A
PROJECT REPORT
ON

ROCKRES BOGIE

Submitted By

ABSTRACT

It is obvious that rovers are important vehicles of today's solar system exploration. Most of the rover designs have been developed for Mars and Moon surface in order to understand the geological history of the soil and rocks. Exploration operations need high speed and long distance traversal in a short mission period due to environmental effects, climate and communication restrictions. Several mechanisms have been suggested in recent years for suspensions of rovers on rough terrain. Although their different mechanisms have found a widespread usage in mobile robotics, their low operation speed is still a challenging problem. In this research, a new suspension mechanism has been designed and its kinematic analysis results were discussed. Standard rocker-bogie suspension mechanism, which has been developed in the late 1990's, has excellent weight distribution for different positions on rough terrain. New design, mostly similar to rocker-bogie suspension system, has a natural advantage with linear bogie motion which protects the whole system from getting rollover during high speed operations. This improvement increases the reliability of structure on field operations and also enables the higher speed exploration with same obstacle height capacity as rocker-bogie. In this thesis study, new bogie mechanism consisted of double-lambda mechanisms, which has been firstly presented by Pafnuty Lvovich Chebyshev in 1869, is solved by analytically to define the positions and singular configurations. A new structural synthesis formula also has been introduced for such suspension mechanisms with lower and higher kinematic pairs. By using structural synthesis methods, a suspension mechanism has been designed with double-lambda mechanism. Equivalent force and moment functions were also derived with equation of motion method. The results are confirmed with the computer analysis made by Visual Nastran 4D®. For this purpose, a computer model has been constructed and assembled with the same design parameters of NASA Mars Exploration Rovers (MER1 and MER2).

CHAPTER 1:- INTRODUCTION/PHILOSOPHY

1.1 THEORY

1.1.1 **Introduction**

NASA recently started an ambitious exploration program of Mars .Pathfinder is the first rover explorer in this program.Future rovers will need to travel several kilometers over periods of months and manipulate rock and soil samples. They will also need to be somewhat autonomous.Rocker-bogie based rovers are likely candidates for these missions The physics of these rovers is quite complex.

To design and control these, analytical models of how the rover interacts with its environment are essential . Models are also needed for rover action planning.Simple mobility analysis of rocker-bogie vehicles have been developed and used for design evaluation.In the available published works, the rocker-bogie configuration is modeled as a planar system.

Improving the performances of a simpler four wheel rover has also been explored .In this work, actuator redundancy and the position of the center of mass of a vehicle (the Gophor) is exploited to improve traction. The method relies on real-time measurements of wheel/ground contact forces, which are difficult to measure in practice. Traction can also be improved by monitoring the skiding of the rover wheels on the ground .However, detailed models of the full 3-D mechanics of rocker-bogie rovers have not been developed. Further models including the manipulator’s influence are also required to effectively planning and controlling the actions of these rovers. For example it is important for a planner to be able to predict if a rover can successfully negotiate a given terrain obstacles, such as a ditch, without being trapped.

This paper describes a physical model of a rocker-bogie rover, the Lightweight Survivable Rover (LSR-1). An efficient method of solving its inverse kinematics and its quasi-static force analysis is outlined. The methods include the effects of the rover’s manipulator, actuator saturation and tire-slip considerations. A graphical interface that enhances the understanding of the physics of the model is also described.

On July 4, 1997, an orange coloured big ball softly bounced on the surface of Mars with an unusual robotic vehicle inside. This was the first planetary mission which has been wide public interest after first man on the moon. Small rover “Sojourner” conducted scientific experiments for 83 Sols (Mars Days) and took hundreds of photographs [1]. Roving on another planet came from dream to real by the help of science and patient ambitious research. This successful mission encouraged the scientists and NASA to continue the Mars exploration with new rovers.

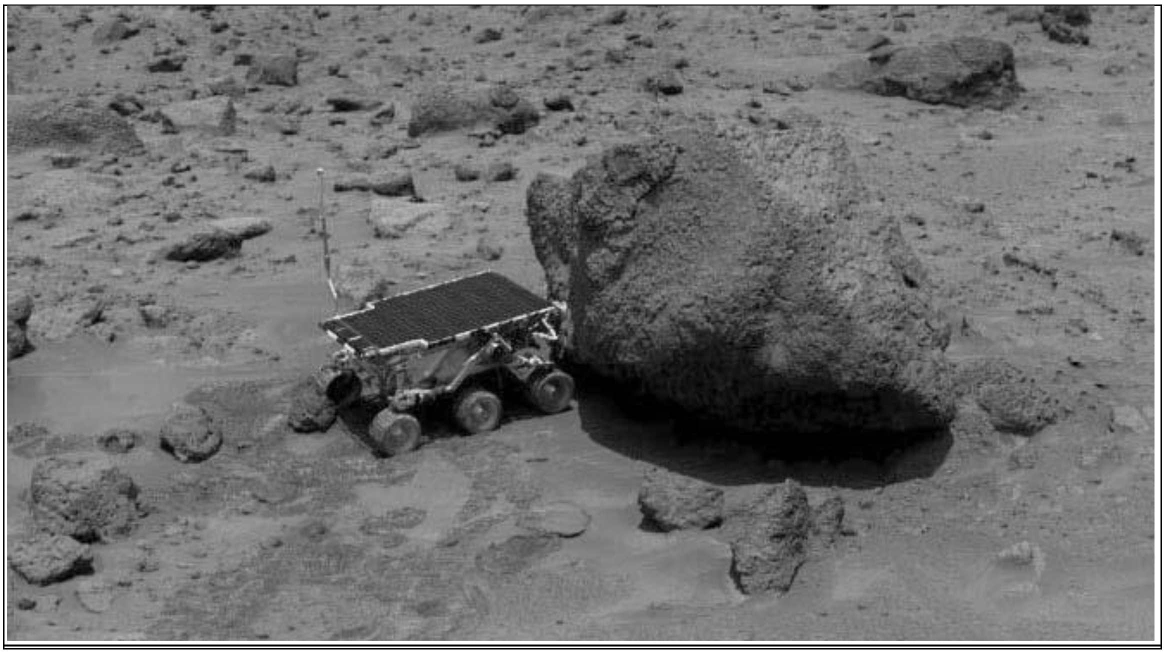

Figure 1-1: Sojourner examining the rock named “Yogi” (Courtesy of NASA/JPL-Caltech)

Many rovers developed after Sojourner with different features and scientific objectives. In early days of January 2004, second and third rovers landed different locations on Mars named Spirit (MER1) and Opportunity (MER2) [2]. Scientific results of these powerful vehicles are bigger than their physical dimensions. All of the three rovers’ success and scientific results show that space agencies will continue robotic geologists frequently in future.

LITRATURE SURVEY

Similar to the International Standards Organization's definition of an industrial robot, mobile robot can be defined as;

"A mobile robot is an autonomous system capable of traversing a terrain with natural or artificial obstacles. Its chassis is equipped with wheels/tacks or legs and possibly a manipulator setup mounted on the chassis for handling of work pieces, tools or special devices. Various preplanned operations are executed based on a preprogrammed navigation strategy taking into account the current status of the environment."

This definition any intelligent machine which moves with respect to environment within limited human interaction (autonomously) called "Mobile robot".

Mobile robots can be classified by significant properties as;

- Locomotion (Legged, wheeled, limbless, etc.)
- Suspension (Rocker-bogie, independent, soft, etc.)
- Steering (Skid, Ackerman, explicit)
- Control Algorithm (Fully-Autonomous, semi-autonomous)
- Body Flexibility (Unibody, multibody)
- Usage Area (Rough Terrain, even surface, etc.)
- Guidance and Navigation (Star field or Sun detection, GPS, sensor-based)

Mobile robots can be used in several applications. Dangerous area operations (Nuclear plants), planetary exploration and pipe investigation, extreme temperature and narrow field investigations (pyramid exploration robots). Moreover, floor cleaning robots and servant robots are common examples for indoor use. It is not a dream that, in near future robots will be a part of our daily life.

1.1.2 Locomotion

Locomotion is a process, which moves a rigid body. There is no doubt that a mobile robot's most important part is its locomotion system which determines the stability and capacity while traversing on rough terrain. The difference of robotic locomotion is distinct from traditional types in that it has to be more reliable without human interaction. While constructing a robot, designer must have decided on the terrain requirements like stability criteria, obstacle height, and surface friction. There is no only one exact solution while comparing the mobility systems.

There are several types of locomotion mechanisms were designed depending on nature of the terrain. Locomotion systems can be divided into groups as; wheeled, tracked, legged (walking robots), limbless (snake and serpentine robots) and hopping robots. Wheeled rough terrain mobile robots are called as “Rover”.

In nature, insects are the fastest creatures, comparing to body/speed with their numerous legs. There is no suspicion that we are going to see legged robots more frequently in future with improved leg control algorithms and new lightweight materials. Limbless locomotion is another terrain adaptive locomotion type for reptile creatures. Snakes can move very fast on uneven terrain, additionally, they can easily climb on trees by their highly flexible body structure.

Although animals and insects do not use wheels, wheeled locomotion has several advantages for human-made machines. Rovers can carry more weight with highspeed comparing to walking robots and snake robots. Another advantage of wheeled locomotion is navigation. Wheeled robot’s position and orientation can be calculated more precisely than tracked vehicles. Opposite to wheeled locomotion, legged locomotion needs complex control algorithms for positioning.

1.2 History of Rovers

1.2.1 Lunakhod

The first planetary exploration rover was “Lunakhod” which has been sent Moon 2 times with USSR – Luna missions to gather information around landing site and send pictures of terrain.

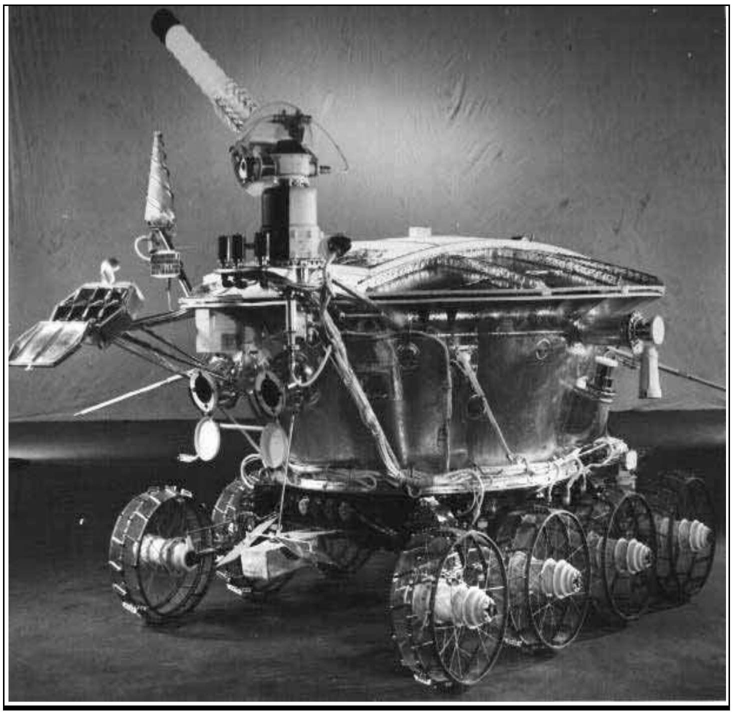

Figure 1-2: First Planetary Exploration Rover "Lunokhod" (Courtesy of Lavochkin Assoc.)

Lunakhod has guided in real-time by a five-person team at the Deep SpaceCenter near Moscow, USSR. Lunakhod-2 toured the lunar Mare Imbrium (Sea of Rains) for 11 months in one of the greatest successes travelled 37 km on Moon surface.

CHAPTER 2:- WORKING PRINCIPLE

1.2.2 Sojourner

In 1996, NASA – Jet Propulsion Laboratory and California Institute of Technology have designed new rovers with identical structure named Sojourner and Marie-Curie. These small rovers were only 10.5 kilograms and microwave oven sized. Rover Sojourner launched with Pathfinder landing module in December 1996. Marie Curie rover was also planning to send Mars with 2001 mission which has been cancelled .

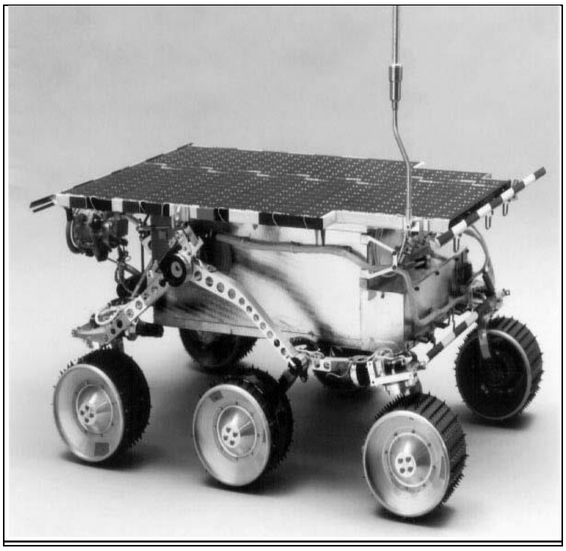

Figure 1-3: NASA - JPL Sojourner Rover (Courtesy of NASA/JPL-Caltech)

Operators have sent commands via lander Pathfinder and they examined rocks and soil components of Mars more than 3 months. Sojourner was a breaking point of exploration rovers with its unique six-wheeled suspension system which can overcome one and a half wheel diameter height obstacles that is similar to an automobile passing over a table sized obstacle.

1.2.3 Inflatable Rover

Another alternative to move on a harsh environment is to have big wheels. If a rover has large wheels compared to obstacles, it can easily operate over most of the Martian rocky surface. Researches show that inflatable rover with 1.5 meter wheel diameter can traverse 99% of the area [16]. Inflatable rover has 3 wheels which are driven by motors.

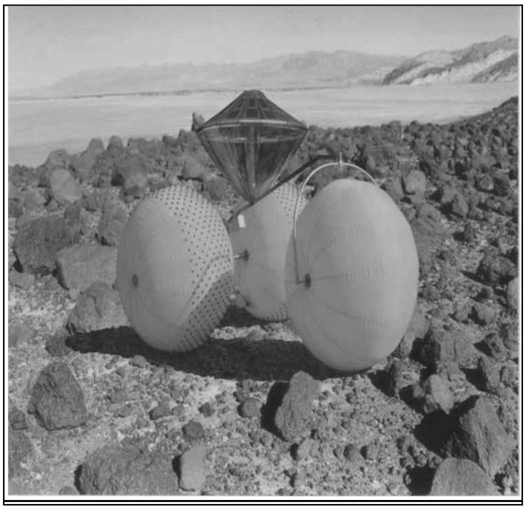

Figure 1-4: Inflatable Rover (Courtesy of NASA/JPL-Caltech)

Robot could be able to travel approximately 30 km per hour on Mars surface by its 100-watt power.

1.2.4 Rocky 7

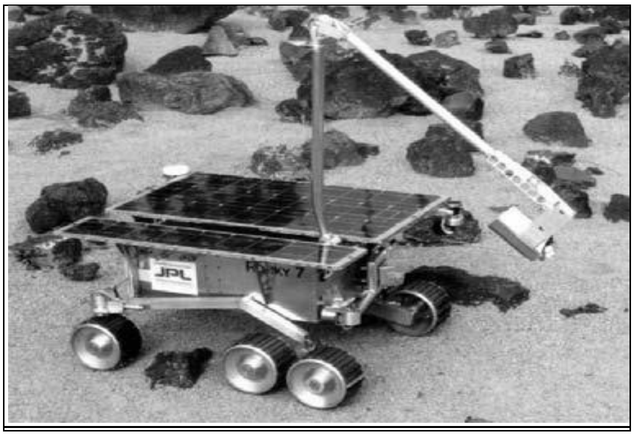

Figure 1-5: Rocky 7 Rover (Courtesy of NASA/JPL-Caltech)

Rocky 7's design and dimensions are similar to Sojourner. A robotic arm is attached to the body for investigation. Mobility system changed to 2-wheel steering similar to Ackerman type [27]. Although this modification decreases the complexity for control systems, manueverability is restricted.

1.2.5 Sample Return Rover

Rough terrain mobility of a mobile robot can be increased by center of gravity shifting methods. A good example to this category is NASA Sample Return Rover (SRR) which has been designed to collect soil and stone sample from Mars surface. SRR has active suspension system with variable angle between linkages

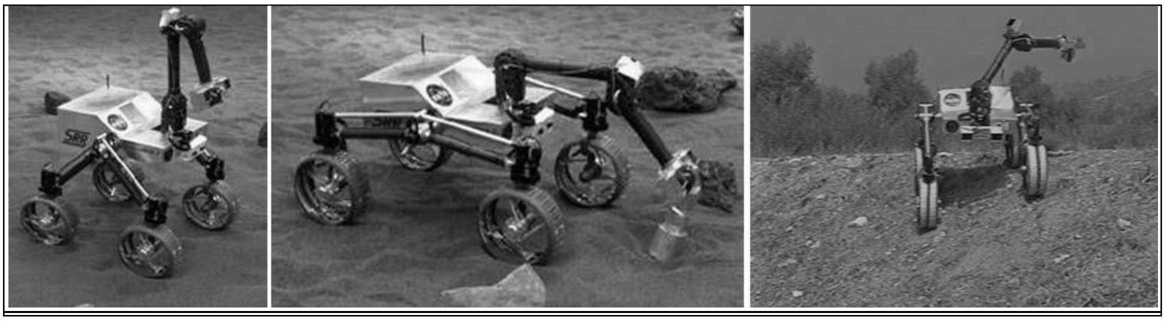

Figure 1-6: Sample Return Rover - (SRR) (Courtesy of NASA/JPL-Caltech)

On inclined surface, active suspension can hold the main body horizontal. Navigation gets easier by this feature of rover.

1.2.6 Nanorover

Another example to active suspension system is nanorover which was designed for exploration of small celestial bodies like comets and asteroids. Small dimensions and lightweight are advantages of this robot.

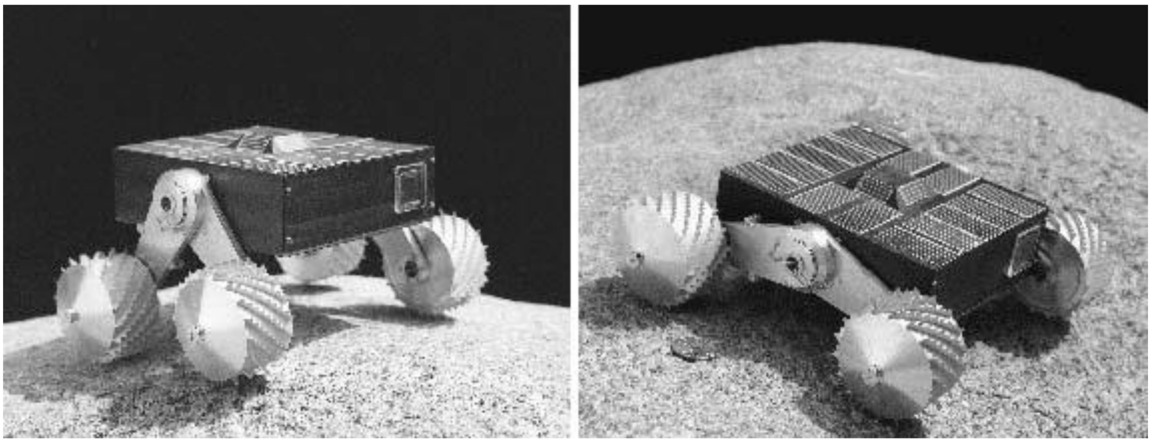

Figure 1-7: Nanorover with active suspension (Courtesy of NASA/JPL-Caltech)

Mobility system consists of four wheels with 6 cm diameter. Each wheel connected to the chassis with independent positioned struts. Since the robot can operate on both sides (upside-down), overturning is not a problem. Onboard computer can manipulate the suspension to arrange traction forces .

1.2.7 Micro5

Japanese Lunar rover Micro5 is a five-wheeled rover. Suspension system named Pegasus; uses a fifth wheel to support the remaining wheels while front wheels climbing
obstacles. The rover with 100 mm wheel diameter is able to climb 150 mm height steps
and rocks.

Figure 1-8: Micro5 rover with suspension named Pegasus(Courtesy of Meiji University – Japan)

Pegasus mobility system has 4 active wheels and one extra wheel which is connected to the body with an actuated joint. When front wheels climb, the fifth wheel carries some part of the weight to help wheels.

1.2.8 Shrimp

Shrimp is another six-wheeled rover which designed by Swiss Federal Institute of Technology – EPFL. It has a one front four-bar to climb over obstacles up to two wheel diameter without any stability problem. Middle four wheels have parallelogram bogie which balances the wheel reaction forces during climbing. Single rear wheel connected directly to the main body also driven by motor to increase the climbing capacity.

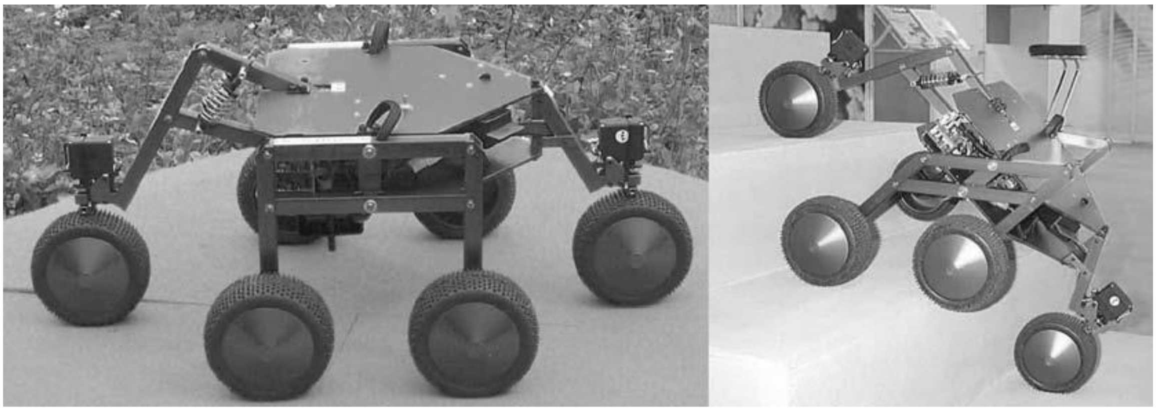

Figure 1-9: Shrimp rover designed by EPFL – Switzerland (Courtesy of EPFL)

1.2.9 Mars Exploration Rovers (MER)

Mars Exploration Rovers are developed designs of Sojourner. Each Mars Exploration Rover is 1.6 meter long and weighs 174 kilograms. Opposite to previous rover Sojourner, which was commanded via lander Pathfinder, these robots carry all required electronic devices on their body. Mobility system is similar to Sojourner rover with Rocker-Bogie suspension and 4-wheel steering.

Figure 1-10: Illustration of Mars Exploration Rover (Courtesy of NASA/JPL-Caltech)

1.3 Rover Operations and Future Requirements

Today's rovers are driven by commands which are sent from ground operators after tested in 3D computer simulator. Some of the critical motions such as climbing high slope, driving near crater rim between rocks which have variety of height, rover motions must be taken under consideration of flight engineers. These operations are need to be decided by a large operator group, which increases the total cost of the planetary exploration project.

Figure 1-11: Rocky terrain on the rim of crater Bonneville (Courtesy of NASA/JPL-Caltech)

As the future space exploration trend includes less cost principle, new rover designs are needed to be more flexible during field operations. Although obstacle detection and avoidance algorithms decrease the average speed, restriction of the overall speed is suspension design of the vehicle. For example, the Mars Exploration Rovers have a top speed on flat hard ground of 5 centimetres per second. To increase the safety of the drive, the rover has hazard avoidance software which causes to stop and reevaluate its position every few seconds. Because of the safety procedures in the field operations, the average speed can go up to 1 centimeter per second . It is nonevitable fact that future rovers will reach high speed compared to current speed with software improvements and with the suspension design.

3.3 MATERIAL PROCUREMENT AND CONSTRUCTION:-

DESIGN CONSIDERATION

Like all other design matters in engineering, robots are designed according to its working environment and purpose. Generally, wheeled robots have advantages on rough, sandy surface with carrying large bodies. Moreover, wheeled robots can rotate even on a spot without any skidding.

2.1 Suspension

Wheeled locomotion's main component is its suspension mechanism which connects the wheels to the main body or platform. This connection can be in several ways like springs, elastic rods or rigid mechanisms. Most of the heavy vehicles like trucks and train wagons use leaf springs. For comfortable driving, cars use a complex spring, damping and mechanism combination. Generally, exploration robots are driven on the rough surface which consists of different sized stones and soft sand. For this reason, car suspensions are not applicable for rovers. The requirements of a rover suspension are;

- As simple and lightweight as possible
- Connections should be without spring to maintain equal traction force on wheels.
- Distribute load equally to each wheel for most of the orientationpossibilities to prevent from slipping.

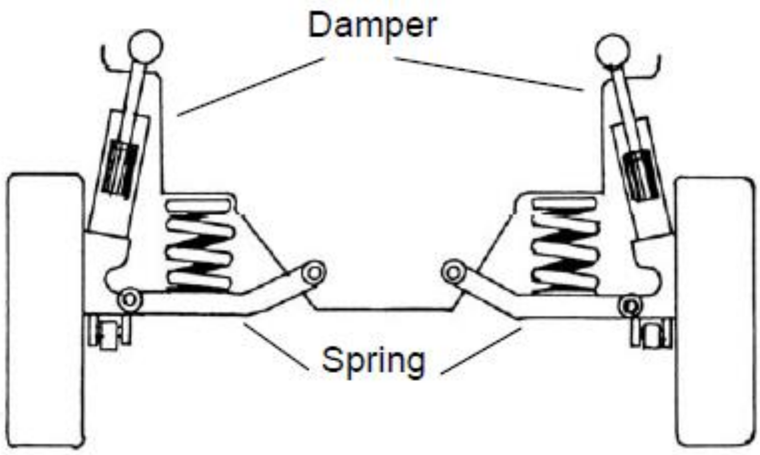

Figure 2-1: Independent car suspension system with damper and spring

Soft suspension systems with spring reduce vibrations and effects of impacts between wheel and ground. However, reaction force of pressed spring increases the force that transmits from wheel to ground. When climbing over an obstacle, higher wheel's traction force is more than the lover one which causes slippage.

2.2 Obstacle Capacity

A rover's obstacle limit generally compared with robot's wheel size. In four wheel drive off-road vehicles, limit is nearly half of their wheel diameter. It is possible to pass over more than this height by pushing driving wheel to obstacle which can be called as *climbing*. Step or stair climbing is the maximum limit of obstacles. The contact point of wheel and obstacle is at the same height with wheel center for this condition.

Field tests show that Mars mobile robots should be able to overcome at least 1.5 times height of its wheel diameter. This limitation narrows the mobile robot selection alternatives and forces scientists to improve their current designs and study on new rovers.

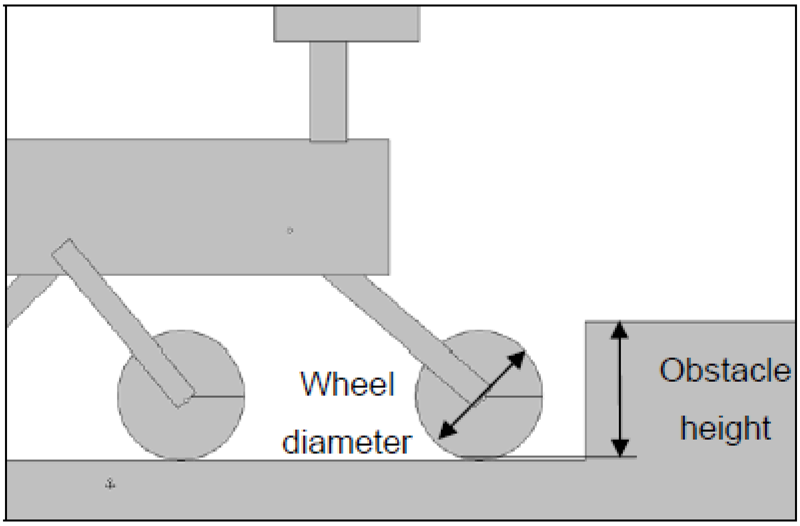

Figure 2-2: Definition of capacity

Former rover designs have different capacities. The rocker-bogie suspension which has been used on NASA Sojourner, Spirit and Opportunity rover can pass over 1.5 wheel diameter obstacles. The "Shrimp III" rover has extensive ability with a climbing wheel connected by rhombic four-bar has 2 wheel diameter height step obstacle capacity Although powerful climbing characteristics, rover's stability loses its advantage while driving down slope.

All these researches show that most of the rover designs have a climbing capacity between 1.5 diameters and 2 diameters of wheel. To reach higher capacities, active climbing methods are required.

2.4 Rocker-Bogie Suspension

Rocker-Bogie suspension has been developed for first Mars rover Sojourner by NASA – JPL .

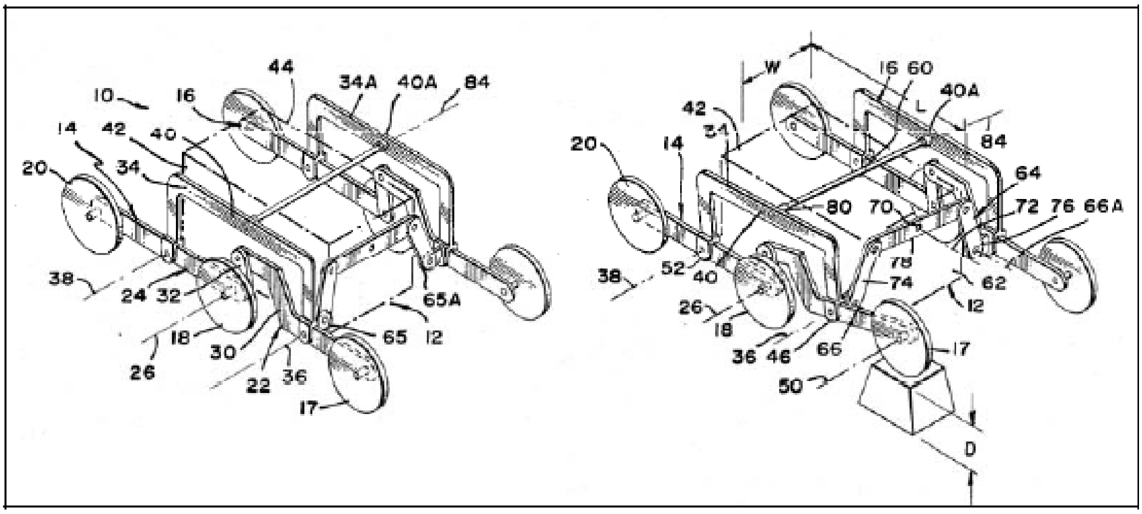

Figure 2-4: Articulated Suspension System (US 4,840,394)

This suspension has 6 wheels with symmetric structure for both sides. Each side has 3 wheels which are connected to each other with two links. Main linkage called *rocker* has two joints. While first joint connected to front wheel, other joint assembled to another linkage called *bogie*, which is similar to train wagon suspension member. In later design of articulated suspension system, called rocker-bogie with small changes.

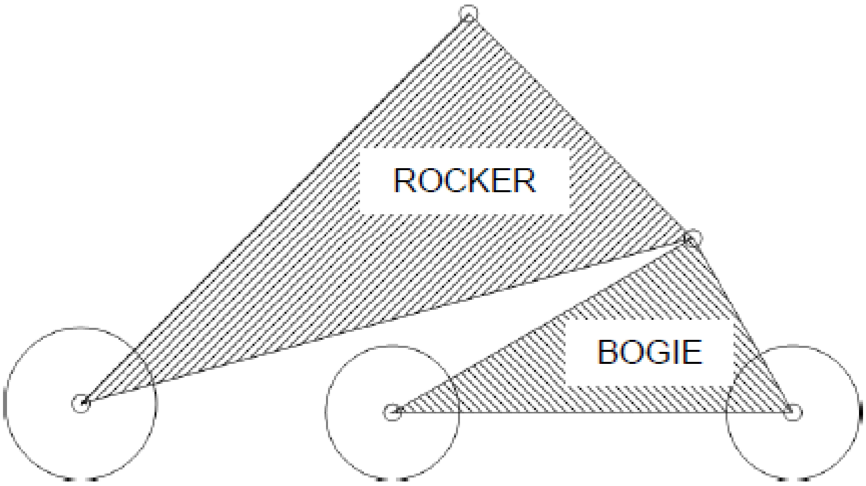

Figure 2-5: Kinematic diagram of Rocker-Bogie suspension

The main advantage of the rocker bogie suspension is load on each wheel isnearly identical. On different positions, wheels' normal force equally distributes contrary to 4 wheel drive soft suspensions .

The connection between symmetrical lateral mechanisms is provided by a differential mechanism which is located inside the body. Rotation of axles which are connected two rockers are averaged, thus, vehicle body pitch angle always adapted even if one side steps over obstacle.

2.5 Wheel Motion

While driving on a flat surface, if there is no slipping, wheel center will move on a line parallel to the surface with constant velocity. Although, obstacle geometries can be different, most difficult geometry which be can climbed by wheel is stair type rectangular obstacle.

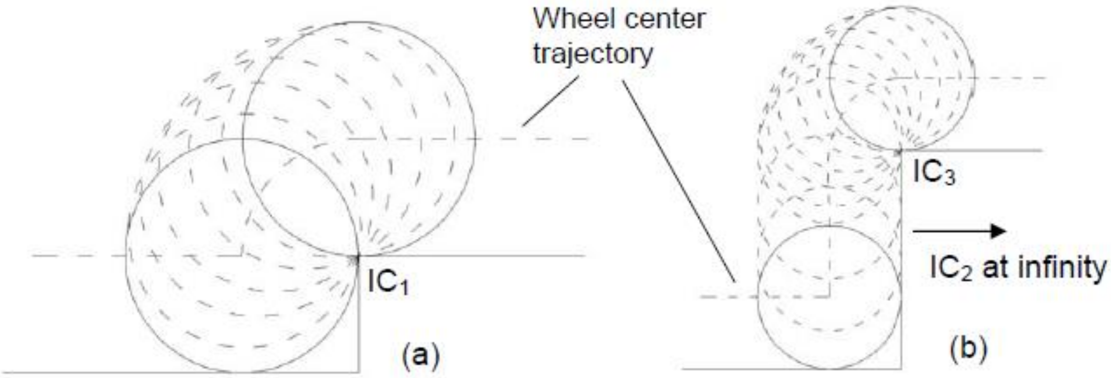

Figure 2-6: Wheel passing over same wheel diameter (a) and more than half wheel diameter (b) height obstacle

In figure 2-6(a), height of the obstacle is same or less than the half diameter of the wheel. For this condition, the wheel's instant center of rotation (IC_1) is located at the contact point of the obstacle and wheel. Trajectory of the wheel centers' during motion generates a soft curve, thus, horizontal motion of the wheel center does not break.

Since in figure 2-6 (b), height of the obstacle is more than the half diameter of wheel, this condition can be classified as *climbing*. Climbing motion consist of two sub motions. First one is a vertical motion, which causes a horizontal reaction force on wheel center . This vertical motion's instant center (IC_2) is at infinity. Second one is a soft rotation similar to figure 2-6 (a) with instant center of rotation (IC_3) at the corner.

2.6 Advantage of Linear Motion

Although, load distribution advantage of rocker-bogie, a critical problem can occur when climbing over an obstacle. Wheel forces on opposite direction of motion produce a moment about pivot joint to rotate bogie.

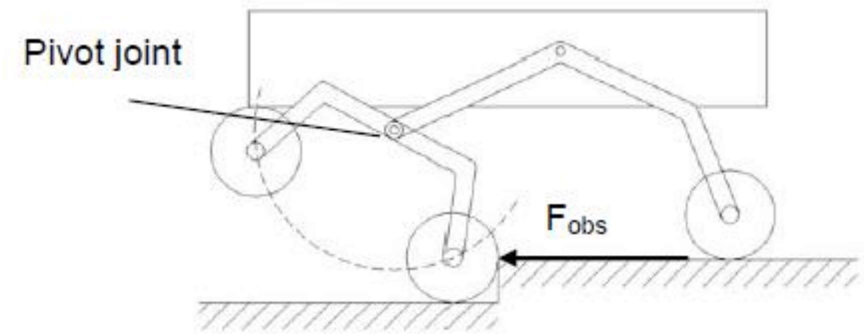

Figure 2-7: Bogie overturn problem

As we discuss in wheel forces, there are several forces act on wheel on x axis. If the surface friction of an obstacle is not enough to climb, obstacle force (Fobs) can reach high values. This problem can also occur while middle wheel actuator failure. Driving velocity is also restricted by bogie overturn problem. Bogie pitch angle can be adjusted by active control methods .

An easy solution method for this problem can be a linear motion suspension usage where obstacle reaction force cannot create any moment.

STRAIGHT LINE MECHANISMS

In machine science, it is important to generate special curves, exact circular motion and straight line. Dimensional synthesis theories are used to generate a special curve with coupler. There are different analytical and graphical synthesis methods for motion generation, function generation and path generation.

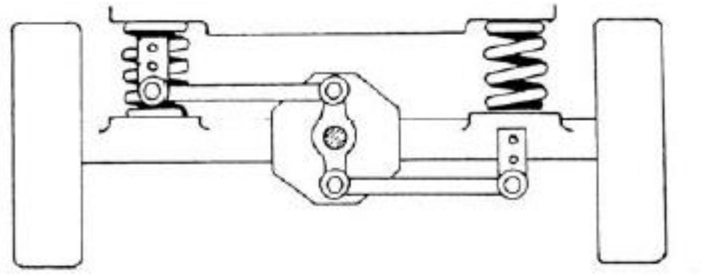

Figure 3-1: Watt's linkage application on rear-suspension

Linear motion mechanisms have wide usage area in suspension mechanism design. Most of the suspension members are needed to move on a straight line for lateral motion of an axle . In theoretically, a four-bar mechanism generates a coupler curve in 6th order equation. Some portion of this curve can be close to a theoretical line with small deviation which can be neglected . Usually, these mechanisms generate linear motion from a rotational motion of a crank. For this kind of design, force transmits from crank to coupler. In suspension designs, force is applied from ground to coupler. This force generates a moment on crank that balanced with a spring's reaction force.

4.2.2 Geometric Trajectory of Lambda Mechanism

By using these parameters, the instant positions and trajectory of lambda mechanism can be drawn as below

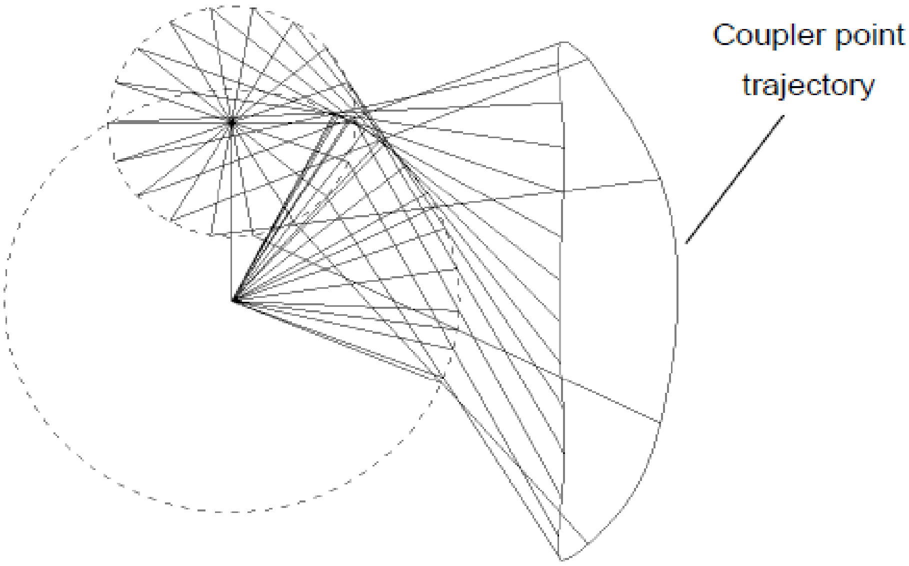

Figure 4-11: Trajectory of one wheel at different positions

Mechanism works linear in approximately 260 degrees angular displacement of crank. During this motion link B displacement is 80 degrees. This linear part with 490mm vertical distance is the workspace of the double lambda mechanism. *Return motion* of the coupler curve will be out of our study.

4.2.3 Singularity

If a mechanism gets into position where displacement of output link is undefined or impossible with driving force of input link, this condition called *dead position* or *singularity* [18]. Four-bar mechanism gets singularity if transmission angle β reaches 0 or 180 degrees where input link (coupler) cannot transmit force to output link (rocker). This problem can be solved with help of other link or inertia effects. If another force applied from rocker to coupler, mechanism can continue its motion. For our bogie design we have to avoid from singular positions near workspace in order to transmit force from one lambda mechanism to other. If one side gets singular angle, whole mechanism will lock.

Lambda mechanism has two singular configurations like other four-bar mechanisms.

4.2.4 Double-Lambda Mechanism Connection

New bogie design consists of two lambda mechanisms which are connected symmetrically. Thus, wheels move on a *straight line* but in *opposite direction* of each other. This design balances the reaction forces on each wheel; therefore the traction force remains same for each wheel whether one wheel is on upper position.

Symmetric connection of two mechanisms is a critical process. Since the both sides of the bogie will work in linear part of the curve, one side will be opposite position of other side. While designing this connection we must avoid from singular configurations of the mechanism.

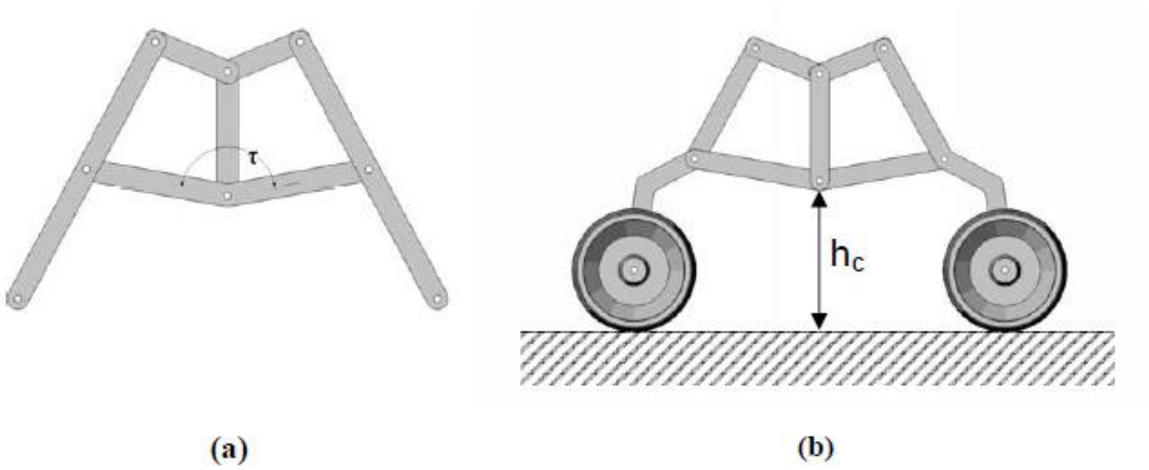

Figure 4-14: (a) Connection between two lambda mechanisms, (b) definition of ground clearance

Symmetric lambda mechanisms are connected to each other with a V-shaped rigid link. Angle τ can be selected by geometrically. The constraint of this angle is ground clearance of bogie (h_c) and maximum obstacle capacity. For our parameters, optimum connection angle $\tau = 160^0$.

4.2.5 Adaptation of Double-Lambda Mechanism into Rocker-Bogie Suspension: LBS

Rocker-bogie mechanism has advantages while distributing load on the wheels nearly equal. To obtain this useful property, double lambda mechanism can be combined with former rocker-bogie design.

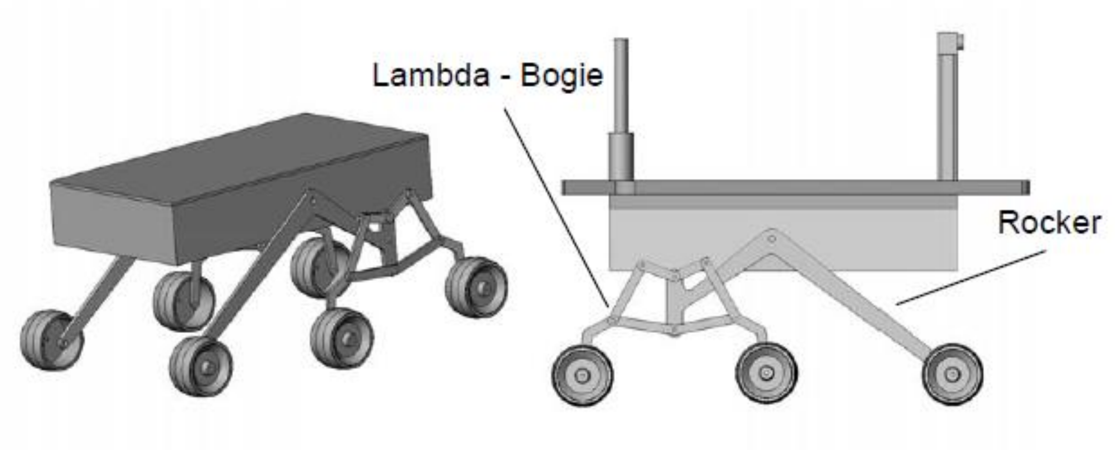

Figure 4-15: Experimental suspension design LBS

Linear Bogie Suspension (LBS) has nearly similar off-road capacity with linear bogie motion. Small angular displacement of rocker which affects linear motion of bogie can be neglected.

Two planar mechanisms are connected to each other by a differential mechanism. When one side climbing over obstacle, this mechanism rotates the main body around the rocker joints by average angle of two sides.

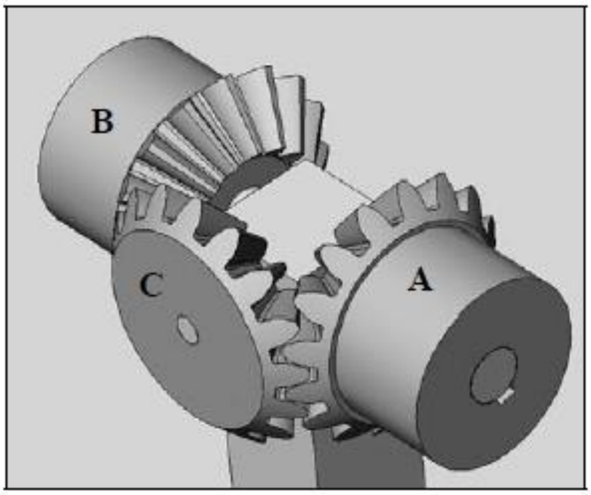

Figure 4-16: Differential gear mechanism between right and left rockers

Rocker

Gear A connected to left, gear B connected to right and C is assembled on the main platform. In differential mechanisms, all gear ratios are same. That means if gear A rotates 10 degrees and gear B rotates 20 degrees, main platform will rotate 15 degrees.

4.2.6 Mobility Analysis of LBS Mechanism

Three-dimensional kinematic diagram of whole LBS mechanism is shown in figure 4-17. We can assume a cardan joint connected between two rockers instead of differential mechanism for easier calculation.

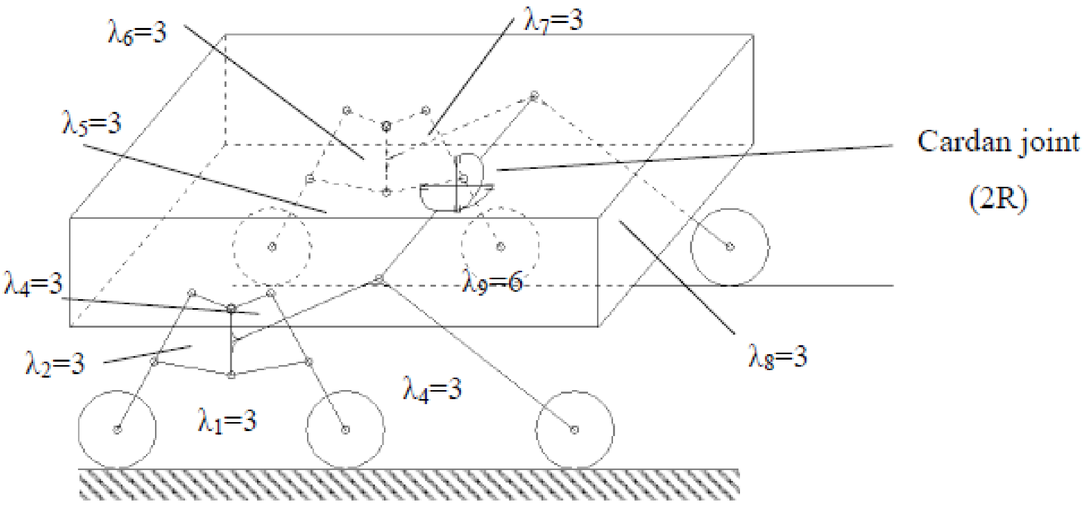

Figure 4-17: LBS kinematic diagram

Structural formula with variable general constraint for the mechanical system (4.2) is;

$$W=\sum_{i=1}^{j} f_i-\sum_{k=1}^{L}\lambda_k$$

For our mechanism;

P_1 – Kinematic pairs with one degree of freedom : 22

P_2 – Kinematic pairs with two degrees of freedom (higher kinematic pairs): 12 and 1 universal joint (with 2R)

On the left and right side of the mechanism, we have 8 loops with λ = 3 and 1spatial mechanism (Cardan joint) λ = 6. Therefore;

$$\sum_{k=1}^{L}\lambda_k=\sum_{k=1}^{8}3+\sum_{k=1}^{1}6=8\cdot 3+1\cdot 6=30$$

$$W=\sum_{i=1}^{j} f_i-\sum_{k=1}^{L}\lambda_k=(22+12+2)-30=6$$

Mobility analysis shows that rover suspension mechanism has total 6 degrees of freedom.

4.2.7MANUFACTUTING PROCESS

Adapting to terrain parameters, there are different possibilities for rover suspension like LBS. Spring and damper application to double lambda suspension good solution for high-speed off-road vehicles.

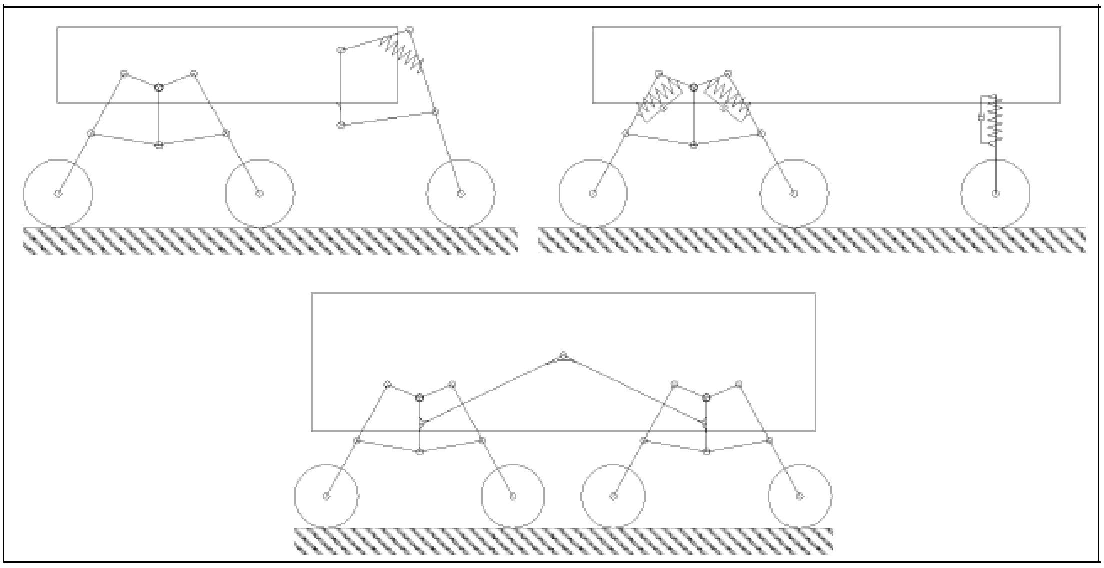

Figure 4-18: Different applications of lambda bogie suspension

STATIC ANALYSIS

6.1 Wheel Reaction Forces

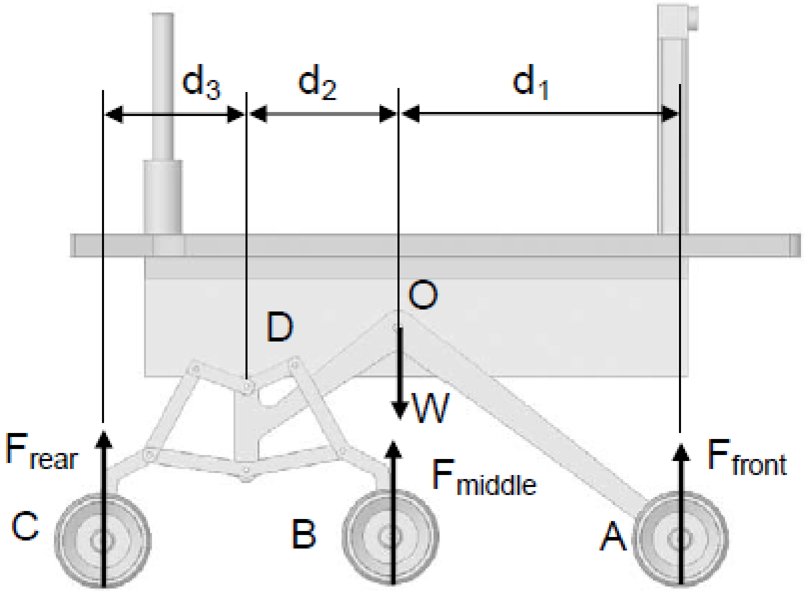

Figure 6-1: Force diagram of LBS

If bogie is symmetrical, distances between CD and DB will be equal. For this reason, reaction forces of rear and middle wheels are the identical.

Moment on point O;

$$M_o = (F_{rear} + F_{middle}) \cdot d_2 - F_{front} \cdot d_1 \tag{6.1}$$

For equilibrium;

$$M_o = 0$$

$$(F_{rear} + F_{middle}) \cdot d_2 = F_{front} \cdot d_1 \tag{6.2}$$

If $\frac{d_2}{d_1} = \frac{1}{2}$

the reaction forces will be equal. Due to fact that, for small angular displacements horizontal displacements will be very small, reaction forces will be very close to each other. For our design,

$$\frac{d_2}{d_1} = 0.75$$

to increase climbing capacity.

6.2 PERFORMANCE AND CALCULATIONS.

During operation on rough terrain, another problem is stability of the rover. If a robot can maintain its balance at all time in freezing position, it can be said that the robot has static stability. Physically, the boundary for stability criteria is related with polygon, which consists of contact points of wheels and ground.

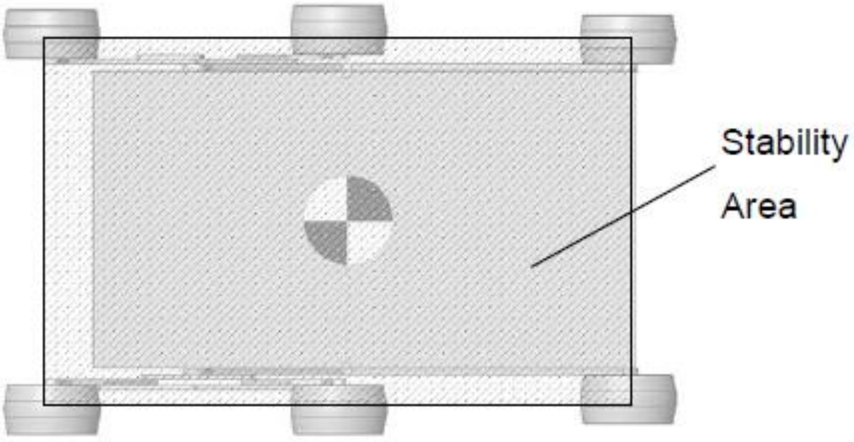

Figure 6-2: Stability area consists of contact points

If center of gravity projection on the ground plane, stays inside of the stability area robot will be stable. This shape can be narrowed depending on safety factor. The stability of robot, which is stationary or moving with constant speed, can be defined with gravitational stability margin . This margin is the minimum distance between projection of center of gravity on the ground plane to the edge of convex region.

The maximum slope of the terrain where robot can climb is called gradebility.

Maximum downhill and cross-hill gradeability definitions are:

6.2.1 Down-Hill Gradeability

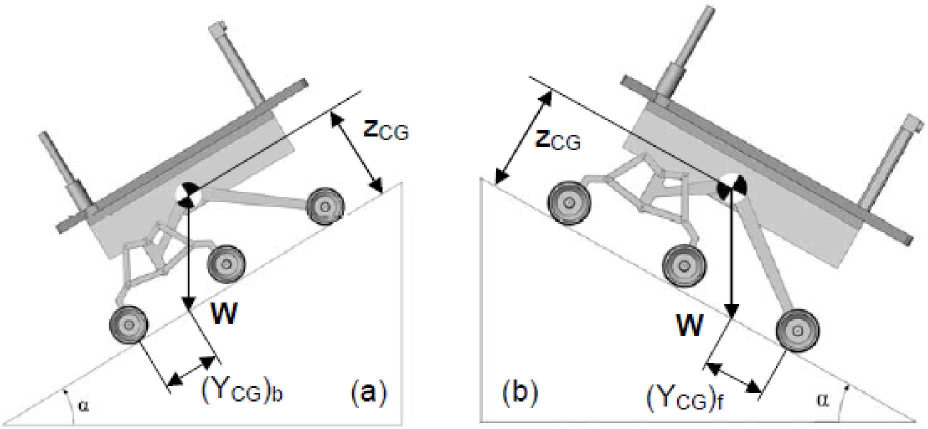

Figure 6-3: Downhill rear (a) and front (b) stability margins and dimensions

$$\alpha_{d\max} = \min\left\{\arctan\left(\frac{(Y_{CG})_f}{z_{CG}}\right), \arctan\left(\frac{(Y_{CG})_b}{z_{CG}}\right)\right\} \quad (6.3)$$

6.2.2 Cross-hill Gradeability

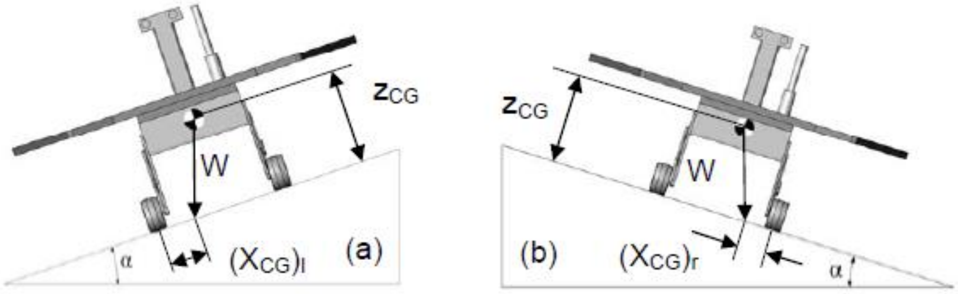

Figure 6-4: Lateral stability margins and dimensions

$$\alpha_{c\max} = \min\left\{\arctan\left(\frac{(X_{CG})_l}{z_{CG}}\right), \arctan\left(\frac{(X_{CG})_r}{z_{CG}}\right)\right\} \qquad (6.4)$$

The maximum slope and stability margins can be calculated by:

$$Y_{CG} \geq Z_{CG} \tan\alpha_{d\max}(1+SM) \qquad (6.5)$$

$$B_{WW} \geq Z_{CG} \tan\alpha_{d\max}(1+SM) \qquad (6.6)$$

In equation (6.5) and (6.6), term SM is called safety margin which is a safety factor for uncertainties of wheel and center of gravity position.

Evaluation of Test Results

After different field and obstacle simulations, LBS design demonstrates a similar obstacle capacity with *rocker-bogie* suspension. Advantage of the linear suspension is its more reliable structure with linear motion. This feature also can be a transition from quasi-static operation to fast-speed operation of planetary rovers.

Since climbing operations need high surface friction, a vehicle which can climb an obstacle more than 2 wheel diameters should have an active climbing system. Passive suspension mechanisms capacity limit depends on wheel diameter where the limit narrowed by overall size of the robot.

Chapter 8:- COSTING

8.1 RAW MATERIAL COST:-

The total raw material cost as per the individual materials and their corresponding rates per kg is as follows,

8.2 COST OF PURCHASED PARTS :-

SR NO.	DESCRIPTION	QTY	COST
1	GEARED MOTORS	08	3000
2	BATTERY	01	960
3	Bolts & Nut	-	160
4	DPDT SWITCHES	02	90
5	SWITCH BOARD AND WIRING	01	450
6	MOTOR CLAMP	6	250

The cost of purchase parts = Rs 6420/-

8.3 TOTAL COST:-

TOTAL COST = Raw Material Cost +Machine Cost + Miscellaneous Cost

+ Cost of Purchased Parts +Overheads

= 12109

Hence the total cost of machine = Rs 12109/-- approx.

Chapter 9:- Advantages and applications

9.1 ADVANTAGES OF ROCKERS BOGIE SUSPENSION SYSTEM:-

1. 5000 kg push force, makes possible suspensioning of heavy sections possible
2. Ease of operation
3. No spring is used.
4. Gradual application of force prevents the chassis damage.
5. Low manufacturing cost.
6. Ease of maintenance.
7. No piston cylinder or fluid is used

9.2 APPLICATIONS

1. Automobile industry
2. Army tankers.
3. Material handling system.
4. Agriculture equipment manufacture.

Chapter 11:- FUTURE SCOPE

The high costs and dangers associated with space exploration have led NASA and other private enterprises to pursue planetary research through the use of unmanned robotic systems. Continued interest in lunar, Martian, and deep-space exploration has created a demand for many surface rovers, for a variety of research purposes. With the moon, much of the interest lies within its potential reserves of frozen water, methane, and ammonia, which have the potential to be converted into fuels (Neal, 2009). These moon-made fuels may greatly reduce the costs of future space exploration, by reducing the amount of fuel that needs to be transported from Earth. The moon‟s potential abundance of Helium-3 is another area of key interest, as it may be used as a fuel for clean fusion power plants on Earth (Blewett, Ouyang, & Zheng, 2008). Similarly, interest in Mars stems from our desire to learn more about its environment and potential to support life and future colonization.

While there are many reasons to explore the moon and Mars, few have had enough economic potential to gain direct interest from the private sector. Due to the high cost of space exploration, most missions to date have been conducted by NASA and other government-supported organizations. However, the continually decreasing cost of technology and economic potential in natural resources has led some private companies to pursue space transportation and exploration as a core business. For example, Astrobotic Technology, Odyssey Moon, and Armadillo Aerospace are just a few companies that are developing rovers and landers for different space missions. While companies like these have made progress in the commercialization of space exploration, the inherently high costs continue to hinder economic feasibility.

There are many factors contributing to the high cost of space exploration. Launch vehicle costs are the most substantial barrier to private enterprise. While the cost associated with getting materials to space varies largely based on the size and capacity of the rocket, some estimates show that it costs about $10,000 per kg to get material into Low Earth Orbit (LEO) (Wilcox, 2006). However, some evidence suggests that the costs of planetary exploration are even higher.

For example, the company Astrobotic Technology currently has a launch agreement to send their

lunar rover to the moon, and is offering to integrate third-party payloads on their lander or rover.

Companies and government organizations have the opportunity to add payloads, such as

scientific equipment or mini-rovers, at the cost of $1,800,000 per kg (Astrobotic, 2011). This

large difference in price between getting material to LEO versus the surface of the moon shows

how prohibitive the costs of planetary exploration can be.

These high launch costs mean that all space vehicles and space-related technologies must be

thoroughly tested on Earth, before they make the expensive journey to space. Whether it is

NASA‟s space shuttle, a robotic arm for the international space station, or a surface exploration

rover, all components and systems are tested in analogous Earth environments. For planetary

exploration rovers these analog tests are normally conducted in harsh Earth environments such as 2

the deserts of Arizona or the frozen tundra of the Arctic. Places like these are also used to test the ruggedness of the rovers and their resistance to large temperature swings. They also have similar

terrain to the Mars or the moon, making them ideal for testing the rover‟s mobility. While this

type of analog testing is very useful, it is not without its own high costs.

The need to develop specialized high-fidelity systems capable of operating in harsh earth

environments typically leads to longer development timelines and greater expenditures. While

specific applications will always require unique designs, there are many commonalities in

planetary rovers. Issues such as mobility, navigation, and vision, may differ slightly between

missions but are largely the same in most scenarios. Given these fundamental characteristics of

many planetary rovers we believe that a modular and ruggedized system meeting these basic

requirements would aid in the process of developing space-ready technology. There are currently

many mobile research platforms available, yet few are designed to operate in the harsh earth

environments that are often used for planetary surface rover testing. By creating a rover that is

suitable for these types of environments, our goal is to facilitate the development of rovers and their related technologies, in addition to lowering development costs. We also hope that the

platform developed can be tested and improved upon, to potentially serve as a model for a rover

that could go to the moon or Mars in the future.

Our mission is to design, develop, and test a rover to serve as a research platform, suitable for

testing planetary surface exploration technologies in harsh earth environments. The design will

focus on incorporating features that are believed to be essential for most planetary exploration

missions including:

1. Mobility and basic navigation
2. Tele-operation and intuitive user controls
3. Low mass and small form-factor

The rover will also aim to be low cost, ruggedized, and modular to allow for easy additions of

custom or Commercial-Off-The-Shelf (COTS) hardware components. It will also have sufficient

computing power and standard I/O ports to support a variety of additional payloads. The goal is to provide a platform that can be easily used for the development, testing, and validation of space

exploration technology, both hardware and software.

Chapter 12:- Conclusion and Result

CONCLUSION

In this thesis study, rover suspension mechanisms have been discussed. Linear motion mechanism of Chebyshev has been improved and applied for a Mars rover suspension mechanism. Results of the simulations and position analysis show that linear motion bogie has good performance during field operations. On the other hand, different designs should be discussed to improve the capacity of suspension.

This research also shows that it is possible to construct useful mechanisms by arranging classical four-bar mechanisms. These design possibilities can be discussed with new structural synthesis formula, which has been introduced and applied on rover suspension design.

Future studies may continue to discuss dynamic behaviour of the suspension mechanism. Anyone can see that planetary exploration will be the future robotics topic with unusual mobility and high stamina robots.

The purpose of this study is to put another stone on the pyramid of scientific knowledge. Although the art of mechanism design seems like it has lost its popularity due to the powerful control algorithms, there is no doubt that future robotics study will continue to search for new mechanisms.

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