Passive Minimization of Pitch of the Payload Platform of a Shrimp Rover

By

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Submitted to the Department of Mechanical Engineering

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Supervisor
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June 2020

Declaration

I certify that this research work titled "*Passive Minimization of Pitch of Payload Platform of Shrimp Rover"* is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledged / referred.

Signature of Student

Sehrish Shahnawaz

2016-NUST-Ms-Mech

Language Correctness Certificate

This thesis has been read by an English expert and is free of typing, syntax, semantic, grammatical and spelling mistakes. Thesis is also according to the format given by the university.

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Copyright Statement

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I am thankful to my Creator Allah Subhana-Watala to have guided me throughout this work at every step and for every new thought which You setup in my mind to improve it. Indeed I could have done nothing without Your priceless help and guidance. Whosoever helped me throughout the course of my thesis, whether my parents or any other individual was Your will, so indeed none be worthy of praise but You.

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Abstract

A modified kinematic model of a shrimp rover is proposed, where passive stability of the payload platform is achieved. An algorithm based on forward kinematics moves the rover on a straight and a sinusoidal path. Three different terrain types are generated in order to configure the platform pitch angle of the rover, Crest, Trough and a combination of these. The rover passes over these terrains through an algorithm which keeps the centre of the wheel axis of the rover in contact with the terrain at all points. The objective function uses reverse kinematics to return the values of the platform pitch angle, rotation angles and the distance the rover moves in the vertical axis. In order to analyse and optimize, the values of the platform pitch angle various combinations of the link lengths are generated with the help of Taguchi DOE. The Taguchi DOE analysis is then performed on the platform pitch angle and the best possible kinematic model is generated with minimum pitch angle of the payload platform. The results are then analysed through motion study in solid works and the rover payload platform model is fabricated with the minimum pitch angle for motion in an unstructured terrain.

Key Words: *Shrimp Rover, Passive Stability, Pitch Angle, Taguchi DOE, Kinematic Analysis, Payload Platform, Link Lengths, Unstructured Terrain*

Table of Contents

Contents

Table of Figures

Chapter 1 INTRODUCTION

1.1 Background

The term robot was presented in 1921 by Karel Capek Czech in his "Rossuum's All-inclusive Robots" to allude to a machine with a human morphology. "Robot" advanced from the word "robota" meaning slave. At first this word was utilized to allude to machine's benefit of man, which imitated their shape and capabilities, but a long time afterward it was generalizing in order to utilize this term to allude to another modern machine's morphology but with comparative capabilities to those as of now known, which helped the man in different tasks. Mechanical autonomy reflects the human want to construct a machine in his esemblance that he could control to his taste and it'll comply him without issues within the effective conduct of day by day assignments. Amid the eighteenth and nineteenth centuries there were a few human formed robots that mirrored a few particular works such as composing, drawing, playing an instrument or play tunes and worked utilizing as it were mechanical components and were moreover reprogrammable. Within the early twentieth century Nikola Tesla outlined robots working with power, but without much usefulness and no insights. During the period of the Primary and Moment World War the improvement of this sort of machine was exceptionally destitute since all logical information was pointed at the military and innovation which numbered was exceptionally fundamental, in any case, the want to construct proceeded inactive. All the mechanical progresses made in later a long time are due to military designing, the rise of computers and progress sciences like science and material science which contributed to the rise of new robots since 1945. The world was curious about portable robots and mechanical applications that had higher require and included less exertion in terms of plan and development which was way better suited to the innovation of the time. The car industry gave energy to mass generation of mechanical robots. Most needed intelligence and by and large were tele-operated or modified to perform settled cycles. Within the 60's they were utilized in a few sullied zones and a few other applications including plans that might adjust to each of the errands and situations in which these were created. In parallel, investigate centres at distinctive colleges around the world, began to create considers within the field of fake insights drawing in the intrigued of numerous engineers and researchers, who centered their work on creating frameworks that will prepare robots to a degree of insights that would permit them to have independence in how they respond to circumstances in uncontrolled environment. Subsequently, the independent robots appeared.

Since its beginning, the reason of space investigation is to discover the prove of life, create an understanding of their attainable climate and testing advances pointed at planning future space missions. Hence, Investigation rovers have been broadly utilized for inaccessible investigation, both in space and on arrive. In any case, all rovers share the building issue of erratic and troublesome landscape, alongside the satisfactory plan determinations to handle these issues. Due to this eccentric of landscape and geography, existing plans utilize sensors and/or engine controls to dodge and overcome deterrents and for the most part harsh landscape. Mechanical wanderers play an awfully critical part in unstructured natural investigation, and around 300 concepts of diverse sorts of these wanderers have been created over the past 2 decades. These rovers contrast in estimate, control frameworks, utilization, control source etc.

According to a new trend in which there has been a critical increment in intrigued in creating rover which might not only adjust to any environment it experiences but too it can be conveyed for long term missions, with the extreme objective being the planets of our sun oriented framework particularly Mars. The most point has been to plan rover which seem adjust to the harsh unstructured environment it may experience on Mars or in that case terrain on earth too, for investigation. These rovers are used for their ability to work for comparatively rough surfaces for a longer period of time,good mobility and comparatively less power consumption.

Historically the wind-driven wagon outlined by Guido da Vigevano in 1335 Afterward Dr. W.G. Walter was known in 1948 for the development of the primary electronic independent vehicle. This robot was called Walter's turtle due to its shape and moderate movement in arrange to see how a little number of neural connections might lead to complex behaviors. This automated vehicle with a motion framework of three wheels was able to move in reaction to light boosts (i.e., phototaxis), overcame deterrents and revive its 45 V batteries that were recharged before getting depleted. This kind of prototype was used by other designs such as Tinius in 1950, an autonomous vehicle also attracted by light sources; Docilis Machina in 1951, a version of the Walter's turtle that included sound detector, anti-shock system and additional capabilities that allowed it to memorize obstacles; Vienna Turtle in 1954, designed by E. Eichler due to the conditioned reflex behavior; Machina Versatilis in 1956, due to its modular design and it had transistorized electronic cards ; Ladybird, which was a beetle design built by D. Muszka and L. Kalmár with added abilities of carrying a microphone, light sensors, seven touchpoints on the skin, capacitive memory and two electric motors powered with 220 V AC. In 1972, Flakey was developed which was a hexagonal platform-based robot and was about 90 cm tall and 60 cm in diameter. It had three-wheeled differential system and had a maximum speed of 30 cm/s.it consisted of 12 sonar rangefinders and it was provided with video camera used to provide depth information. Another worth mentioning mobile robot was Microtron which was developed in 1976.It was an octagonal shaped robot. This robot had a aluminum chassis which was of 180 cm wide and its weight was 30 Kg. This robot carried a 12 V battery car with the help of this, it interpreted up to 10 voice commands. Another rover Newt was developed in 1977 which was an intelligent device and its shape was just like a tower. This vehicle had vision sensors and manipulators mounted on an arm. Another robotic vehicle known as Toddler Tee was produced in 1978.This vehicle was of medium size; it was autonomous and had a speed as high as 1.6 km/h. It had a 12 V rechargeable battery. This rover had the added abilities of having a rotating sensor which can search for light. Moreover, it was equipped with a shock sensor, sound system and Z-80 microprocessor.

There had been a part of exertion within the past 50 a long time in arrange to create the concepts and working models for lunar investigation vehicles.The to begin with Moon investigation vehicle utilized in an test stage was an unmanned roving vehicle for the JPL/NASA Surveyor Shuttle program in 1963 in 1965, a self-propelled mockup pointed at checking specialized choices, investigating of control frameworks and examining the interaction of the chassis with lunar soil. This driven after a long time of building development and preparing to the primary mechanical space investigation vehicle called Lunokhod 1

Lunokhod 1 was a large-sized remote vehicle that traveled almost 10.5 km amid its lunar travel along eleven months, in this way surpassing the 90 days of life for which was anticipated. The wheels were not planned to turn, so that the turn of the vehicle was accomplished by shifting the revolution speed of the wheels within the cleared out and right trains. It transmitted more than 20,000 tv pictures and 200 high-resolution all-encompassing sees of a range around 80,000 m2. It finished about 500 exploratory tests. The induction of the meaning of mechanical vehicle was the term wanderer, too known as Lunar Wandering Vehicle (LRV). This term served to assign an all-terrain, bogie-type, vehicle utilized by the space travelers on their move on the lunar surface after conducting the primary lunar portability studies respectively.

Sojourner robot was utilized within the Mars Pathfinder mission of NASA in 1997. This term has been changed these days into the acronym MER – Mars Investigation Rover – to assign the Soul and Opportunity rovers conveyed since 2004. Taking after the Apollo XV mission, Apollo XVI and XVII arrangement proceeded. These medium-sized vehicles vary from the Sojourner rover in measure and capability.

FIDO rover could be a six-wheeled prototype prepared with independent route innovation to create planetary science some time recently the MER mission. Zoe could be a vehicle able of performing exact developments, climbing slants, maximizing vitality and transporting logical payload to examine the Atacama Forsake. Pluto, a vehicle planned with programmable rationale utilized for the improvement of planetary investigation innovation mechanically comparable to FIDO.ATHLETE, a vehicle able of moving over direct landscape and walk on extraordinary lands by implies of six legs with autonomous wheels. GoFor , a tall portability robot vehicle created with wheels- on-legs arrangement able to climb vertical steps of stature 70% of the greatest stowed vehicle measurement .LAGR, a vehicle with two differential wheels prepared with stereo cameras and GPS/IMU utilized independently or remotely as a stage for information collection on sandy soil.

Hence there are a assortment of distinctive rovers created over the past 5 decades and the search of life on other planets, the understanding of the physical and climatic phenomena or the testing of frameworks to plan for future missions have interested people to embrace the career of space investigation.

1.2 Research Objectives:

Following are the research objectives

- To modify a passively intelligent robotic system (Shrimp Rover) kinematic design
- To develop the shrimp rover in MATLAB and to simulate it over a set of uneven terrains.
- To identify the pitch angle of the platform for the rover
- To minimize this pitch angle of the platform with the help of an optimization technique.
- To develop this new passively minimized pitch angle platform in a simulation software and to simulate the results
- To fabricate the proposed design and to validate the results

1.3 Layout of the Thesis

This dissertation is divided into 5 chapters

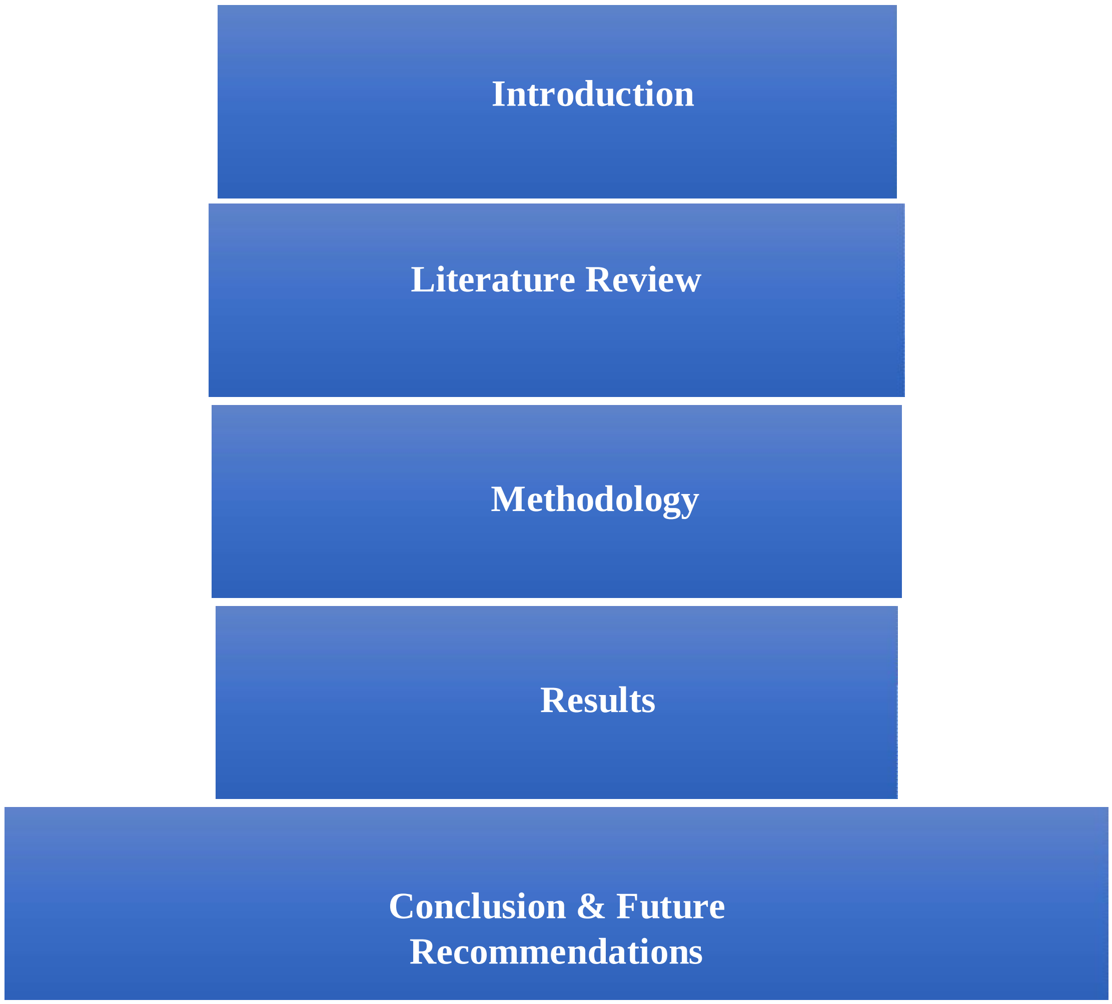

Figure 1:Layout of Thesis Report
Figure 1

Chapter 2 Literature Review

2.1 Classification of Exploration Rovers

2.1.1 According to their Degree of Intelligence

A. **Manual Control or Tele-Operated**: These are robots that require a human operator to perform the task for which they were designed. On their own lack of knowledge of their environment and their movements depend exclusively on the orders given by the operator. Communication with the control station can be done by different types of wireless link and even using mobile phone networks as in H2X HUMMER, or through a cable as some robot's submarines as Swordfish.

B. **Programmable**: Due to lack of knowledge of their environment, they have a cyclically repeating program to perform its function. Most industrial robots like polyarticulated and Cartesians are of this type. Motion paths are predefined and programmed. They do not respond satisfactorily to unexpected changes in their environment.

C. **Autonomous**: Have the basic elements and functions of a feedback control system with the ability to acquire data from their environment by means of sensors, do adaptation (amplify, rectify, filter) and processing of signals from said sensors and convey signals the actuators. The processor has recorded a program that allows the robot to make decisions in response to changes imposed by its environment and retrain their functions. Doesn't involve the hand of an operator, which is replaced by the program that governs the operation of the robot.

2.1.2. According to their Movement

A. Static: Most polyarticulated and Cartesian industrial robots are of this type. These robots work in a limited space in which they are installed and are anchored to the ground. They do not have a mechanism of locomotion.

B. Phones: They have a mechanism that allows them to move in a certain space to perform their duties or missions. They can be designed to travel over land, water or air. They can be autonomous or tele-operated scheduled. They can usually communicate wirelessly with a remote control or monitoring station, although in specific cases such as submarines or explosion-proof robots can use any type of cable for communication.

2.1.3. According to their Morphology

A robot is characterized by a certain body morphology that gives you the ability to have own movements, which allow you to perform the tasks for which it was designed. Any of the known robots so far has any of the following generic forms:

A. Polyarticulated:

This type of robot is mainly characterized by being static and having several sections hinged together and servo-actuated position and that allow moving accurately in a limited space. Its shape can usually be associated with a human arm. In some cases they can have up to nine degrees of freedom and some have the ability to move in a work cell. They are programmable. The "SCARA" (Selective Compliant Articulated

Robot Arm) and "PUMA" (Programmable Universal Machine for Assembly) are two famous designs of such robots.

B. Cartesians: They can controllably position a manipulator, a tool or working element, in a plane which is generally horizontal, with linear or circular movements resulting interpolations made between their orthogonal axes. Most Cartesian robots used in industry, have a structure that supports a horizontal beam is moved in the X direction, on which the carriage which is coupled with the manipulator or tool (Y direction) moves. Some applications require a third axis in the Z direction for vertically moving the working element and others, however, require movement in one axis (X). Market are cartesian robots with up to four axes.

C. Vehicle type: They are like those vehicles typically designed for each of these means land, water or air mobile robots. That is, their mechanical structures are like terrestrial wheeled or tracked vehicles, submarines, jet boats, helicopter aircraft. Figures 3, 4 and 5 show examples of air, water and land respectively robots. In terrestrial robots vehicle type there is a greater divergence from road transport vehicles. These robots can have from two to eight wheels in various configurations and suspension systems varied so can be sub classified into "wheeled robots" when they have a basic suspension system, or they have suspension system and "Walking wheels robots" using complex suspension systems. The "tracked robots" or robots moving through caterpillars, can have two, three or four caterpillars also in various configurations.

 

Figure 2.2:Exploration Rover Types(Hybrid)
Figure 3

2.1.4. Depending on Application

A. Industrial: industrial robots are reprogrammable mechatronic devices designed to automatically perform certain manufacturing processes or handling. They are currently the most widely used and production, generally following the architecture and Cartesian robots polyarticulated already mentioned. Japan and the United States leads the production and consumption of industrial robots with Japan's number one.

B. Exploration: These robots are used for exploration work in places difficult for humans or that pose a risk to the integrity, such as volcanic areas, deserts, Polar Regions, contaminated areas, shipwrecks, planetary exploration, disaster areas (robots legless), detection of explosives, etc. They can be tele-operated or autonomous case in which the robot must be programmed according to the characteristics and capabilities of its locomotion system designed according to the space to explore, to autonomously evasion insurmountable obstacles and planning the paths to follow to reach their destination. All exploration mission consists of three phases: reach the area you want to explore, an inspection and supervision of it and develop some activity like collecting a sample, identify a target, analyze the environment or just taking pictures. To carry out its mission must have the following characteristics

- One type of locomotion according to the environment where it will play
- Manipulators and / or specialized tools in the tasks required by the mission. This makes some of these robots can be considered hybridizes morphology.

2.2 Walking Robot Wheels

These robots are moved by means of wheels and are equipped with suspension systems able to adapt to uneven ground and to overcome obstacles. In this type of robots can be distinguished in two particular classes according to the complexity of the suspension system using: the Walking Wheels with active suspension system having the ability to control the position of the suspension rods and / or center of gravity and Walking Wheels with suspension system passive. For simplicity in its design, construction and control and also because it is more economical to develop the robot will be a Walking Robot Wheel with passive suspension system. Some examples of these two classes of robots is.

2.2.1Walking Wheels with Active Suspension Systems.

They use servo motors or hydraulic or pneumatic servo-assist cylinders to modify in a controlled manner its center of gravity and / or arrangement, configuration or relative position of the suspension members to thereby obtain greater mobility and improve their ability to overcome obstacles and adaptation ground. They have high power consumption due to the greater number of servos used, a higher weight and higher cost.

2.2.2. Walking Robots Wheels Passive Suspension Systems.

In this type of robot suspension system is comprised of bars and interconnected elements passively, therefore, no joint is motorized and the position of the suspension rods only changes depending on the shape of the land on which find the robot, by gravity. They are easy to control, generally provide maneuverability and relatively high stability, the designs are generally simple, its weight is smaller, which allows them to carry more payload (payload), consume less power, are efficient and adapt to uneven terrain and overcoming obstacles is good depending on the design.

2.2.3Applications of Mobile Robots

Primarily the Mobile Robots are implied for these major applications

1.Exploration

2.Surveillance

3. Path Tracking

4.Rescue and Operations

The most important application of these mobile robots so far has been the exploration of a variety of different terrains. For this purpose, the significant research has been done on the development of designs and prototypes for Earth, Lunar and Mars exploration vehicles. Robotic vehicles are widely being used for space exploration purpose.

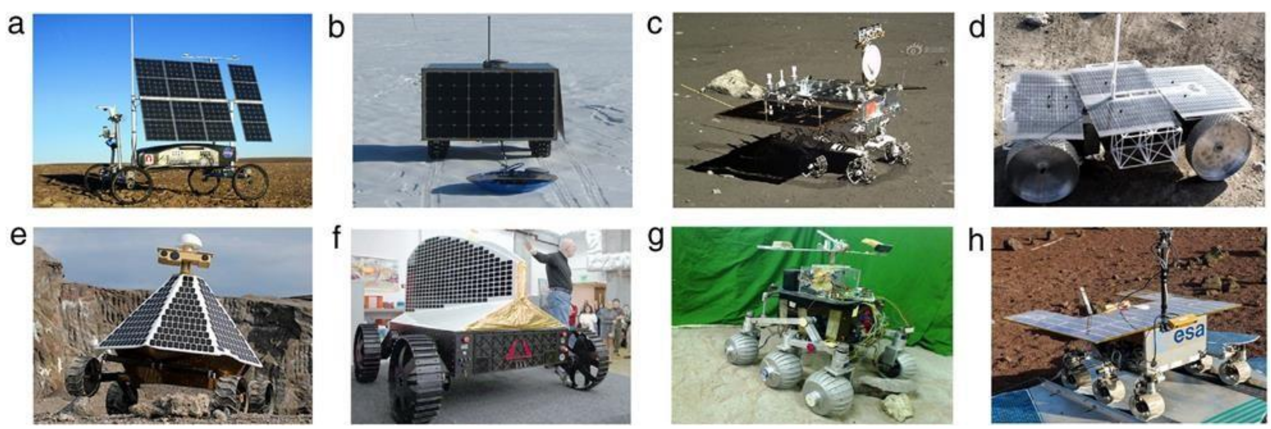

Figure 2.3: Exploration Rover Types (Wheeled Rovers)
Figure 4

2.4 Rocker Bogie Mechanism:

This is the most widely used mechanism primarily invented by NASA to be used in mars rovers in order to overcome comparatively rough terrains and due to its stability. It is considered to be NASA's favorite mechanism for the fabrication of space rovers and vehicles. The rocker bogie mechanism consists of two arms with wheels mounted on each arm. Both these arms are connected through a moveable joint between them. There is a differential that allows the motion between the two arms or rockers. Due to this, there is a suspension-based mechanism that distributes the load of the vehicle as evenly as possible even when it is moving on unstructured road or irregular surfaces. The design comprises of a spring free suspension based differential drive framework that permits the bogie to move over rocks, stones with ease. The sensors and cameras mounted on a rover must be steady to work appropriately conjointly to extend their life spam. More vibrations and jerks lead to quicker wear and tear in in sensors, circuit sheets and cameras. The rocker bogie component was planned by giving most extreme stability in all landscapes.

This bogie can stand up to mechanical failures caused by the harsh environment on Mars. The essential mechanical include of the Rocker Bogie plan is its drive prepare effortlessness, which is finished by two rocker arms. In arrange to go over a deterrent, the front wheels are constrained against the impediment by the raise wheels. The revolution of the front wheel at that point lifts the front of the vehicle up and over the obstacle. The center wheel is squeezed against the obstacle by the rear wheel and pulled against the impediment by the front, until it is lifted up and over. At last, the raise wheel is pulled over the obstacle by the front two wheels. Amid each wheel's traversal of the impediment, forward advance of the vehicle is moderated or totally stopped. These meanderers move gradually and climb over the impediments by having wheels lift each piece of the suspension over the impediment one parcel at a time. The start of rocker bogie suspension framework can be followed to the improvement of planetary rover, which is versatile robots, particularly planned to move on a planet surface. Early rovers were tele-operated, whereas later ones are completely independent, such as FIDO, Disclosure and as of late created Interest defaces investigation rover. The rovers required to be exceptionally strong and solid, because it must withstand tidy, solid winds, erosion and huge temperature changes beneath secretive conditions. Most of the rovers stay fueled by batteries which are energized by sun oriented boards amid the day present on their surface. The motion framework of rovers or the locomotion system remains significant to empower it to reach objective locales, conduct investigate, and collect information and to position itself concurring to the request. There are three primary sorts of rover motion created so distant i.e. wheeled, legged and caterpillar motion. The most contrast between the various plans of planetary robots lies within the sort of motion framework. Indeed after creating numerous legged and cross breed robots, most analysts still center on wheeled movement for rovers since of its train ease and preferences and among wheeled movement plan, the rocker bogie suspension system-based plan stay most favored. The antiquated FIDO rover and the Sojourner contain 6 autonomously controlled and driven wheels suspended from a rocker-bogie mechanism for greatest suspension and ground clearance. Rough Seven Wanderer includes a comparative suspension framework fair vary in front wheels. The Nano rover & Wanderer Rovers have four directed wheels suspended from two intruders & CRAB Wanderer utilizes two parallel bogie instruments on each side to overcome impediments and huge gaps. As distant as the starting inquire about is concerned, the computer program optimization looks for for an ideal within the obliged arrangement space given an starting arrangement and Dr. Li et al. determine a scientific show to generalize wanderer suspension parameters which characterize the geometry of the rocker-bogie framework. The purpose of advancement of rocker bogie suspension framework is to create a framework which minimizes the vitality utilization, the vertical uprooting of the rover's Middle of mass and its pitch point. In this inquire about, our endeavor is to exchange these major focal points inserted with the rocker bogie framework into customary vehicles in arrange to expel distress and complexities show in ordinary suspension framework in common and suspension framework of overwhelming vehicles in specific

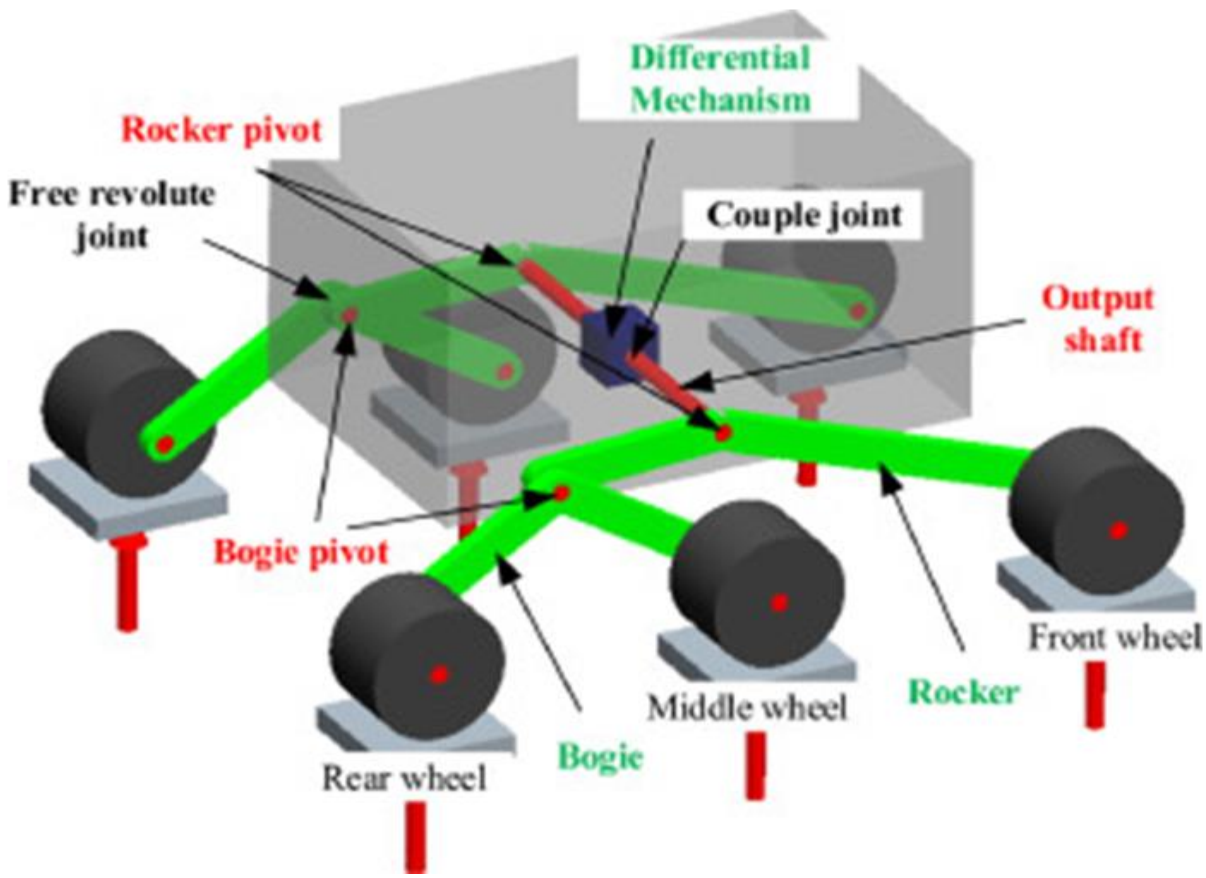

Figure 2.4: Rocker Bogie Mechanism(Links and Joints)
Figure 5

Figure 2.5: Rocker Bogie Mechanism(2)
Figure 6

The rocker-bogie design comprising of no springs and stub axles in each wheel which permits the chassis to climb over any impediments, such as rocks, trench, sand, etc. that are up to two fold the wheel's distance across in estimate whereas keeping all wheels on the ground most extreme time. As compared to any suspension framework, the tilt steadiness is constrained by the tallness of the Middle of gravity and the proposed framework has the same. Frameworks utilizing springs tend to tip more effectively as the stacked side yields amid deterrent course. Since it depends upon the centre of its weight, bogie suspension can withstand a tilt of at slightest 50 degrees in any heading without toppling which is the greatest advantage for any overwhelming stacking vehicle. The framework is planned to be executed in moo speed working vehicles such as overwhelming trucks, Bulldozers which works at moderate speed of around 10 centimeters per moment (3.9 in/s) so as to play down energetic stuns and noteworthy harm to the vehicle when surmounting sizable impediments.

Due to the presence of the differential and the centre of gravity, when one rocker moves up, the other goes down. The chassis plays imperative part to preserve the normal pitch point of both rockers by permitting both rockers to move as per the circumstance. If the acute design is considered then, one side of a rocker is fitted with a drive wheel and the other side is rotated to a bogie, due to which required motion and the degrees of freedom are achieved.

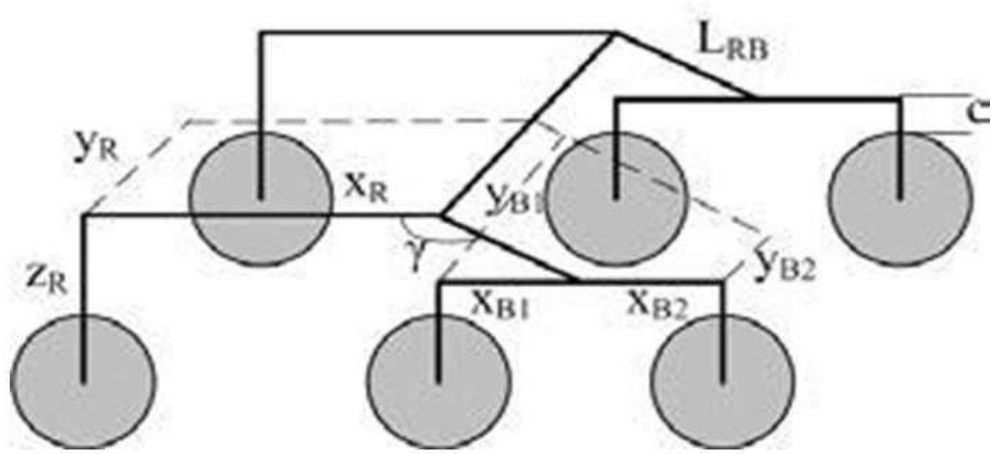

Figure 2.6: Rocker Bogie Mechanism (Positioning of wheels centres and angles)
Figure 7

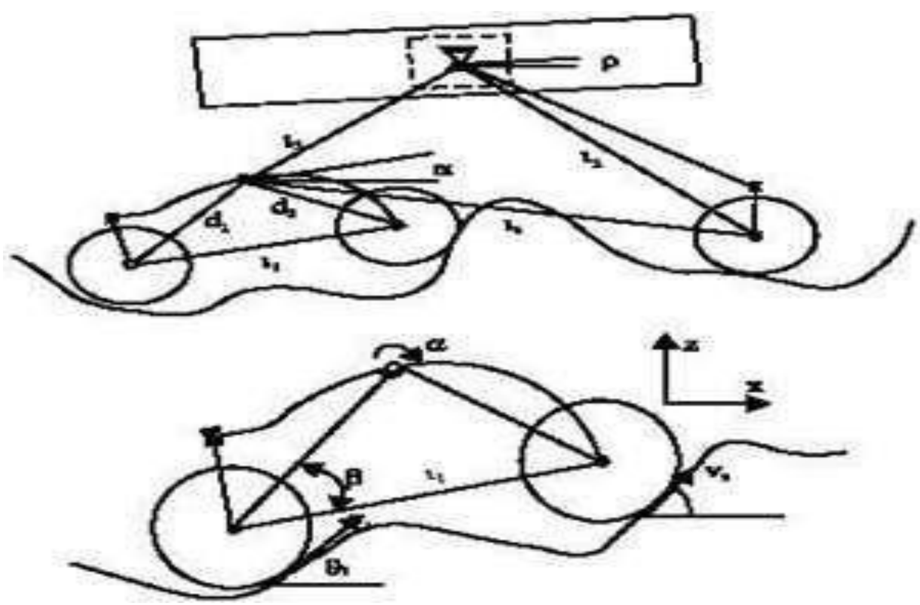

Figure 2.7: Rocker Bogie Mechanism(3)
Figure 8

2.5 Shrimp Rover

A shrimp rover is based on rocker bogie mechanism. It has a rhombus configuration, with a frontal and a rear wheel attached through a link. It is deployed for long range missions. The rover has 6 motorized wheels, two wheels are arranged on the bogie on each side. The front wheel of the rover is provided with a spring suspension that has ground contact all times during its motion. The steering of the rover is established by the steering motion of the front and the rear wheel and the speed difference between the bogie wheels. This permits for tall accuracy moves and indeed turning on the spot with least slip. The utilize of parallel articulations for the front wheel and the bogies empower to set a virtual middle of turn at the level of the wheel hub whereas keeping up a tall ground clearance. This guarantees greatest steadiness and climbing capacities indeed for moderately moo contact coefficients between the wheel and the ground. This rover is able to latently overcome unstructured deterrents of up to two times its wheel breadth. With this tall portability, this design is the idealize candidate for long extend planetary missions.

2.5.1 Mechanical design

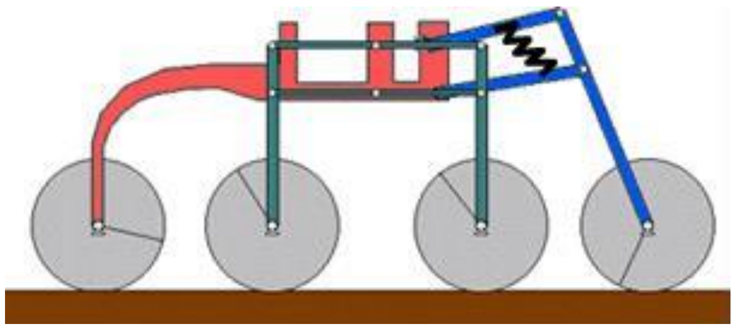

Figure 2.8:Shrimp rover(Basic Model)
Figure 9

Employing a rhombus setup, the rover has one wheel mounted on a fork within the front, one wheel within the raise and two bogies on each side. In spite of the fact that our bogies have a uncommon geometry, it is the same essential rule as utilized for a prepare suspension: a few of two wheels mounted on a support which can openly pivot around a central turn. The front fork has two parts: its spring suspension ensures ideal ground contact of all wheels at any time and its specific parallel instrument create an rise of the front wheel on the off chance that an deterrent is experienced.

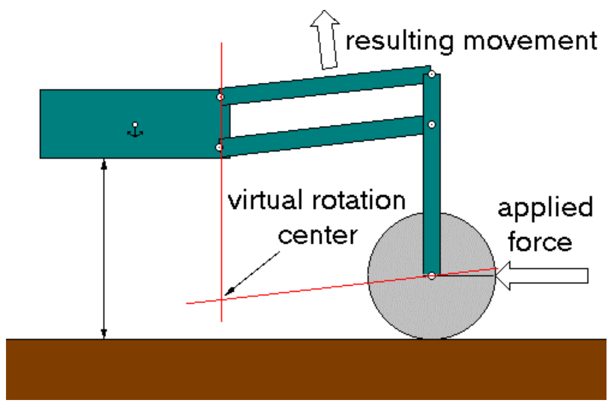

Figure 2.9: Shrimp rover Front Fork(Virtual Centre of Rotation)
Figure 10

The parallel design of the bogies and the spring suspended fork gives a non-hyper inactive arrangement for the 6 motorized wheels whereas keeping up a tall ground clearance. This insurrection most extreme soundness and flexibility as well as amazing climbing capacities. The controlling framework permits the rover to carry out a pure revolution indeed in these extraordinary circumstances.

2.5.1A BOGIES

The bogies are considered to be the primary and most important part of the rover. They give the sidelong stability during motion and movement of rover on exceptionally harsh landscape. To guarantee great flexibility of the bogie, it is essential to set the turn as low as conceivable and within the same time to keep a greatest ground clearance. This issue is solved by utilizing the parallel setup appeared on figure. 11 that bring the virtual center of turn of the bogie at the tallness of the wheel hub.

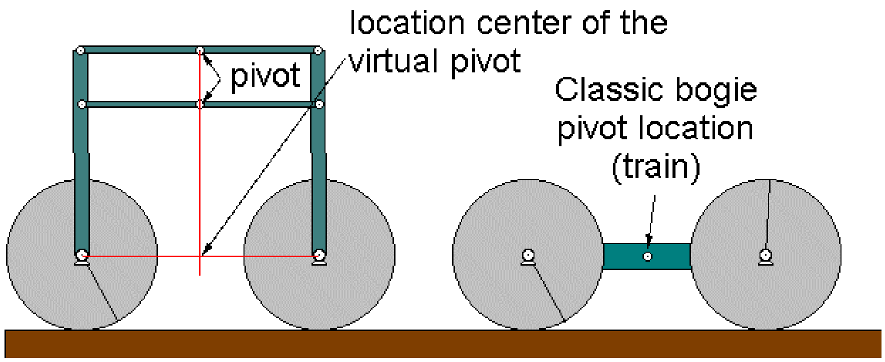

Figure 2.10: Explanation of the parallel bogie architecture

Figure 11

2.5.1 B FRONT FORK

The front fork provides overall stability to the rover’s structure.Figure 11 shows a trajectory traced by the front wheel with an instantaneous center of rotation situated under the wheel axis.This becomes helpful in order to overcome an obstacle. Front fork also provides maximum vertical amplitude to the wheel.

2.5.2 STEERING

The steering of the rover is established by the synchronizing steering of the front and the rear wheels and the speed difference between the bogie wheels.Due to this high precision movements are caused and the turning is possible even in the places with minimum slip.

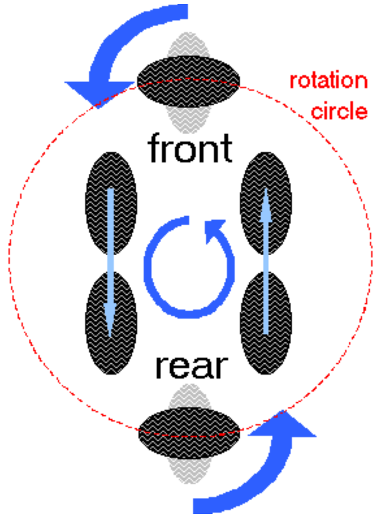

Figure 2.11: Configuration of the wheels on ground

Figure 12

2.7 Evaluation of existing Mechanism: Decision Matrix Analysis

Comparison of various properties of a shrimp rover with other wheeled rovers is generated with the help of Weighted Decision Matrix.

Weighted Decision Matrix is created after analyzing various properties of different wheeled rovers is shown in the table. This table is called Weighted decision Matrix and it provides a comparative analysis constructed over the literature review for various parameters of different rovers. It is evident that Shrimp by far is the most optimal design among other rover designs due to its various abilities, passive nature, and low power consumption.

Parameters	Category Weight	Spacecat	Athelete	Zoe	Impass	Chaos	Shrimp	Rocker Boggie	
Suspension	5	1	3	3	3	4	4	4	
Obstacle	4	3	2	3	3	2	4	4	
Control	5	4	3	3	3	3	5	4	
Size	3	2	3	2	2	3	3	3	
Power	3	1	2	2	2	2	3	3	
Topple	2	2	1	1	1	2	2	2	
Payload	2	2	1	1	1	2	2	2	
Speed	2	2	1	1	1	1	2	2	
Cost	4	4	2	3	4	3	3	3	
Total	30(45)	21	18	19	20	22	28	27	
Rank		4	7	6	5	3	1	2	

Chapter 3 Methodolgy

3.1 Kinematic Model

The kinematic model of the shrimp rover was proposed by Siegwart et al. It is based on the four bar mechanism as is shown in fig 3.1. The links c and d are connected through four bar mechanism to links b and d, where b is the pivot link which guarantees rotational motion of the front fork with the rotation angle θ. The most significant is the center axis point P(x,y) located at a distance h from d and this center point traverses a trajectory depending upon the link lengths and the angles of the four bar mechanism

Figure:3.1 Kinematic model of the front fork

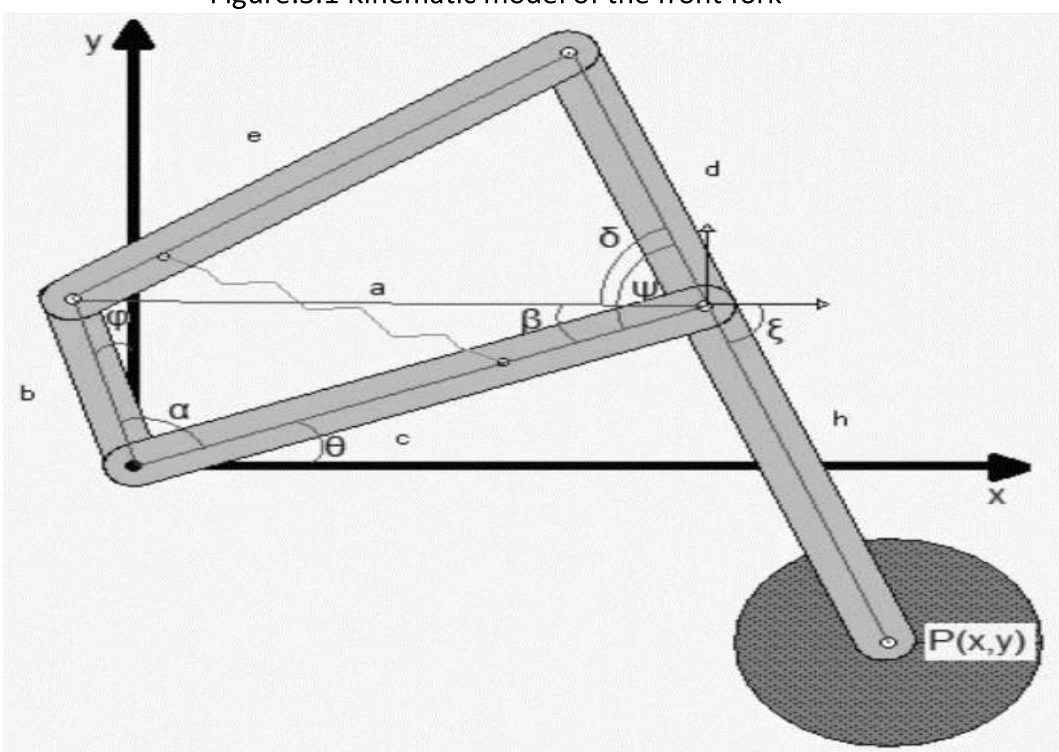

Figure 13

The trajectory traversed by the centre of the wheel axis is shown in fig3.2 .The horizontal axis of the graph defines the height of the wheel axis with reference to the horizontal plan. This capability is required to ensure a good stability when the rover is on a convex or a concave ground like obstacle in unstructured environment. Using this method of optimization different values of length for the front fork are tested and the value with the maximum amplitude is used to overcome maximum possible obstacles based on this model's dimensions and capacity restricted by wheel size.

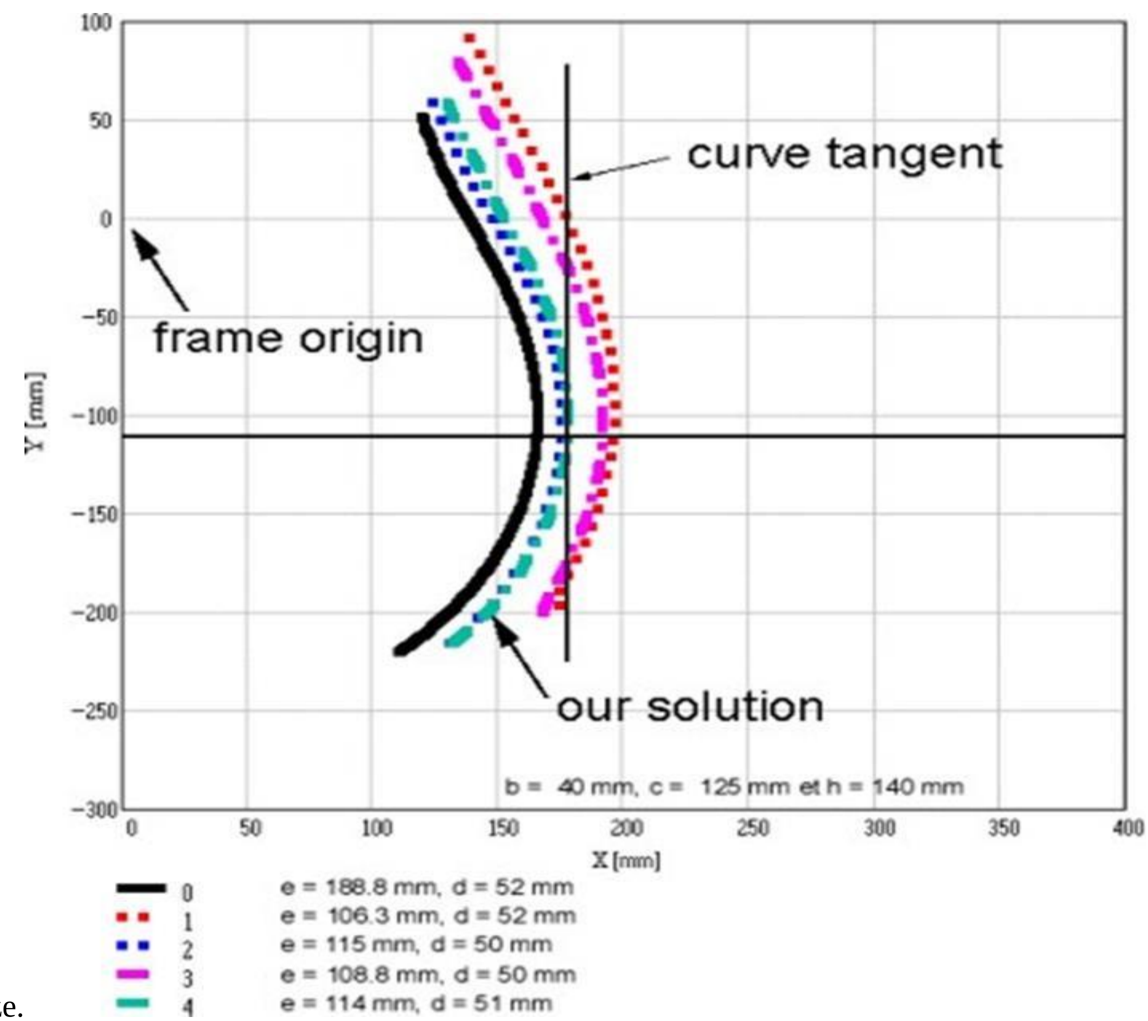

Figure: 3.2 Trajectory Traversed by the wheel axis centre of the front fork

Figure 14

The modified design of a Shrimp Rover. The kinematic model of the front fork is shown i while its configuration is shown

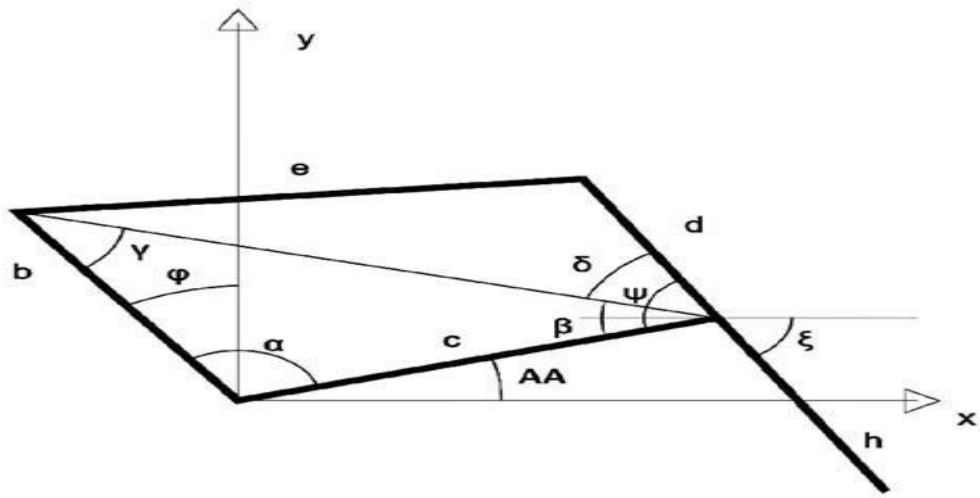

Figure: 3.3 Modified kinematic Model of front fork

Figure 15

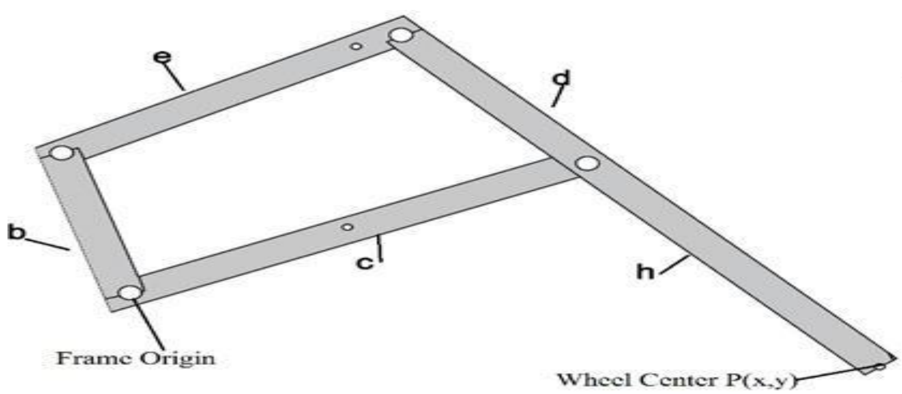

Figure 3.4 Modified kinematic Model of front fork with link lengths (4-bar Mechanism)

Figure 16

The parametric equations of ξ, α and ψ as function of the angle AA are given in Eq. 1, 2 and 3

$$\alpha\,(AA) = \frac{\pi}{2} - AA + \phi \quad (1)$$

$$\psi(AA) = acos\left[\frac{c - bcos[\alpha(AA)]}{\sqrt{b^2+c^2-2bccos[\alpha(AA)]}}\right] + acos\left[\frac{b^2+c^2-2bccos[\alpha(AA)]+d^2-e^2}{2d\sqrt{b^2+c^2-2bccos[\alpha(AA)]}}\right] \quad (2)$$

$$\mathcal{E}(AA) = AA - \psi(AA) \quad (3)$$

The point P(x,y) is the center of the wheel axis and the angle AA is the rotation angle of the front fork. Moreover, with the above equations, the movement of the wheel center P can be established as a function of the angle AA as given in Eq. 4:

$$P(AA) = \begin{pmatrix} (ccos(AA) + hcos[\mathcal{E}(AA)]) \\ csin(AA) - hsin[\mathcal{E}(AA)] \end{pmatrix} \quad (4)$$

Where

$$Px \;=\; c\,cos(AA) + h\,cos[\mathcal{E}(AA)] \quad (4a)$$

$$Py = \; c\,sin(AA) - \,h\,sin[\mathcal{E}(AA)] \quad (4b)$$

Next, with the help of the obtained equations of the trajectory of the center point P, the center point equations for the bogie wheel centers and the rear wheel were also established, and the complete kinematic model of the rover was generated. The front fork, here, is a 4-bar mechanism and forward kinematics is applied in order to resolve the angles and link lengths to find the equation for the center of the axis of the front fork's wheel.

Fig.3.3 shows the complete illustration of the kinematic model of the rover generated with the help of laws of forward kinematics.

$$\alpha\,(AA_b) = \frac{\pi}{2} - AA_b + \phi \qquad (4c)$$

$$\psi(AA_b) = acos\left[\frac{c_b - b_b cos[\alpha(AA_b)]}{\sqrt{{b_b}^2 + {c_b}^2 - 2b_b c_b cos[\alpha(AA_b)]}}\right] + acos\left[\frac{{b_b}^2 + {c_b}^2 - 2b_b c_b cos[\alpha(AA_b)] + {d_b}^2 - {e_b}^2}{2d_b\sqrt{{b_b}^2 + {c_b}^2 - 2b_b c_b cos[\alpha(AA_b)]}}\right] \qquad (4d)$$

$$\mathcal{E}(AA_b) = AA_b - \psi(AA_b) \qquad (4e)$$

$$P(AA_b) = \begin{pmatrix} (c_b cos(AA_b) + h_b cos[\mathcal{E}(AA_b)]) \\ c_b sin(AA_b) - h_b sin[\mathcal{E}(AA_b)] \end{pmatrix} \qquad (4f)$$

With the above kinematic equations of the rover the complete kinematic model of the rover is generated as shown in the figure 3.5

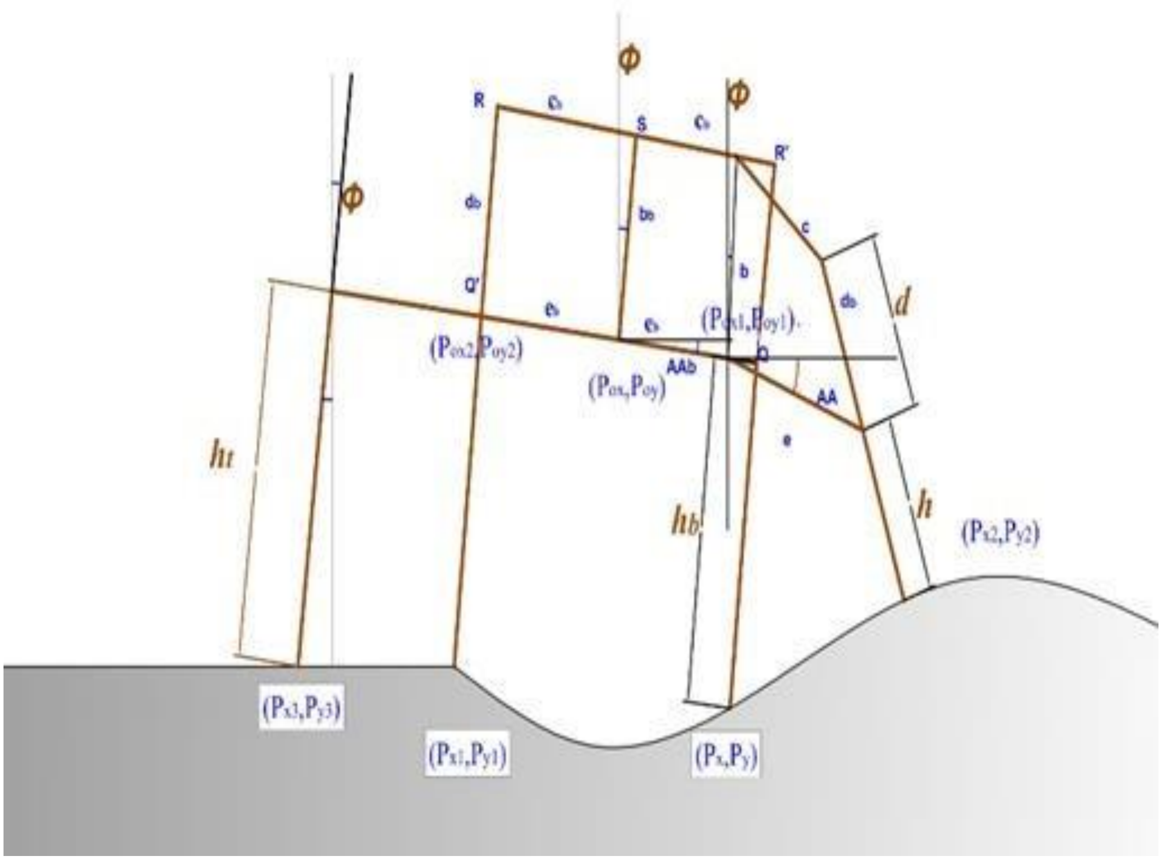

Figure 3.5 Complete Modified kinematic Model of Shrimp Rover

Figure 17

3.1.1 Bogie Mathematical Modelling

For the bogies the angle of rotation becomes AAb and all the parametric equations are deduced from this angle of rotation

The parametric equations of ξ, α and ψ as function of the angle AA_b are given in Eq. 1, 2 and 3:

Taking the pivot point for bogie (P_{ox},P_{oy}) in the global coordinate system as the reference point, (please refer to Fig. 3.5), the kinematic equations for the point (P_{ox} , P_{oy}) is shown in Eq (4g) :

$$P_o\,(AA_b) = \begin{pmatrix} \frac{\pi}{2} - c\ _b cos(AA_b) \\ (h_b - 1) - c\ _b sin(AA_b) \end{pmatrix} \qquad (4g)$$

The equations of the point (P_{ox} , P_{oy}) for the front fork are given below

$$P_o(AA) = \begin{pmatrix} P_o(AA_{b(x)}) + 0.5 * cos(\phi) \\ P_o(AA_{b(y)}) + 0.5 * sin(\phi) \end{pmatrix} \qquad (4h)$$

With the help of these equations for the pivot of the front fork and boggies the equations for the link lengths were generated

3.1.2 Front Fork Links Mathematical Modelling

$$\alpha_{1=} \frac{\pi}{2} - AA + \phi \qquad (5A)$$

$$\beta_{1=}\ acos\left(\frac{c - b * \cos\alpha_1}{a_1}\right) \quad (5B)$$

$$\delta_1 = acos\frac{a_1^2 + d_1^2 - e_1}{2 * d_1 * a_1} \qquad (5C)$$

$$\psi_1 = \ \beta_1 + \ \delta_1 \qquad (5D)$$

$$\mathcal{E}_1 = \ \psi_1 - AA \qquad (5E)$$

Bogie Link Equations

$$\alpha_{b=} \frac{\pi}{2} - AA_b + \phi \qquad (6A)$$

$$\beta_{\;=}\; acos\left(\frac{c_b - b_b * \cos\alpha}{a_b}\right) \qquad (6B)$$

$$\delta = acos\left(\frac{a_b^2 + d_b^2 - {e_b}^2}{2 * d_b * a_b}\right) \qquad (6C)$$

$$\psi = \beta + \delta \qquad (6D)$$

$$\mathcal{E} = \psi - AA_b \qquad (6E)$$

$$a_b = \sqrt{b_b^2 + c_b^2 - 2 * b_b * c_b * cos\alpha} \qquad (6F)$$

3.1.3 Objective Function

The objective function is created on MATLAB with the help of the geometry and the kinematic model as described in the last section. This objective function is used for the sinusoidal wave and the straight line.

The kinematic model of the rover was generated on MATLAB in order to move this rover on two kind of trajectories: straight line and a sinusoidal wave. The centers of the wheel axis were brought into contact with the trajectory created using (DIST) as the Objective function that finds the point of contact between the wheel axis center and the trajectory as the rover moves.

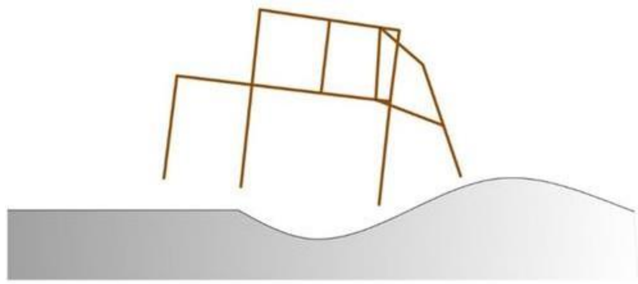

Figure: 3.6 The un-converged rover legs on the terrain

Figure 18

The following steps were adopted to optimize the objective function:

Function: ObjectiveFunction(x_o)

Input $x_o = [AA \quad AA_b \quad p_{oy} \quad \phi]'$

Output: dist: effective total distance between all rover wheels and target terrain

1: Get link lengths as global variables: b, c, d, h, e, b_b, c_b, d_b, h_b, e_b, c_t, h_t

2: Compute angles $\alpha, \beta, \delta, \psi, \epsilon$ for front fork and boogie using (i), (ii), (iii), (iv)

3: Compute x and y positions (p_x, p_y) of wheels of front fork, boogie and rear wheel

4: Define trial terrain: $y(x) = 0 \quad ; \quad 0 < x < 15$

$$y(x) = -0.4 \sin \frac{2\pi x}{15} \quad ; \quad 15 < x < 50$$

5: Compute minimum distance between individual wheels and terrain: d_1, d_2, d_3, d_4

$$d_i = \min \sqrt{(x - p_{xi})^2 + (y - p_{yi})^2}$$

6: Add penalties if any of the wheels are inside the terrain

7: Add penalties if d_1, d_2, d_3, d_4 has imaginary components

4

8: Return $dist = \sum_{i=1} d_i$

Algorithm: Generate rover kinetic positions passing over trial terrain, between $0 < p_{ox} < 50$

1: Define link lengths as global variables: b, c, d, h, e, b_b, c_b, d_b, h_b, e_b, c_t, h_t

2: Initialize $x_o = [AA \quad AA_b \quad p_{oy} \quad \phi]' = [0 \quad 0 \quad 0 \quad 0]'$

3: Set lower bounds and upper bounds on paramaters in x_o

3: **for** $p_{ox} = 0\ to\ 50\ \boldsymbol{do}$

4: $\quad x_o^* = \underset{x_o}{\text{argmin}}\ \text{ObjectiveFunction}(x_o)$

5: $\quad$ Store and Update guess value: $x_o = x^*_o$

6: **end for**

7: Plot results

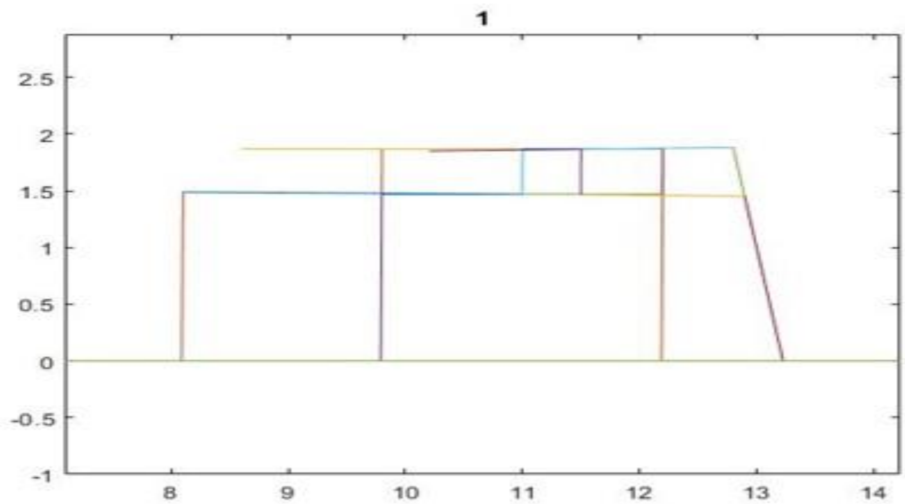

Figure:3.7 Rover Converged rover on straight line terrain

Figure 19

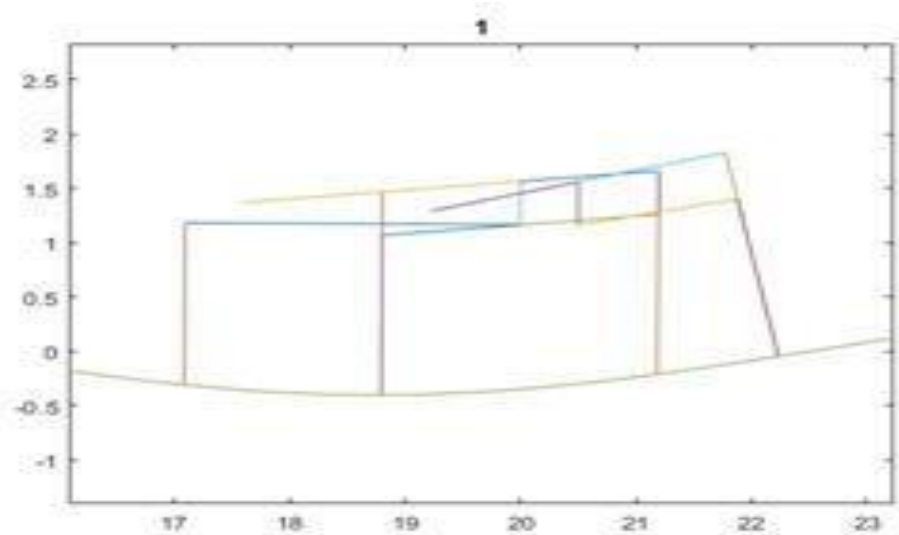

Figure:3.8 Rover Converged rover on Trough

Figure 20

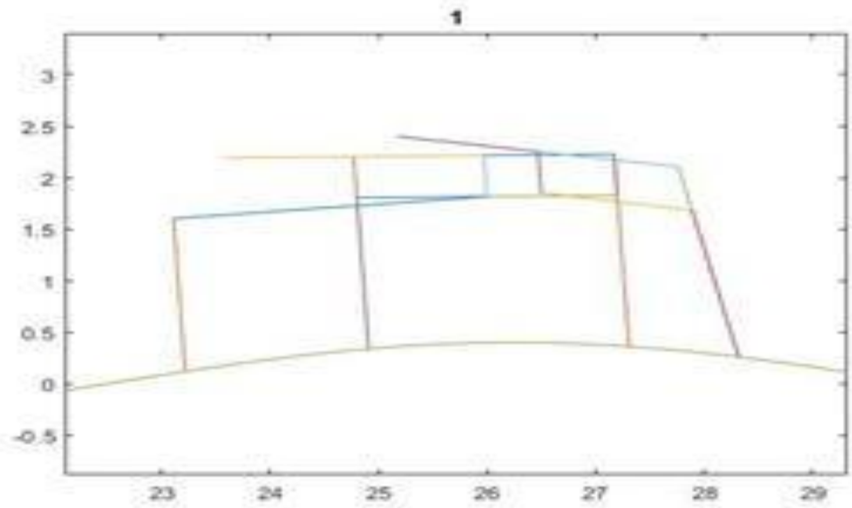

Figure:3.9 Rover Converged rover on Crest
Figure 21

3.1.4 Roughness Parameters

In order to solve fundamental problems like contact deformation, heat and electric current conduction, friction, tightness of contact joints and positional accuracy, the evaluation of surface roughness is one of the most important criteria. Many experimental and theoretical investigations have been done to find surface roughness for the past many years. It is not possible to understand the real surface geometry due to its complicated nature that it is impossible for a finite number of parameters to provide all information about it. By increasing the number of parameters, the accuracy of the description can be improved. For this reason, new parameters are introduced for surface evaluation. There are three categories of the of surface roughness based on its functionality. These include amplitude parameters, hybrid parameters and spacing parameters.

It is possible to calculate the roughness parameters in two-dimensional or three-dimensional forms. In science and engineering, the 2D profile is more often used for the past 50 years. Quite recently ,3D surface analysis has become more popular due to its increased requirement. Due to the increasing importance of 3D surface topography in various scientific and engineering applications, there are various publications on this topic.

Instead of single line,3D roughness parameters are calculated for an entire area. Therefore, the specific region from the surface to be measured is divided into a variety of parts in order to measure the 3D roughness parameters. Such sections are indicative of many consequent surface profiles. The 2D roughness parameters are then determined separately for each section, and the average for each section is taken.

3.1.4a Arithmetic average height (R_a)

This parameter is also known as center line average (CLA) and its is universally used roughness parameter for the general quality control. It is defined as the average absolute deviation in order to find roughness irregularities from the mean line over a single sampling length. This parameter can be defined easily and it can be measured easily and thus it provides a good estimation of variations in height. However no information about the wavelength or small changes in profile are provided through it.

3.1.4b Root mean square roughness (R_q)

Root mean square roughness is also known as RMS. Since this parameter is a representation of the standard deviation of the surface heights distribution thus it is considered to be an important parameter that explains the surface roughness with the help of y statistical methods. This parameter is considered to be more sensitive than arithmetic average height(Ra) to a large deviation from the mean line

$$R_a = \frac{1}{l}\int_0^l |y(x)|\,dx \qquad (7a)$$

$$R_a = \frac{1}{n}\sum_{i=1}^{n} |y_i| \qquad (7b)$$

The mathematical formulation of this parameter is:

$$R_q = \sqrt{\frac{1}{l}\int_0^1 \{y(x)\}^2 dx} \qquad (7c)$$

$$R_q = \sqrt{\frac{1}{n}\sum_{i=1}^{n} {y_i}^2} \qquad (7d)$$

The line that divides the profile so that the sum of the squares of the deviations of the profile height from this line becomes zero is called the RMS mean line.

3.1.4 c Ten-point height (R_z)

This parameter reflects the sensitivity to occasional high peaks or deep valleys as compared to Ra. There are two methods by which it is defined. ISO system International has defined this parameter as the height difference between the average of the 5 highest peaks and the 5 lowest valleys taken along the length of assessment of the profile.

In the German DIN system, this parameter is defined as the average value of the sum of the 5 highest and 5 lowest peaks and valleys taken along the length of the profile. Mathematically it is defined as

$$R_{z(ISO)} = \frac{1}{n}\left(\sum_{i=1}^{n} p_i + \sum_{i=1}^{n} v_i\right) \qquad (7e)$$

where n is considered the number of samples along the length of the profile.
The above set of equations were used in order to create the profile with random nature and to settle the coefficients of roughness estimates of the profile. The above equations are used in the objective function where the conversion of the Sinusoidal wave to the random rough terrain is done with the help of the values provided by these constants.

3.14d.Pseudocode for the creation of Objective function on MATLAB

ObjectiveFunction(x_o)

Input $x_o = [AA \quad AA_b \quad p_{oy} \quad \phi]'$

Output: dist: effective total distance between all rover wheels and target terrain

1: Get link lengths as global variables: $\mathrm{b, c, d, h, e, b_b}, c_b, \mathrm{d_b, h_b, e_b, c_t, h_t}$

2: Compute angles $\alpha, \beta, \delta, \psi, \epsilon$ for front fork and boogie using (i), (ii), (iii), (iv)

3: Compute x and y positions (p_x, p_y) of wheels of front fork, boogie and rear wheel

4: Define trial terrain: $y(x) = 0 \quad ; \quad 0 < x < 15$

$$y(x) = yy\,; \quad 15 < x < 50$$

5: Compute minimum distance between individual wheels and terrain: d_1, d_2, d_3, d_4

$$d_i = \min\sqrt{(x - p_{xi})^2 + (y - p_{yi})^2}$$

6: Add penalties if any of the wheels are inside the terrain

7: Add penalties if d_1, d_2, d_3, d_4 has imaginary components

8: Return $dist = \sum_{i=1}^{4} d_i$

In the above objective function, "Dist" is the output which is the effective total distance between the wheel's centres and the terrain. It has 4 inputs that include the rotation angle of the front fork and bogies, the pitch angle and the motion of the rover along the Y-axis.

The above objective function "Dist" which is the effective distance between the rover's wheels and the points on the terrain is called by the algorithm as shown below:

3.4e.Algorithm:

Generate rover kinetic positions passing over trial terrain, between $0 < p_{ox} < 50$

1: Define link lengths as global variables: $\mathrm{b, c, d, h, e, b_b}, c_b, \mathrm{d_b, h_b, e_b, c_t, h_t}$

2: Initialize $x_o = [AA \quad AA_b \quad p_{oy} \quad \phi]' = [0 \quad 0 \quad 0 \quad 0]'$

3: Set lower bounds and upper bounds on paramaters in x_o

3: **for** $p_{ox} = 0$ to 50 ***do***

4: $\quad x_o^* = \underset{x_o}{\operatorname{argmin}} \text{ ObjectiveFunction}(x_o)$

5: $\quad$ Store and Update guess value: $x_o = x_o^*$

6: **end for**

7: Plot results

The above algorithm calls the Objective Function “Dist” and then with the help of a minimization argument (argmin)it minimizes the objective function within certain constraints with an initial guess value provided to “x_o”. Thus, the rover is brought into contact with the terrain at all discrete points as it moves over the terrain with a value of roughness. The values of the pitch angle ϕ are saved for all points on the terrain and then retrieved from the memory in order to be optimized through a robust optimization scheme.

3.1.5 Optimization of the Pitch Angle of platform:

Taguchi DOE has been the first effectively utilized strategy which can choose the driving combinations of levels of plan variables and interaction impacts (Peace, 1993). It isn't because it were essential, practical and strong for decreasing gotten and moving forward quality, but as well diminishes the number of tests basically compared to other DOE techniques (Roy, 2010). In show disdain toward of the reality that quality characteristics like flexible quality, ductility, dimensional precision, surface unpleasantness, era time, etc. are the first basic concerns, but there are still no perfect conditions for all sorts of materials and parts as there persistently various Taguchi plans are based on Factorial plans (2-level plans and Placket & Burman plans, as well as factorial plans with more than 2 levels). Taguchi’s L8 arrange, for outline, may be a standard 23 (8-run) factorial arrangement.

Taguchi's plans are customarily exceedingly fractionated, which makes them uncommonly appealing to pros. Doing a half-fraction, quarter-fraction or eighth division of a full factorial arrange inconceivably decreases costs and time required for a laid out test.

There are a number of issues related with the fractionated plan and one of them is that few intelligent are more affected with other effects. The most vital thing for the implementation of Taguchi is the understanding of the foremost critical intuitive of the factors.

Numerous Taguchi plans are based on Factorial plans (2-level plans and Plackett & Burman plans, as well as factorial plans with more than 2 levels). Taguchi’s L8 arrange, for case, may be a standard 23 (8-run) factorial plan. Taguchi's plans are ordinarily exceedingly fractionated, which makes them exceptionally alluring to specialists. Doing a half-fraction, quarter-fraction or eighth division of a full factorial plan incredibly diminishes costs and time required for a planned explore.

The downside of a fractionated plan is that a few intuitive may be bewildered with other impacts. It is imperative to consider carefully the part of potential confounders and assumed names. Disappointment to require account of such perplexed impacts can result in erroneous conclusions and misunderstandings. When employing a Taguchi plan, one ought to figure which interactions are more significant as compared to others—even some time recently any try is performed. Taguchi made a few linear charts to assist professionals select the interactions they need to think about, based on their earlier prepare knowledge.

3.1.5a An orthogonal Array

$L_9(3^4)$ Orthogonal Array		
	Independent Variables	Performance Parameter Value

Experiment #	Variable 1	Variable 2	Variable 3	Variable 4	
1	1	1	1	1	P1
2	1	2	2	2	P2
3	1	3	3	3	P3
4	2	1	2	3	P4
	2	2	3	1	P5
6	2	3	1	2	P6
7	3	1	3	2	P7
8	3	2	1	3	P8
9	3	3	2	1	P9

Table 3.1.5a Orthogonal array

The Table 3.1.5a appears an L9 orthogonal array. There are completely 9 tests to be conducted and each try is based on the combination of level values as appeared within the table. For case, the third test is conducted by keeping the free plan variable 1 at level 1, variable 2 at level 3, variable 3 at level 3, and variable 4 at level 3.

3.1.5 B Important Properties of the Orthogonal Array

Following are the properties of the orthogonal array. These are the reasons for which the number of experiments to be conducted are considerably reduced using Taguchi DOE:

1. All independent variables have a vertical column beneath them which have special settings for the combination or levels. For an equal no of

times all the level settings appear. Under variable 4, level 1, level 2 and level 3 appear thrice for the L9 array. This property is known as balancing property of the orthogonal arrays.

2. In order to conduct experiments, all values at different levels of independent variables are used.

3. The grouping of level values for conducting the tests might not be changed. This implies one cannot conduct test 1 with variable 1, level 2 setup and explore 4 with variable 1, level 1 setup. The reason for this can be that the cluster of each calculate columns is commonly orthogonal to any other column of level values. The internal item of vectors corresponding to weights is zero. In case the over 3 levels are normalized between -1 and 1, at that point the weighing components for level 1, level 2, level 3 are -1, 1 individually. Consequently, the inward item of weighing variables of autonomous variable 1 and autonomous variable 3 would be

$$(-1 * -1+-1*0+-1*1)+(0*0+0*1+0*-1)+(1*0+1*1+1*-1)=0$$

3.1.5c Minimum Number of Experiments to be conducted

The plan of tests utilizing the orthogonal cluster is, in most cases, proficient when compared to numerous other statistical plans. The least number of tests that are required to conduct the Taguchi strategy can be calculated based on the degrees of flexibility approach.

$$N_{Taguchi} = 1 + \sum_{i=1}^{NV} (L_i - 1) \qquad (8a)$$

For illustration, in case of 8 free factors consider having 1 free variable with 2 levels and remaining 7 free factors with 3 levels (L18 orthogonal cluster) , the least number of tests required based on the over condition is 16. Since of the adjusting property of the orthogonal arrays, the whole number of tests should be numerous of 2 and 3. Thus the number of experiments for the above case is 18.

3.1.5 d Different assumptions for Taguchi DOE

The added substance presumption infers that the individual or primary impacts of the autonomous factors on execution parameter are divisible. Beneath this presumption, the impact of each factor can be straight, quadratic or of higher order, but the show accept that there exists no cross-product impacts (intelligent) among the person components. Meaning the impact of free variable 1 on execution parameter does not depend on the diverse level settings of any other free factors and bad habit versa. On the off chance that at any time, this presumption is violated, then all the main effects lose their additivity, and it is possible for different factors to interact called variables

3.1.5e Designing of a (Simulation) experiment

This process has the following steps:

1. Independent variables selection
2. For each independent variable, level settings selection.
3. Orthogonal array selection
4. Each column is assigned independent variable

5. To conduct the various experiments/Simulations
6. Analysing the data
7. Conclusion or Inference

Following section gives the details of all the steps written above.

3.1.5f Selection of the independent variables:

In order to conduct the experiment, the information of the product/process beneath examination is of prime significance for distinguishing the components likely to impact the result. For compiling a comprehensive list of variables, the input to the test is for the most part gotten from all the individuals included within the venture.

3.1.5f1 Deciding the no of levels for orthogonal array

After choosing the independent variables, the number of levels for each variable is chosen. The choice of number of levels depends on how the execution parameter is influenced due to distinctive level settings. If the execution parameter could be a direct work of the free variable, at that point the number of level setting should be 2. Be that as it may, on the off chance that the independent variable isn't straightly related, at that point one seems go for 3, 4 or higher levels depending on whether the relationship is quadratic, cubic or higher order. In the nonattendance of correct nature of relationship between the free variable and the execution parameter, one may select 2 level settings. After analyzing the test information, one can choose whether the presumption of level setting is right or not based on the percent commitment and the mistake calculations

3.1.5g Selecting the Orthogonal Array

For the selection of the orthogonal array, the slightest number of tests to be conducted may well be settled based on the complete number of degrees of flexibility show within the consider. The slightest number of tests that must be run to think approximately the components can be more than the generally degrees of opportunity available. In counting the total degrees of opportunity, the analyst commits 1 degree of adaptability to the by and large unfeeling of the response beneath think around. The number of degrees of adaptability related with each figure underneath consider breaks indeed with one less than the number of levels available for that calculate. In this way the complete degrees of opportunity without interaction affect is 1 +. For case, in case of 11 independent components, each having 2 levels, the complete degrees of adaptability is 12. Along these lines the chosen orthogonal cluster might have at smallest 12 tests. An L12 orthogonal fulfills this need.

3.1.5h Columns are assigned Independent Variables:

All the variables are arranged in a vertical column and are ordered conveniently. In case of blended level factors and interaction between factors, the factors are to be relegated at right columns as stipulated by the orthogonal cluster. At long last, sometime recently conducting the test, the genuine level values of each plan variable might be chosen. It should be famous that the noteworthiness and the percent commitment of the free variable’s changes depending on the level values allotted. It is the designer’s duty to set legitimate level values

3.1.5i Conducting the Simulations/Runs/Experiment

After the selection of the orthogonal array, the tests are conducted as per the level combinations. It is vital that all the tests be conducted. The interaction columns and dummy variable columns might not be considered for conducting the test but are required whereas dissecting the information to get it the interaction impact. The execution parameter beneath think about is famous down for each try to conduct the affectability investigation or the sensitivity analysis.

3.1.5j Analysis of the data

Since each experiment is the combination of different factor levels, it is essential to segregate the individual effect of independent variables. This will be done by summing up the execution parameter values for the comparing level settings. For example, in arrange to discover out the most impact of level 1 setting of the autonomous variable 2, total of the execution parameter values of the tests 1, 4 and 7. So also for level 2, total of the exploratory comes about of 2, 5 and 7 and so on. Once the cruel esteem of each level of a specific free variable is calculated, the whole of square of deviation of each of the cruel esteem from the fantastic cruel esteem is calculated. This entirety of square deviation of a specific variable shows whether the execution parameter is delicate to the alter in level setting. In the event that the whole of square deviation is near to zero or inconsequential, one may conclude that the plan factors isn't impacting the execution of the method. In other words, by conducting the affectability investigation, and performing investigation of change (ANOVA).

3.1.5k Inference

With the help of this experimental analysis, we deduce that the performance parameter is influenced more by the higher value of the sum of square. It is also possible to calculate the ratio of independent sum of square of an independent variable to the total sum of squares of all variables. Through this ratio one can find the percentage contribution on the performance parameter by the independent variable.

With the help of this methodology it is possible to find the near optimal solution of problems.

3.1.5l Robust Design

In many engineering processes it is difficult to control the effects of noise on the product. With the help of a robust design these effects are minimized, thus Taguchi DOE is considered much effective to optimize the performance characteristics and to enhance them with the help of ANOVA and S/N ratio criteria. For the optimization of the pitch angle the Taguchi DOE with the above-mentioned steps were followed on MINITAB.MINITAB is a statistical tool in order to apply different statistical techniques on a given problem. Taguchi DOE is one technique that can be used on MINITAB along with various settings of factors and Orthogonal array.

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3.2Taguchi DOE for the Optimized Rover pitch angle of the Platform

3.2.1 Identification of process parameters and relevant settings:

Following are the settings done for the identification of the process parameters, these link lengths were regarded as the process parameters for minimization of pitch angle.3 levels were selected, and the relative values of theses 3 levels were suggested through the literature. It was seen that if the no of levels are increased than 3,the effectiveness is unaltered.

Sr. No.	Control factors	Unit	Level 1 (L1)	Level 2 (L2)	Level 2 (L3)
1	Front fork left link (b)	m	0.10	0.40	0.70
2	Front fork horizontal lower link (c)	m	1.05	1.40	1.85
3	Front fork horizontal upper link (e)	m	1.00	1.30	1.60
4	Front fork right link (d)	m	0.10	0.44	0.62
5	Front fork Leg (h)	m	1.30	1.49	1.92
6	Bogie leg (hb)	m	1.28	1.47	1.90
7	Rear horizontal link (ct)	m	2.75	2.9	2.961
8	Rear leg (ht)	m	1.30	1.49	1.92

3.2.2 Orthogonal Array Selection :

With the help of the control factors settings, and the number of levels decided, an orthogonal array is established with 8 factors,3 levels and 27 simulation experiments. All control factors are considered as independent and there is no interaction between them.

***3.2.2A Orthogonal array (L27) for Link Length DOE with 3 levels**

Combinations			Control Factors					
	Front fork left link (b) (A)	Fronk fork lower horizontal link (c) (B)	Fronk fork upper horizontal link (e) (C)	Front fork right link(d) (D)	Front fork leg (h) (E)	Bogie leg (hb) (F)	Rear horizontal link (ct) (G)	Rear leg (ht) (H)
1	0.10	1.05	1.00	0.10	1.30	1.28	2.75	1.30
2	0.10	1.05	1.00	0.10	1.49	1.47	2.9	1.49
3	0.10	1.05	1.00	0.10	1.92	1.90	2.96	1.92
4	0.10	1.40	1.30	0.44	1.30	1.28	2.75	1.49
5	0.10	1.40	1.30	0.44	1.49	1.47	2.9	1.92
6	0.10	1.40	1.30	0.44	1.92	1.90	2.96	1.30
7	0.10	1.85	1.60	0.62	1.30	1.28	2.75	1.92
8	0.10	1.85	1.60	0.62	1.49	1.47	2.9	1.30
9	0.10	1.85	1.60	0.62	1.92	1.90	2.96	1.49
10	0.40	1.05	1.30	0.62	1.30	1.47	2.96	1.30
11	0.40	1.05	1.30	0.62	1.49	1.90	2.75	1.49
12	0.40	1.05	1.30	0.62	1.92	1.28	2.9	1.92
13	0.40	1.40	1.60	0.10	1.30	1.47	2.96	1.49
14	0.40	1.40	1.60	0.10	1.49	1.90	2.75	1.92
15	0.40	1.40	1.60	0.10	1.92	1.28	2.9	1.30
16	0.40	1.85	1.00	0.44	1.30	1.47	2.96	1.92
17	0.40	1.85	1.00	0.44	1.49	1.90	2.75	1.30
18	0.40	1.85	1.00	0.44	1.49	1.90	2.75	1.30
19	0.70	1.05	1.60	0.44	1.30	1.90	2.9	1.30
20	0.70	1.05	1.60	0.44	1.49	1.28	2.96	1.49

21	0.70	1.05	1.60	0.44	1.92	1.47	2.75	1.92
22	0.70	1.40	1.00	0.62	1.30	1.90	2.9	1.49
23	0.70	1.40	1.00	0.62	1.49	1.20	2.96	1.92
24	0.70	1.40	1.00	0.62	1.92	1.47	2.75	1.30
25	0.70	1.85	1.30	0.10	1.30	1.90	2.9	1.92
26	0.70	1.85	1.30	0.10	1.49	1.28	2.96	1.30
27	0.70	1.85	1.30	0.10	1.92	1.47	2.75	1.49

3.2.2B Orthogonal Array with Pitch angles

Combinations	Control Factors								
	Front fork left link (b) (A)	Fronk fork lower horizontal link (c) (B)	Fronk fork upper horizontal link (e) (C)	Front fork right link(d) (D)	Front fork leg (h) (E)	Bogie leg (hb) (F)	Rear horizontal link (ct) (G)	Rear leg (ht) (H)	Pitch Angle $\phi - \phi_o$
1	0.10	1.05	1.00	0.10	1.30	1.28	2.75	1.30	0.001903
2	0.10	1.05	1.00	0.10	1.49	1.47	2.9	1.49	0.006308
3	0.10	1.05	1.00	0.10	1.92	1.90	2.96	1.92	0.006459
4	0.10	1.40	1.30	0.44	1.30	1.28	2.75	1.49	0.039129
5	0.10	1.40	1.30	0.44	1.49	1.47	2.9	1.92	0.040174
6	0.10	1.40	1.30	0.44	1.92	1.90	2.96	1.30	0.063122
7	0.10	1.85	1.60	0.62	1.30	1.28	2.75	1.92	0.079704
8	0.10	1.85	1.60	0.62	1.49	1.47	2.9	1.30	0.030153
9	0.10	1.85	1.60	0.62	1.92	1.90	2.96	1.49	0.030178
10	0.40	1.05	1.30	0.62	1.30	1.47	2.96	1.30	0.043372
11	0.40	1.05	1.30	0.62	1.49	1.90	2.75	1.49	0.2
12	0.40	1.05	1.30	0.62	1.92	1.28	2.9	1.92	0.07357
13	0.40	1.40	1.60	0.10	1.30	1.47	2.96	1.49	0.003578

14	0.40	1.40	1.60	0.10	1.49	1.90	2.75	1.92	0.024021
15	0.40	1.40	1.60	0.10	1.92	1.28	2.9	1.30	0.02
16	0.40	1.85	1.00	0.44	1.30	1.47	2.96	1.92	0.02001
17	0.40	1.85	1.00	0.44	1.49	1.90	2.75	1.30	0.02
18	0.40	1.85	1.00	0.44	1.49	1.90	2.75	1.30	0.02
19	0.70	1.05	1.60	0.44	1.30	1.90	2.9	1.30	0.007729
20	0.70	1.05	1.60	0.44	1.49	1.28	2.96	1.49	0.035132
21	0.70	1.05	1.60	0.44	1.92	1.47	2.75	1.92	0.04495
22	0.70	1.40	1.00	0.62	1.30	1.90	2.9	1.49	0.2001
23	0.70	1.40	1.00	0.62	1.49	1.20	2.96	1.92	0.1432
24	0.70	1.40	1.00	0.62	1.92	1.47	2.75	1.30	0.2100
25	0.70	1.85	1.30	0.10	1.30	1.90	2.9	1.92	0.023987
26	0.70	1.85	1.30	0.10	1.49	1.28	2.96	1.30	0.023897
27	0.70	1.85	1.30	0.10	1.92	1.47	2.75	1.49	0.023987

Chapter 4 Results

4.1 ANOVA(Analysis of Variance for Signal to Noise Ratios)

The Taguchi DOE give the optimized link lengths for the minimum pitch angle of the payload platform.

S = 4.954 R-Sq = 91.2% R-Sq(adj) = 77.0%

Figure:4.1 Coefficient of Determination

Figure 22

From fig 4.1, it is evident that the R^2 value is 91.2% which means that the independent variables in our model or the link lengths are affecting our output a lot. Since the higher R-squared ensures more variation by the input variables thus the model is better. Adjusted R-square penalizes you for adding variables which do not improve your existing model. A 77% adjusted R squared therefore has a comparatively less value. The difference between the R^2 and adjusted R^2 is comparatively less which means that the variance in the output is not effecting the output and the effect of the useful variables is significantly high.

The following table is the P chart for the calculation of the P value for different links. P-value is the probability of rejecting the evidence against the Null hypothesis. Lower the probability stronger is the evidence. Thus, all the P-values that are lower or equal to 0.05 are considered more effective on the output. From the table below we can see that Link “d” has the lowest P-value thus it is the most effective link, similarly the links “b”, “c” and “e” also have a P-value less than 0.05 so these links also effect the results. The F-ratio is the statistical factor that calibrates the P-value and is opposite to the P-value. More the F-ratio, effective is the parameter. So the F-ratio of link “d” is the highest.

Variation source	**Df**	**Sum of squares (SS)**	**Mean square (MS)**	**F-ratio**	**p-value**
Left FF link (b)	2	260.54	130.27	5.31	0.027
Upper FF link (c)	2	258.84	129.42	5.27	0.027
Lower FF link (e)	2	190.67	95.34	3.88	0.056
Right FF link (d)	2	1540.75	770.37	31.39	0.000
FF leg link (h)	2	139.32	69.66	2.84	0.106
Bogie leg link(hb)	2	22.15	11.08	0.45	0.649
Rear wheel link (ct)	2	44.42	22.21	0.90	0.435
Rear leg link (ht)	2	74.46	37.23	1.52	0.266
Error	10	245.45	24.54		
Total	26	2776.60			

4.2 Effect of the most Dominant Link Lengths /Ranks

The following table gives us the ranking of the factors which are most significant in the analysis to minimize the pitch angle of platform.

Response Table for Signal to Noise Ratios

Smaller is better

DOE						
Control Factors	Symbol	L1	L2	L3	Delta	Rank
Left Front Fork link	b	33.88	31.24	26.38	7.50	2
Upper Front Fork link	c	33.82	26.37	31.31	7.45	3
Lower Front Fork link	e	31.79	26.80	32.91	6.11	4
Right Front Fork link	d	39.41	31.14	20.94	18.47	1
Front Fork leg link	h	33.70	28.68	29.11	5.02	5
Bogie leg link	hb	30.07	31.76	29.67	2.09	8
Rear wheel link	ct	28.69	31.29	31.52	2.83	7
Rear leg link	ht	32.52	30.53	28.45	4.07	6

Figure: 4.3 The Rank table of Taguchi Analysis

Figure 23

Figure 4.3 gives us the valuable information of the ranks of the link lengths with their effectiveness on the pitch angle variation. Link “d” which is the right link of the front fork has been ranked as the most effective link length. Varying this link length will definingly vary the pitch angle and the stability of the platform. Similarly the front fork links “b”,” c”, and” e” which are the left, upper and lower links of the front fork are very significant in the overall analysis of the shrimp rover.

The leg links of the front fork, bogie and the rear link are also important and the change in these factors cause the change in the final resultant pitch angle of the platform. These legs are significant since they ensure the complete convergence of all the rover wheels on the terrain at all points as it moves over it. Thus, the objective function depends upon these independent variables and we can configure the variation in the pitch angle of the platform with the help of this Rank provided by the Taguchi DOE analysis.

4.3 Mean Effect Plot for SN ratios

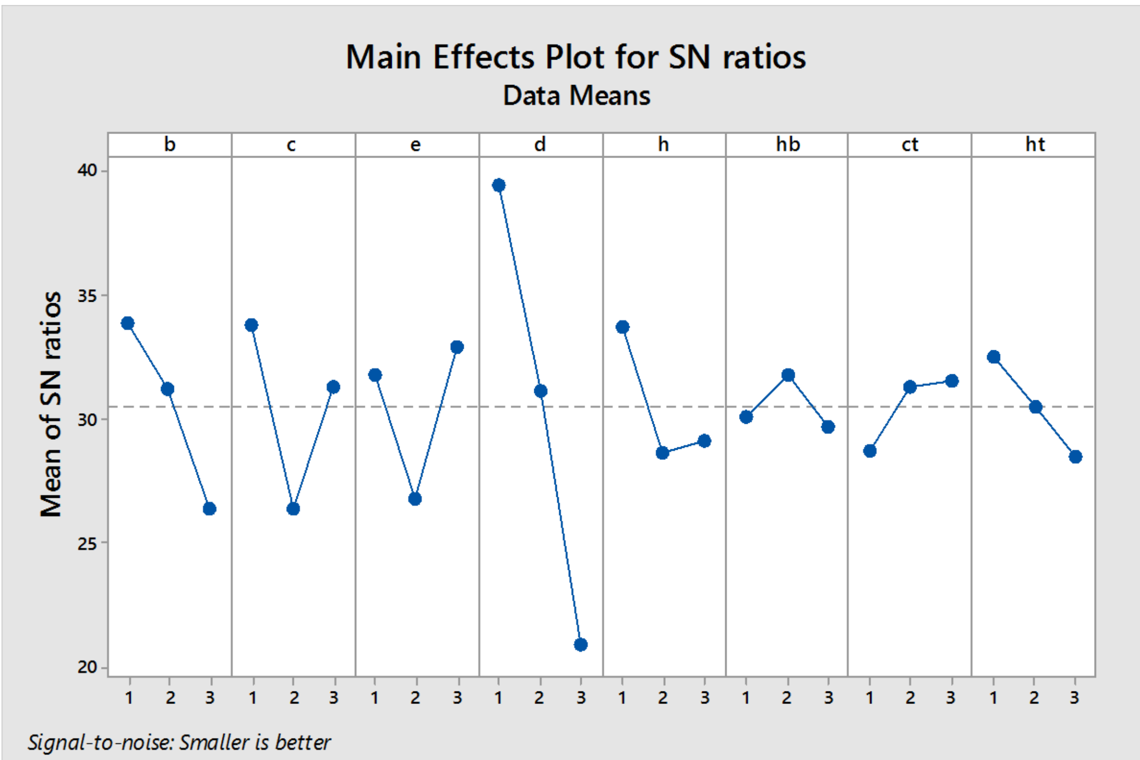

Figure:4.4 Main effects plots for SN ratios

Figure 24

4.4 Main Effect plot for Means:

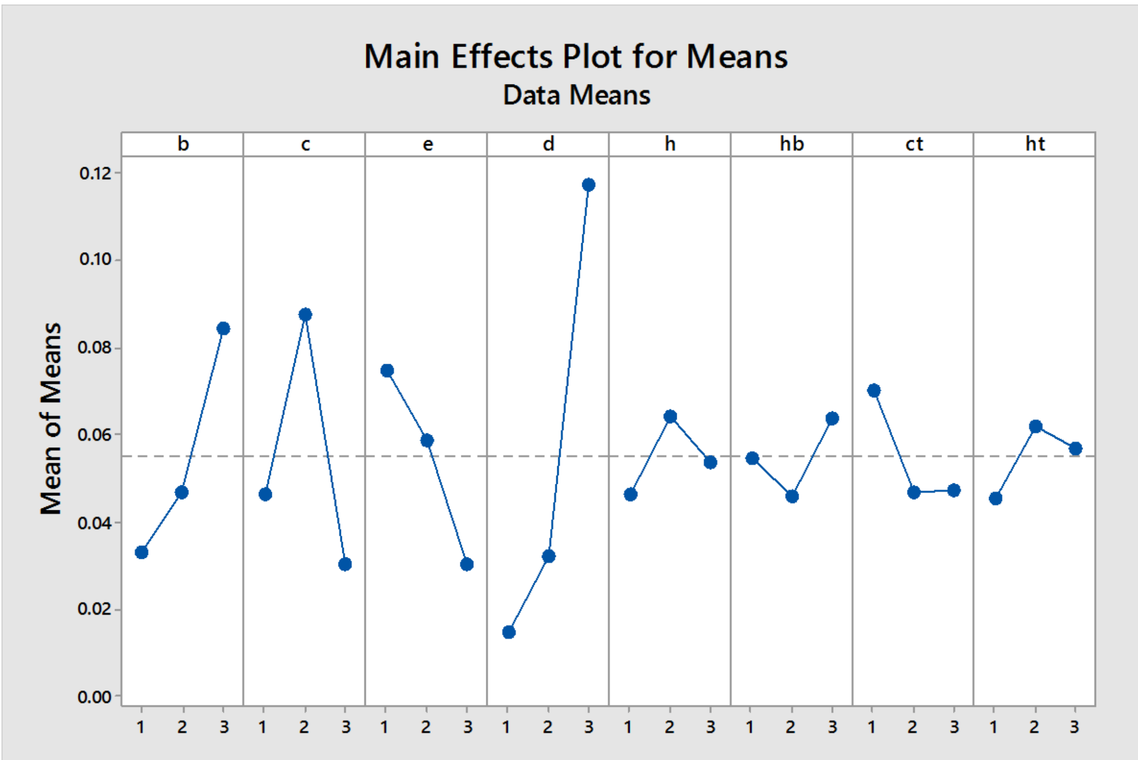

Figure:4.5 Main Effect Plots for means

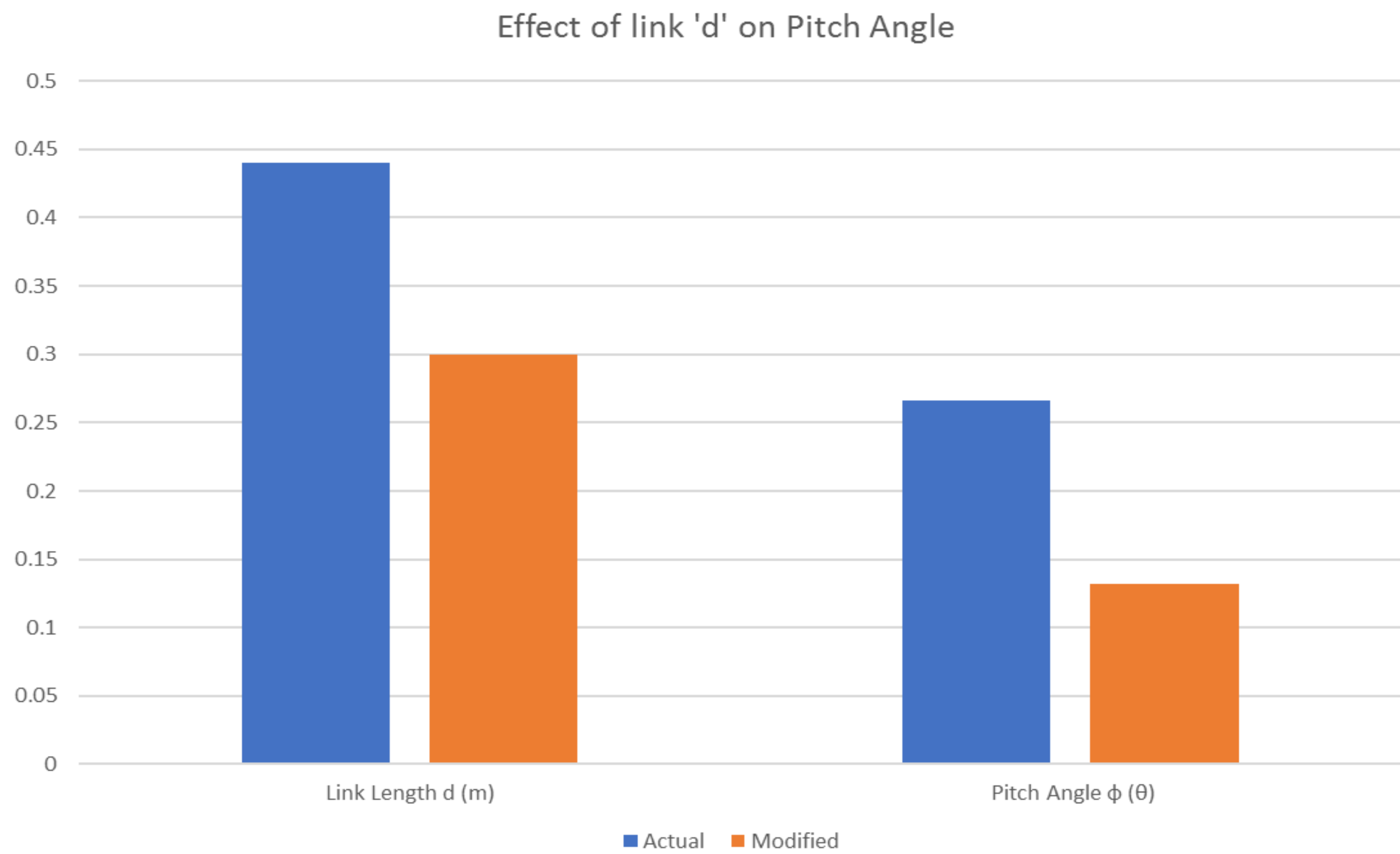

Figure25

Pitch Angle minimization = (40-50) %

4.5 Simulation Results of MATLAB and Solidworks

The output of the platform angle minimization achieved as a result of the Taguchi DOE analysis gave the best possible combinations of link lengths and those link lengths were applied to the run the rover on the terrain created in MATLAB.

It was seen that the rover platform was stabilised, and the link lengths were convenient enough to minimize the pitch angle of the platform.

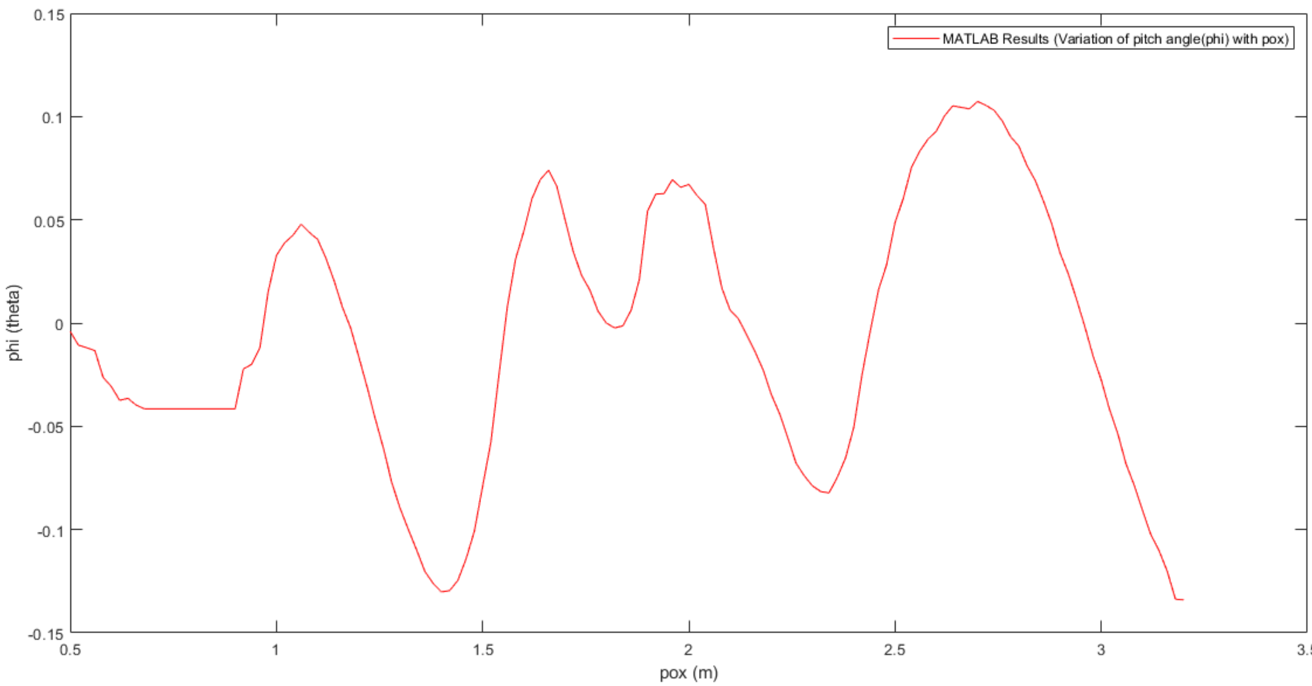

Figure:4.6 Variation of “P_{ox}” with the Pitch angle “ϕ”(MATLAB)

Figure 26

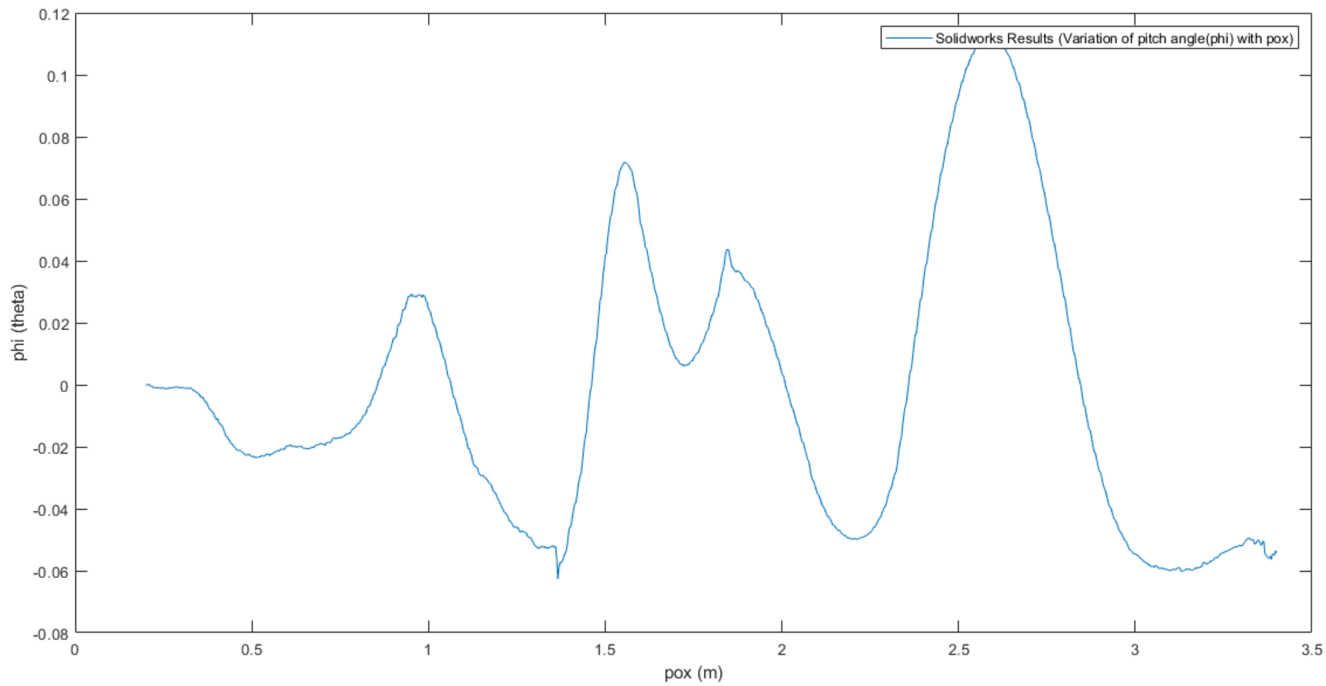

Figure:4.7 Variation of “P_{ox}” with the Pitch angle “ϕ”(SOLIDWORKS)

Figure 27

4.5a Comparison between Solidworks and MATLAB results of the optimized Pitch angle

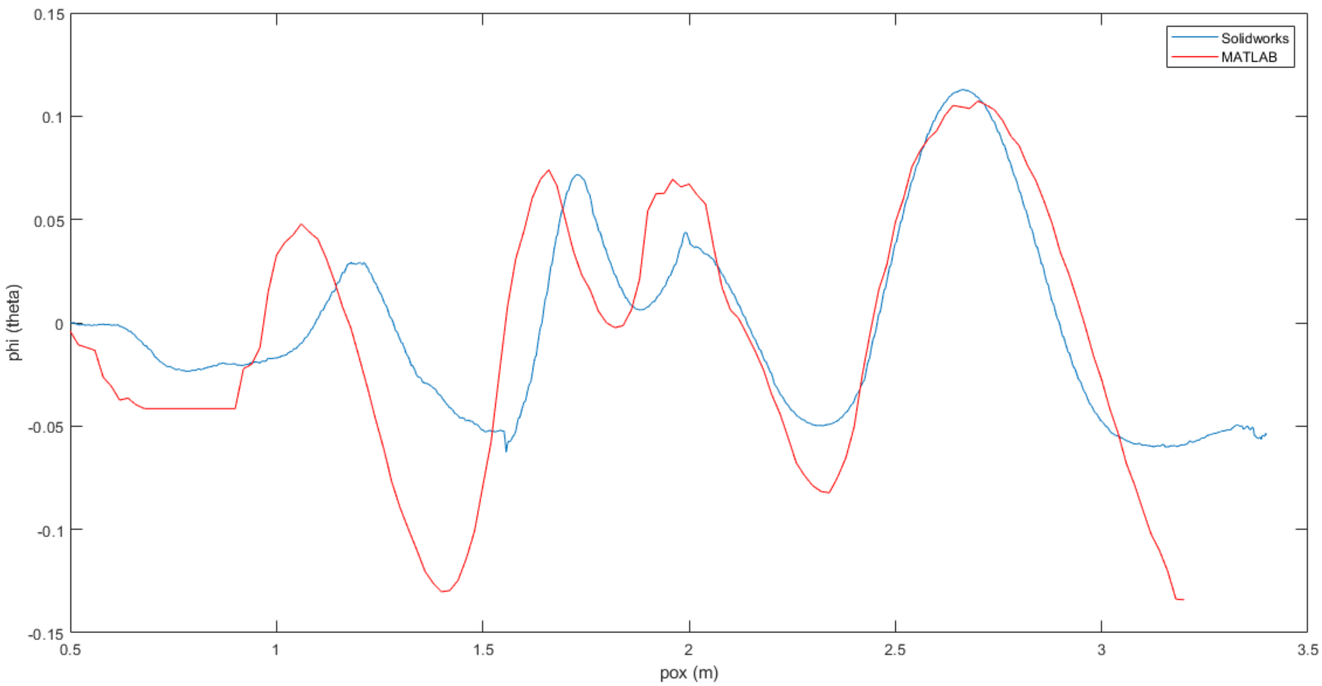

Figure:4.7 Variation of “Pox” with the Pitch angle “φ”(SOLIDWORKS and MATLAB)

Figure 28A

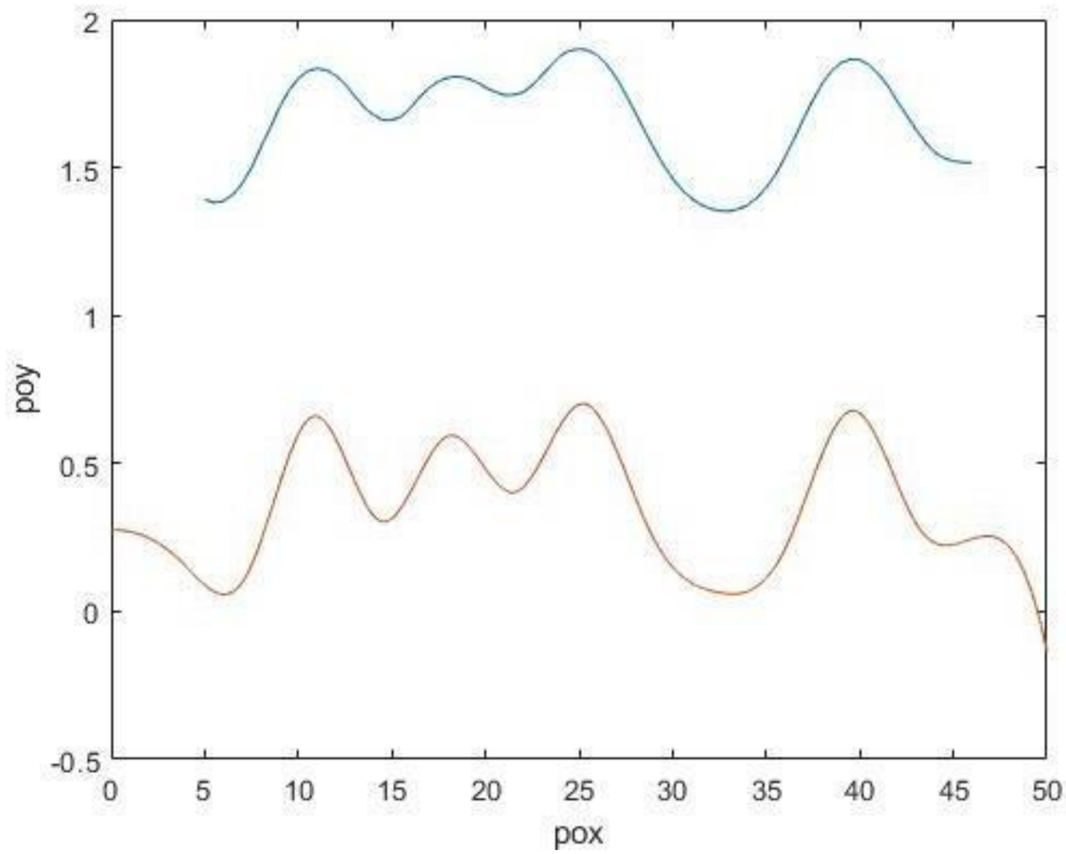

Figure:4.8 Variation of “P_{ox}” with “P_{oy}”(MATLAB)

Figure 29

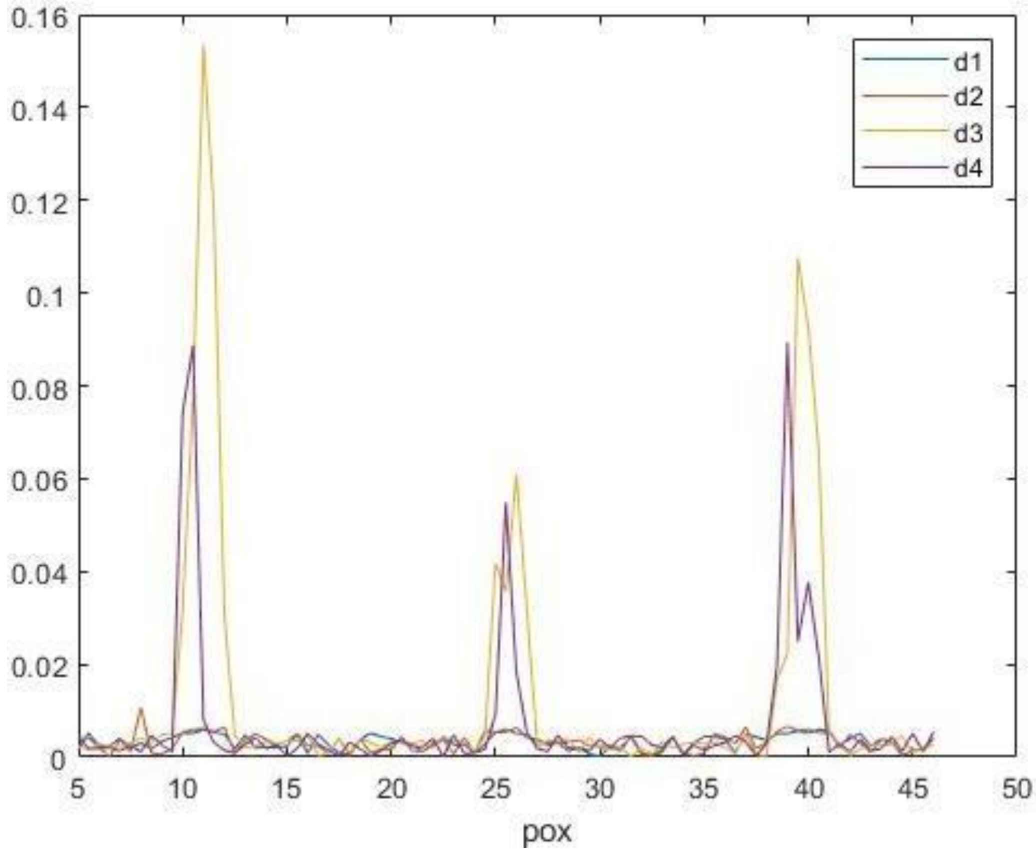

Figure:4.8 Variation of objective function “Dist” with “P_{ox}”(MATLAB)

Figure 30

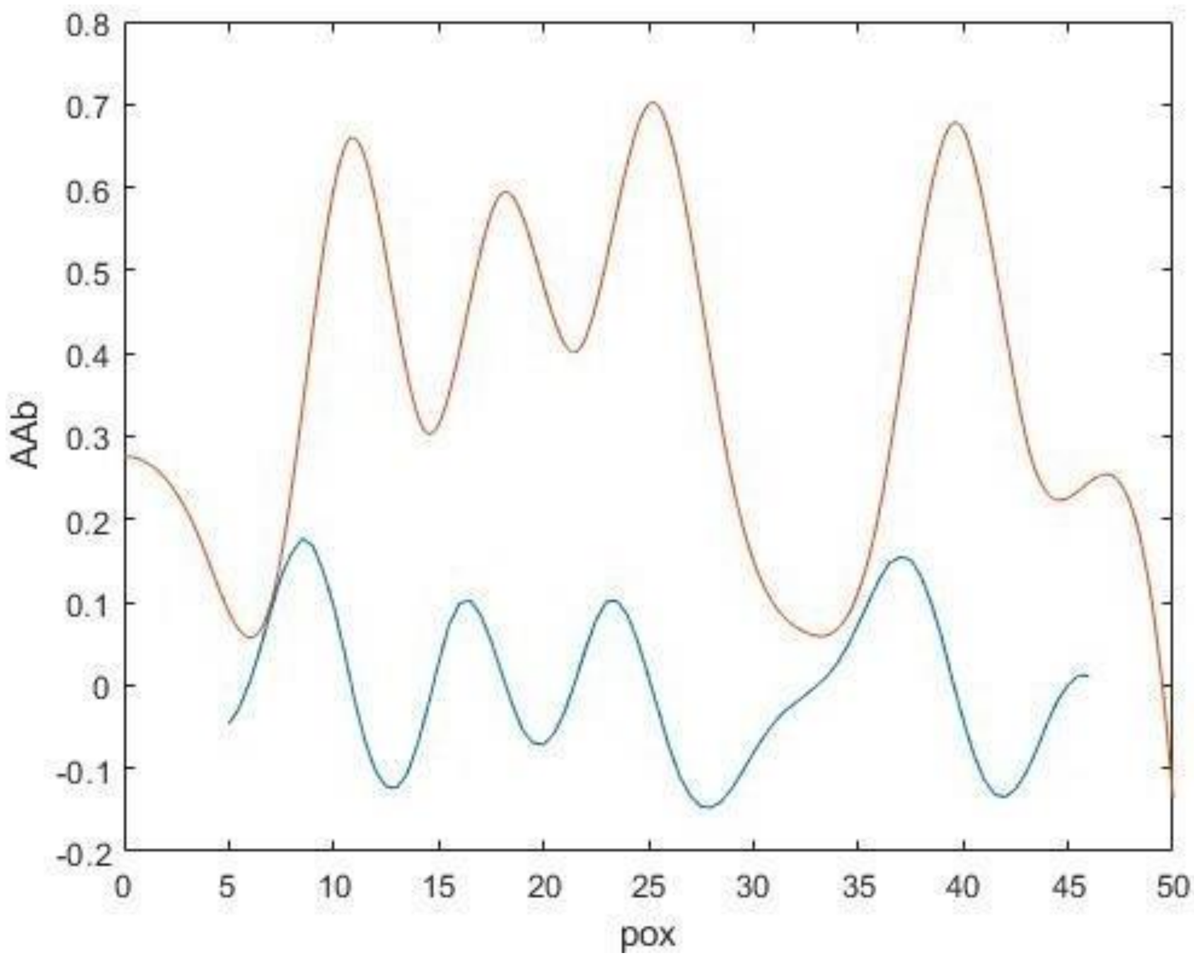

Figure:4.9 Variation of “P_{ox}” with the rotation angle of bogie “AA_b”(MATLAB)

Figure 31

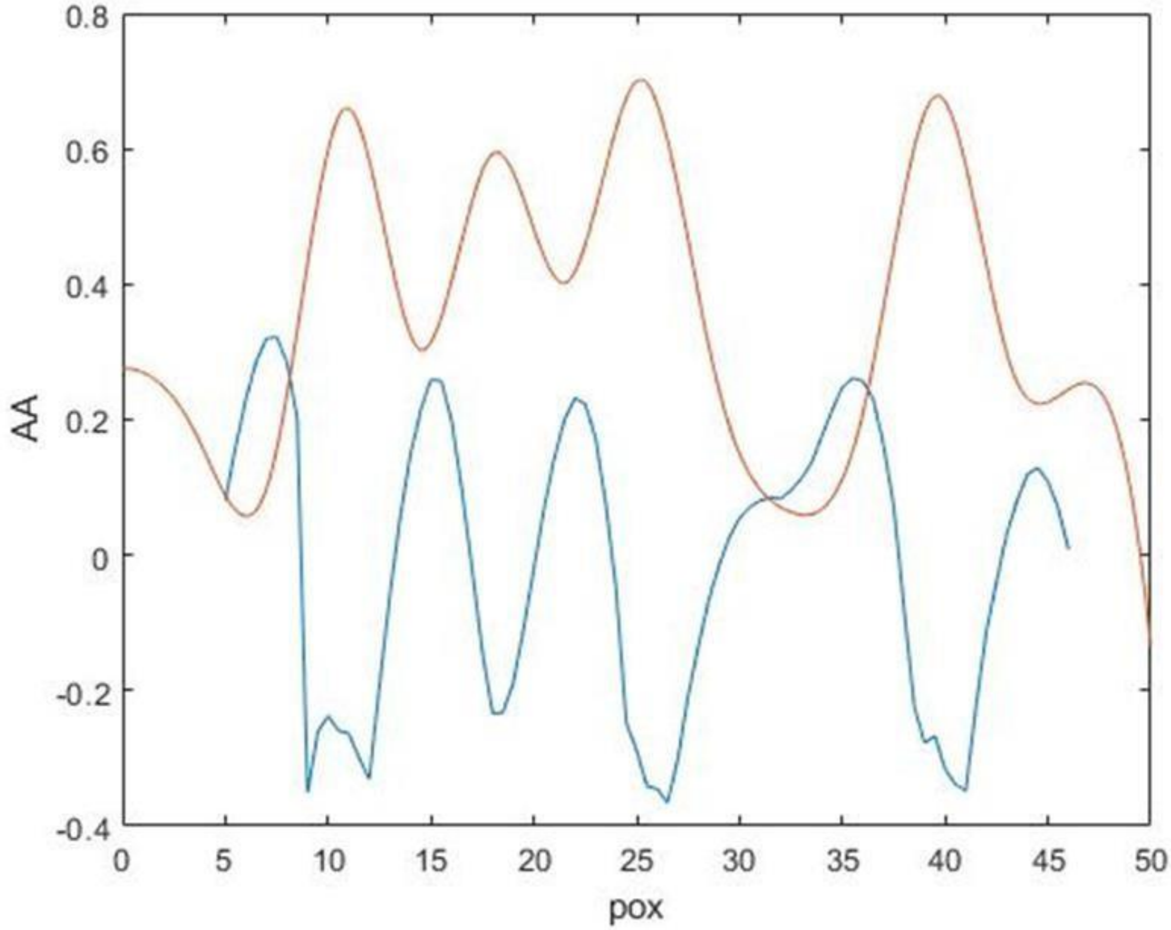

Figure:4.10 Variation of “P_{ox}” with the Rotation angle of front fork “AA”(MATLAB)

Figure 32

Chapter 5 Conclusions and Future Recommendations

5.1 Conclusion

The core objective of this research work is to minimize the pitch angle of the Shrimp Rover and the Taguchi DOE is implemented on the Shrimp Rover Kinematic Model generated in MATLAB. The rover attains good convergence under certain constraints. The stability of the rover is also analyzed with multiple variables. The platform pitch angle of the rover gives valuable information about the behavior of the rover as it moves on a certain trajectory. Finally, the MATLAB developed model of the rover showed reasonable agreement with the SolidWorks developed model, analyzed in motion study.

Taguchi DOE is a reasonable approach towards analyzing and minimizing the objective function. With the 27 sets of combinations and 3 different levels the Taguchi DOE is implemented with SN ratio and ANOVA which provides valuable information through a regression model about the configuration of the rover links in order to minimize the pitch angle. The resulting link lengths are then computed inorder to find the Pitch angle of the platform and it is found to be minimized for the combination given by the Taguchi DOE. The motion study generated on solid works also reinforces the minimized pitch angle results.

The passive stability of a shrimp rover in general is therefore improved with respect to the pitch angle minimization of the payload platform. Thus, this rover due to the passive nature is a better option to work and explore in various unstructured environments.

5.2 Future Recommendations

- For Future work the intention is to work on the waviness and roughness of the unstructured terrain and to work on the Kinetic Model for the minimization of the Traction Forces of the rover wheels and the terrain. Various forces like gravity, friction and tractive effort can be configured for this rover in order to move it in any unstructured terrain. Passive stabilization in terms of its Roll can also be an interesting topic to discover.
- Moreover, the development of the kinematic chain of the linkages and the sensitivity analysis can also add value into this model of the shrimp rover.

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Completion Certificate

It is certified that the contents of thesis document titled **Passive Minimization of Pitch Angle of Payload Platform of a Shrimp Rover** submitted by **Ms. Sehrish Shahnawaz** Registration N0. **NUST2016-ME-00000172337** have been found satisfactory for the requirement of degree

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