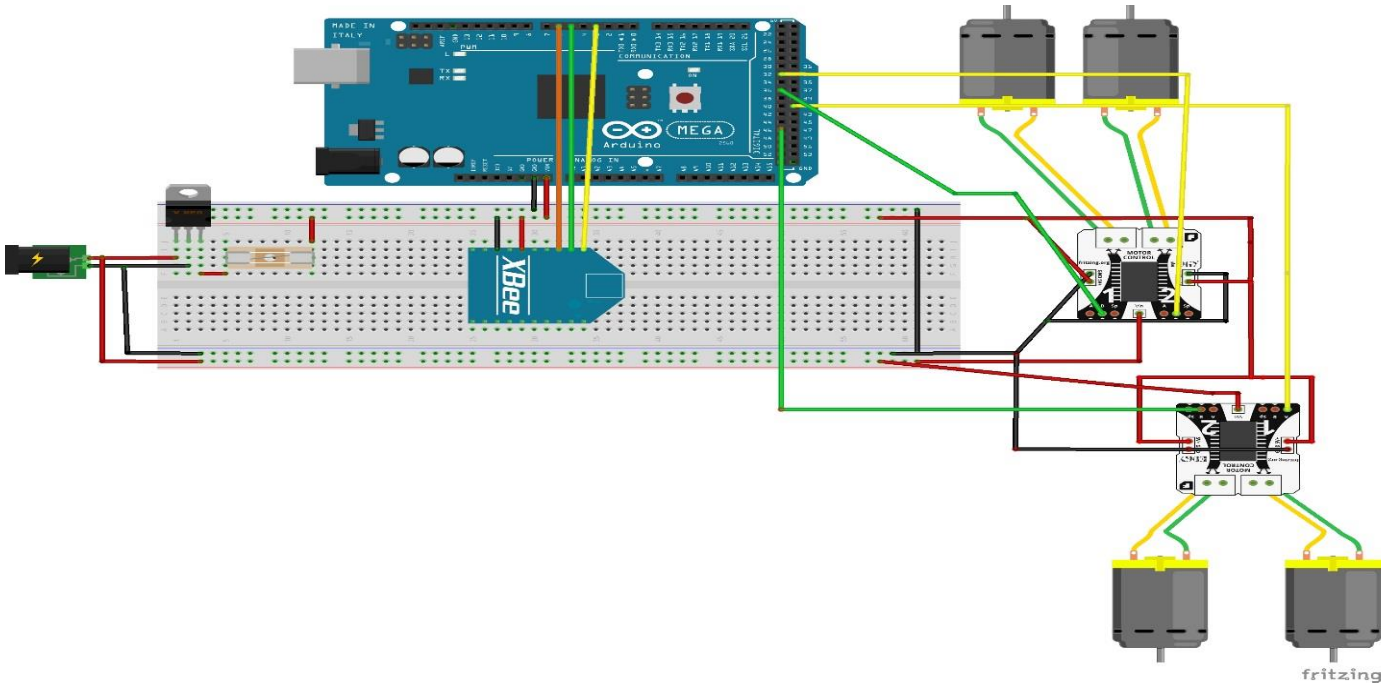


Figure 5.2 Fritzing Image of the hardware used for control of the robot.

The schematics is shown in Fig 5.4. The microcontroller is Arduino Mega, which is a family of ATMEGA 2560. The four motors are controlled by four motor drivers which is controlled using PWM signals from the Microcontroller. The ZigBee Module allows a wireless communication to control the robot using PC. The RF signals contain frequency of 760 MHz. The battery provides 12 V voltage to the motor drivers. The 7805 voltage regulates the 12V to 5V, which is used by Arduino.

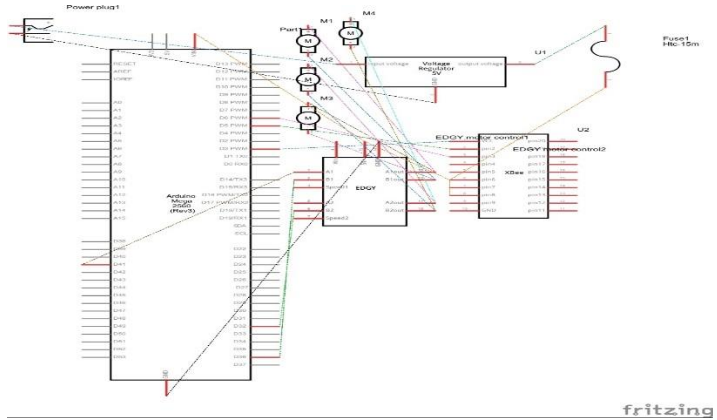


Figure 5.3 Schematic of the Control System

TABLE 7. Electronic Parts and its specifications

	COMPONENT	SPECIFICATIONS
	Side Shaft Super Heavy Duty DC Gear Motor	10 RPM at 12V Voltage: 4V to 12V Stall torque: 106.08 Kg-cm at stall current of 4.4 Amp.
	Lithium Polymer discharge Battery	3 Cell, 11.1V, 2000mAh, 20C.
	ATmega2560 MEGA Microcontroller Board	5V, Clock Speed 16 MHz, EEPROM 4KB SRAM 8KB.
	Hercules 6V-36V, 16Amp Motor Driver	Operating voltage: 6V to 36V Continuous output current: 15Amp Peak output current: 30Amps Maximum PWM Frequency: 10 KHz

The motors are heavy duty, 10 RPM with a central shaft. To protect the motors from high current, a fuse is provided which is connected to the ground. Table 7 shows the specifications of all the components.

CHAPTER 6

EXPERIMENTAL RESULTS

6.1 Stair Climbing Test

As mentioned in the objective of the thesis, the aim of my work is to develop a stair climbing robot which is capable of climbing the stairs of a height at least equal to the outer radius of the legged wheel. The mobility performance of the robot is confirmed through experiments.

We tested the robot for climbing a stair consisting of a number of stairs, with different height and width. The time was recorded for these tests and analysis was done to evaluate the performance of the robot. Fig. shows the robot climbing a staircase of a step height of 13cm and a width of 30cm. As can be seen in the figure, the robot's front wheel axle is slightly rolled as compared to the rear axle. The legs grip the step which is at the front and pushes the body forward to the next step.

6.1 Observations

To check our design and the robot performance in different conditions, the robot was tests on a staircase of 30 steps with height and width as given in Table 8 . The results were compared with the simulation result and the results were near to the real time results, which approves our simulation and design.

The robot was able to climb stairs of a height upto 20 cms, which proves a successful design of the robot. The robot has exceeded its goal of climbing a stair case of 12 cms. The motors have a torque of 102 kg-cm which limits its power in very high stairs.

As already demonstrated by the simulation in previous section, the required friction coefficient between the wheels and the ground are largely reduced by the proposed locomotion concept. As we expected, the robot was not able to climb the step anymore with all wheels covered by tape.

TABLE 8. Comparison of Climbing time in Simulation and Experiments

S. No.	Step height (in cm)	Step width (in cm)	Simulated Climbing Time (in sec)	Experimental Climbing Time (in sec)	Error %
1.	10	30	42	45	6.67
2.	13		54	58	6.89
3.	15		60	65	7.69
4.	17.5		79	88	10.22
5.	20		101	108	6.48

The robot was also tested on a level ground surface. It covered a distance of 480 cms in a time of 27 seconds, which means it can achieve a ground velocity of 0.6 kmph. This is relatively slow on a level surface. The major reason can be contributed to the weight of the robot, which can be reduced in future by using some light material like carbon fibre.

Nevertheless there is a large number of parameters which are not optimized on this first prototype like the weight distribution or the control of the individual motors. This will for sure improve the climbing ability of the robot.

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

7.1 Conclusion

The work describes the design, modelling, simulation, fabrication and testing of a stair climbing robot based on a new design paradigm of the wheel which is called as "Wheeled-Leg". Multidisciplinary design approach is applied to develop the robot. After MBD and FEA simulation we have concluded our design. The robot is structurally safe at applied loads and material selection and robot mechanism is capable of climbing stairs of a height up to the outer radius of the robot.

So far we have been successful in eliminating the slip of the wheels while climbing, which was successful after adding rubber tire with treads at the legs of the wheel. This allowed to better grip the surface and provide a higher coefficient of friction, needed to get the required frictional torque. The roll shaft mechanism has also been specifically allowed the front and rear leg-axles to roll about the robot body to get a "good "contact with the ground. The simulations and experiments were performed for three road shapes. In every case, the robot was able to move on the rough terrain by maintaining the horizontal position. This has allowed the wheels to develop independent wheel torques and thus avoid the slip when tested in different unstructured terrains.

7.2 Future Scope of Work

The following directions could be pursued for the future enhancement of the present project in terms of fully or partial (function specific) autonomous operation:

- Develop control algorithms and sensing techniques that allow the hybrid mobile robot system to operate autonomously in unstructured environments.
- Redesign the system for overall weight reduction without trading off with it payload capacity.
- In the future work, sensors, cameras, manipulators can be added to the robot frame. The robot can then serve complex tasks in dangerous areas remotely.

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