An Advanced Spider-Like Rocker-Bogie Suspension System for Mars Exploration Rovers

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Abstract This paper describes the working of the system design for the Mars rover. The rover, developed to compete in the Mars Society's University Rover Challenge 2015, was designed to perform various tasks such as site survey, sample return, equipment servicing, and astronaut assistance in a Mars-like landscape of dry, non-vegetated, rocky terrain. The complete design features a bioinspired eight-wheeled drive mechanism, an integrated robotic arm along with a stereo vision technique for advanced image processing. This paper focuses on the drive mechanism of the rover design. The 8-wheeled rover combines the rocker-bogie mechanism with four rocker wheels and four spider-leg wheels. The spider legs ensure that it can traverse over heights greater than the chassis height, which could be three times as much as the diameter of the wheels. NASA's current rover can only traverse a height twice the diameter of the wheel. Additionally, the wheels are actuator-powered, and hence, the slope of the rover can be adjusted in such a way that it does not topple for a wide range of inclination allowing the rover to traverse over highly rugged terrain. The rover design can be modified for many applications notably the exploration of alien planets, deep sea trench, and other environments

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where human exploration is almost impossible. This effort to make the rover mechanism more efficient may one day be instrumental in detecting life and many such possibilities, in Mars and other planets.

Keywords Drive mechanism · Mars rover · Spider legs

1 Introduction

The Mars rover is a vehicle that has been designed to traverse the rugged terrains of Mars and collect samples of various items on Mar's surface. Scientists over the years have tried to explore the possibility of life on Mars. Such explorations have been mostly done using rovers. Hence, rovers need to be specially designed to traverse all kinds of terrains and must be equipped with state-of-the-art technology. A common design element is most rovers over the years, which is the rocker-bogie mechanism. The rocker-bogie mechanism has quite a lot of advantages and is hence a well-established mechanism. The main advantage is that it ensures that all the wheels of the rover are in contact with the ground at all times. This advantage is key to creating a stable all-terrain system. Consequently, the traction of the rocker-bogie provides is equal and reliable, allowing a smooth running even on the uneven terrains.

The earliest notable Mars explorer, the *Pathfinder*, landed on Mars with a fully function rover on Mars on July 4, 1997. The rover carried a wide array of scientific instruments to analyze the Martian atmosphere, climate, geology, and its rock and soil composition. Sojourner, the Pathfinder's rover, made observations that answered numerous questions about the origin of the rocks and other deposits on Mars. Following its stead, the *Opportunity* successfully investigated soil and rock samples and managed to take panoramic images of its landing site giving us valuable information about the Martian terrain and other site conditions. It is the data that were collected in these missions, using sampling technology, which allowed scientists at NASA to theorize about the presence of hematite and consider exploring the possibility of finding water on the surface of Mars. *Curiosity*, another historic milestone in the history of alien planet exploration, was assigned the role of investigating Martian climate and geology. It assessed whether the selected field site, Gale Crater, had ever offered environmental conditions favorable for microbial life and future investigated the role of water in planetary habitability as preparation for future human exploration [1–4]. In these types of rovers, only 6-wheeled rocker-bogie [5–12] suspension is used.

This paper proposes an 8-wheeled rover which combines four rocker wheels which form the rocker-bogie mechanism along with four spider-leg wheels. Figure 1 shows the SolidWorks model of the rover. The spider legs ensure that it can traverse terrains with heights much greater than the chassis height. Additionally, since the wheels are actuator-powered, the slope of the rover can be adjusted in such a way that it does not topple for a wide range of inclination and allows the

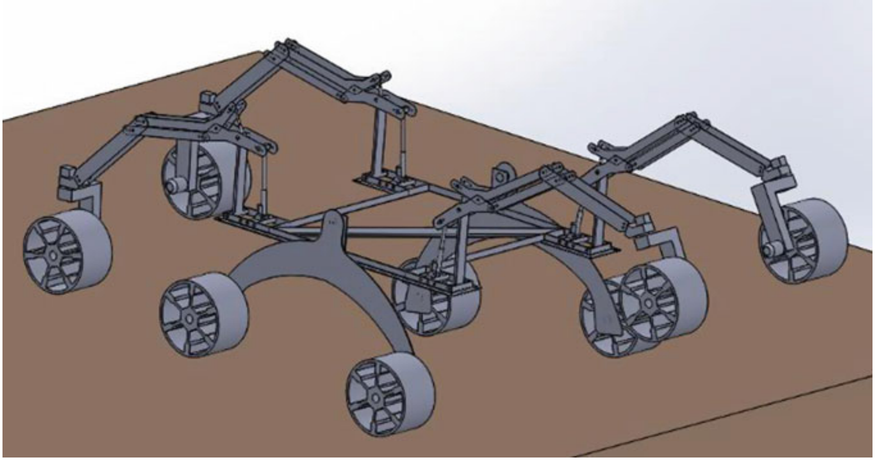


Fig. 1 SOLIDWORKS model of the rover with front spider legs elevated

rover to traverse over highly rugged and uneven terrain. It provides a significant amount of supplemented traction with the ground even in terrains where there is a negative slope or vertical drop of around 1 m using a spring–damper suspension mechanism. This is a significant improvement to the existing rocker-bogie mechanism which provides traction using its body weight alone. Moreover, this is done without compromising the strength of the chassis. The chassis has a factor of safety of 3.2 as per finite element analysis. The leg, which is a combination of the four-bar linkage, spring–damper, and the linear actuator, provides assistance for the rover to traverse over small hindrances. A member is hinged to the chassis. One end of that member is pinned to the actuator and the outer end to a four-bar linkage, making the system stable and flexible at the same time. Thus, the rover mechanism that has been described in this paper allows the rover to traverse all kinds of surfaces while maintaining stability and protecting the instruments that the rover carries.

2 Rover Mechanical Design

The design of the rover is to allow it to traverse rough and rocky terrain which at present is not possible using conventional vehicle design. Therefore, the major aim is to design a rover which has an effective mechanism removing the disadvantage of modern day rovers. The chassis designed is in accordance with the set of rules and requirements that have to be met in order to contest in the event. There are certain restrictions set on the length and width of the chassis, its overall weight, ground clearance, etc., by the governing body of the “University Rover Challenge 2015,” and it was made mandatory that the rules be followed by the competing teams.

Table 1 Material properties of Aluminum 6061 alloy

Property	Value
Ultimate strength	310 MPa
Density	0.0975 lb/in^3
Strength-to-weight ratio	Moderate
Machinability	Highly machinable/weldable using TIG
Cost	Moderate
Availability	Available in Indian market

2.1 Material Selection

Performance and strength are the major parameters which reflect the reliability of a vehicle. While designing and fabrication of the rover chassis, suitable low cost material had to be selected which maintained high strength-to-weight ratio, thereby improving the performance of the rover. Considering various parameters such as yield strength, material availability, density, strength-to-weight ratio, and mainly the availability and cost of the material, various options were explored. The search narrowed down to either graded aluminum or composite materials. Composite materials such as carbon fiber are mainly used in the conventional NASA designs of MARS rovers. Based on the factors in Table 1, we choose our material of construction as Aluminum 6061 just to produce the prototype required for Mars Desert Research Station mars-like terrain.

Aluminum 6061, a precipitation hardening alloy, majorly comprises of magnesium and silicon. It was chosen for its good physical properties and great weldability. Being one of the most common alloys of aluminum, it is easily available and cheap. Pretempered grades such as 6061-O (annealed) and tempered grades such as 6061-T6 (solutionized and artificially aged) and 6061-T651 (solutionized, stress-relieved stretched, and artificially aged) are the commonly available types [13].

2.2 Chassis Model

In order to design and manufacture the original chassis, continuous optimization had to be done. The FOS has to be higher, and the deflection should be minimal. Hence, the careful selection of the channel type is required for further modeling. For minimal deflection and increased FOS, a rectangular channel of 3 mm thickness was selected as the suitable channel. The rectangular channel of 3 mm thickness is capable of withstanding both vertical and longitudinal load. Figure 2 shows the channel dimension, and Table 2 shows the channel specification. As most of the loads are exerted upon the mounting regions of linear actuators, the channel can now take fluctuating loads. The final design incorporates enough space which

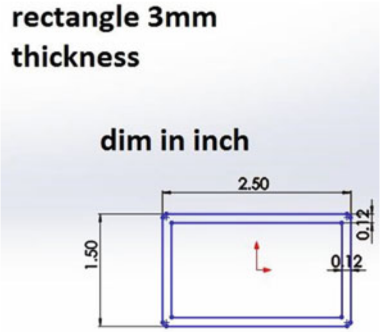


Fig. 2 Dimensions of the channel used

Table 2 Channel Specifications

Material Specification	Al-6061 T6
Type of channel used	Rectangular channel
Channel size	2.5 in * 0.5 in
Thickness	3 mm
Chassis dimensions	105 cm * 80 cm
Weight	4.1 kg

satisfies the component restraints and provides necessary strength for the rover. The chassis analysis was done after designing the final chassis. Figure 3 shows the final chassis design.

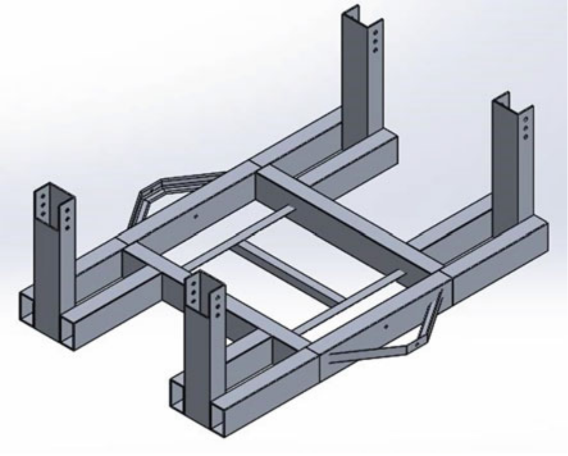


Fig. 3 Final design of the chassis

3 Static Analysis of Model

For the static analysis, the fixed supports were given as the support members of C arms. The overall weight requirement comes around to be 50 kgf. So a force of 500 N is given to each of the leg members. Figure 4 shows the distribution of forces and the fixed support, whereas Fig. 5 shows the meshing. Figures 6 and 7 show the safety of factor and total deformation.

The values obtained from the FEA analysis are as follows: factor of safety = 5.8571(withstand high load), deformation = 0.001886 cm (little deformation), and max equivalent stress = 4.263 * 10^7 Pa (low stress). Analyzing the data, it can be concluded that the chassis is strong and can easily withstand high strength. Therefore, the chassis need not be further optimized. The chassis is then built with real-time boundary conditions. Figure 8 shows the real chassis model.

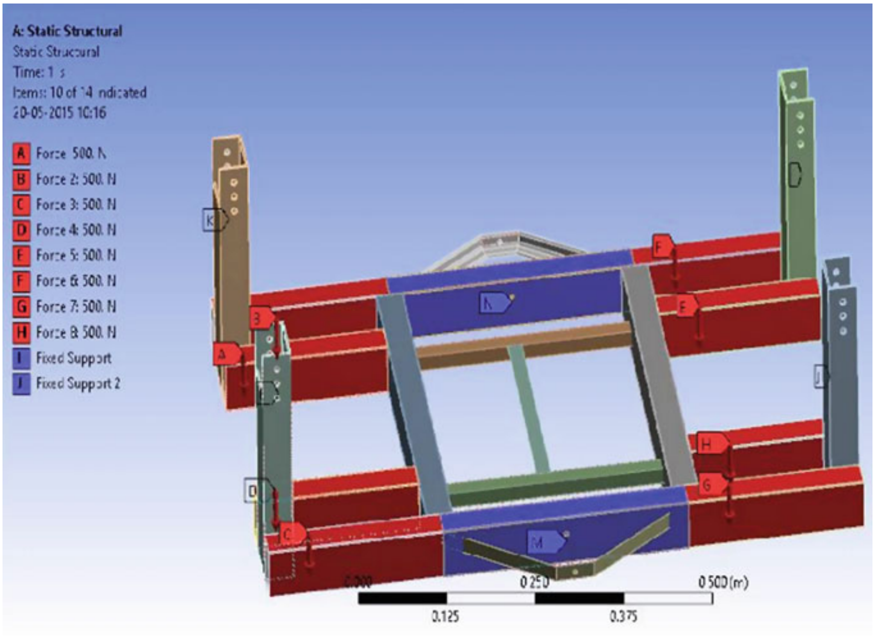


Fig. 4 Distribution of forces and the fixed supports

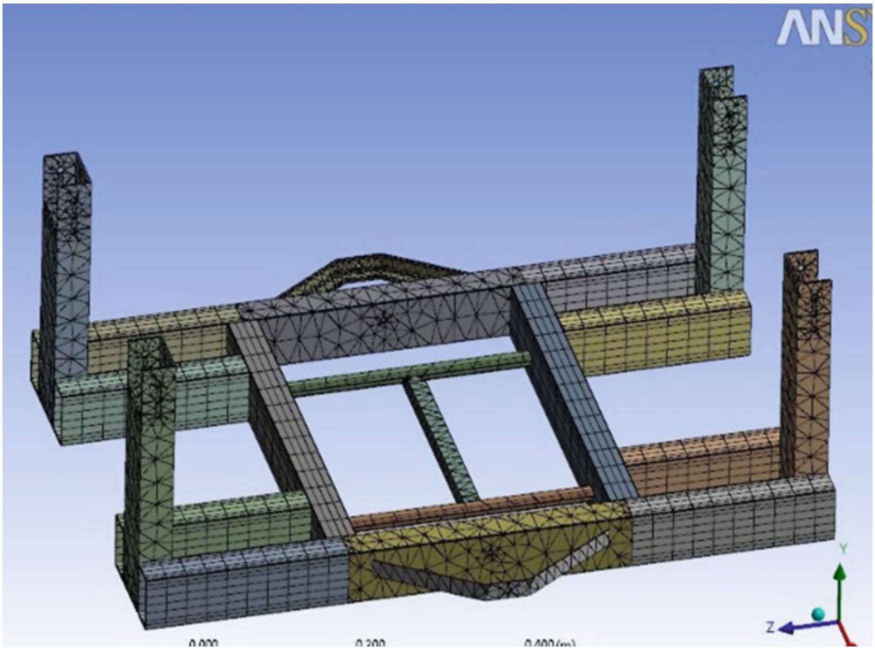


Fig. 5 Meshing

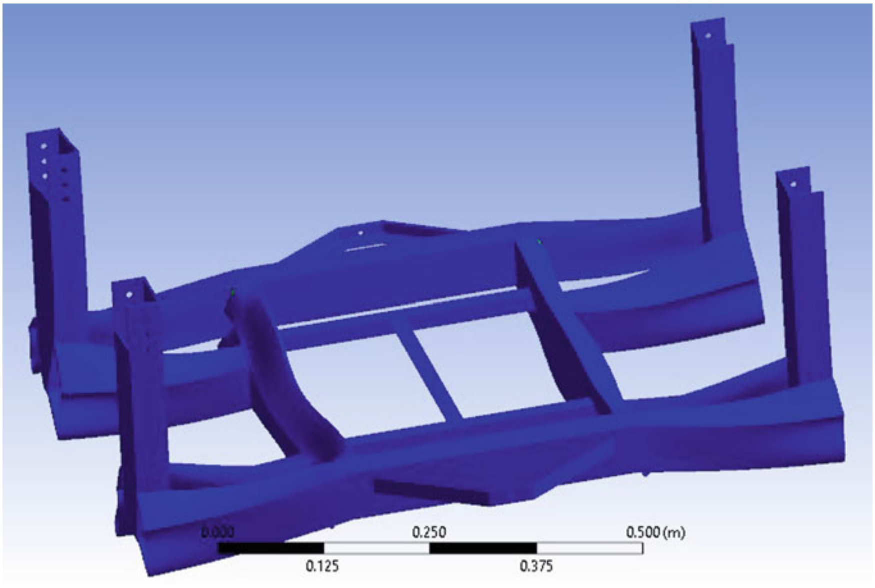


Fig. 6 Factor of safety

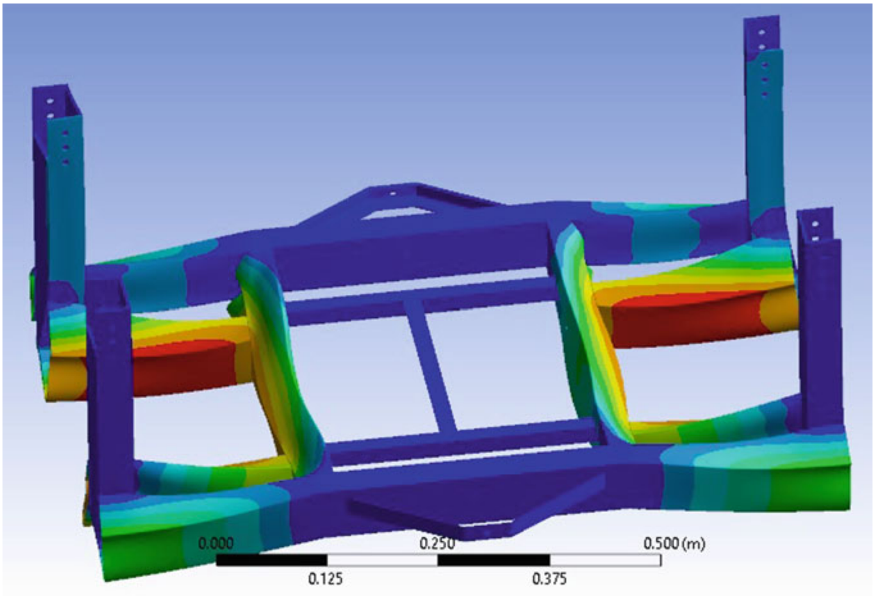


Fig. 7 Total deformation

4 Mechanical Development and Kinematic Analysis

For the chassis that has been built, a proper mechanism has to be developed which enables the legs of a vehicle to traverse up steps/rocks and still be able to take the impacts of varying ground terrain. The primary motive of the mechanism is to allow the rover to a climb high stepped terrain and still have a suspension system in place to provide restoring force for the legs to come down and provide traction for the wheels over the ground terrain. Such a mechanism will allow rovers to travel rough and rocky terrain while at present is not possible for conventional rovers.

In currently used designs, there is a limit to the height that the rover can traverse, and it is extremely difficult for these designs to climb up very high steps. Using suspension designs with very soft shocks can cover rough and rocky terrain to an extent, but unfortunately, it is impossible for it to climb up huge steps and rocks. It is well known that an unexplored terrain can have unexpected challenges. Thus, it is essential for a mechanism to exist which can overcome such unexpected challenges. It is possible to test the conventional designs in unexplored areas, but these designs tend to suffer from disadvantages which would prevent them from prolonged use; hence, such designs are not feasible. Thus, there is a need for a novel and innovative design which will enable rovers to face unaccounted landscape challenges and allow it to carry on with the unmanned exploration, without human intervention or repair issues.

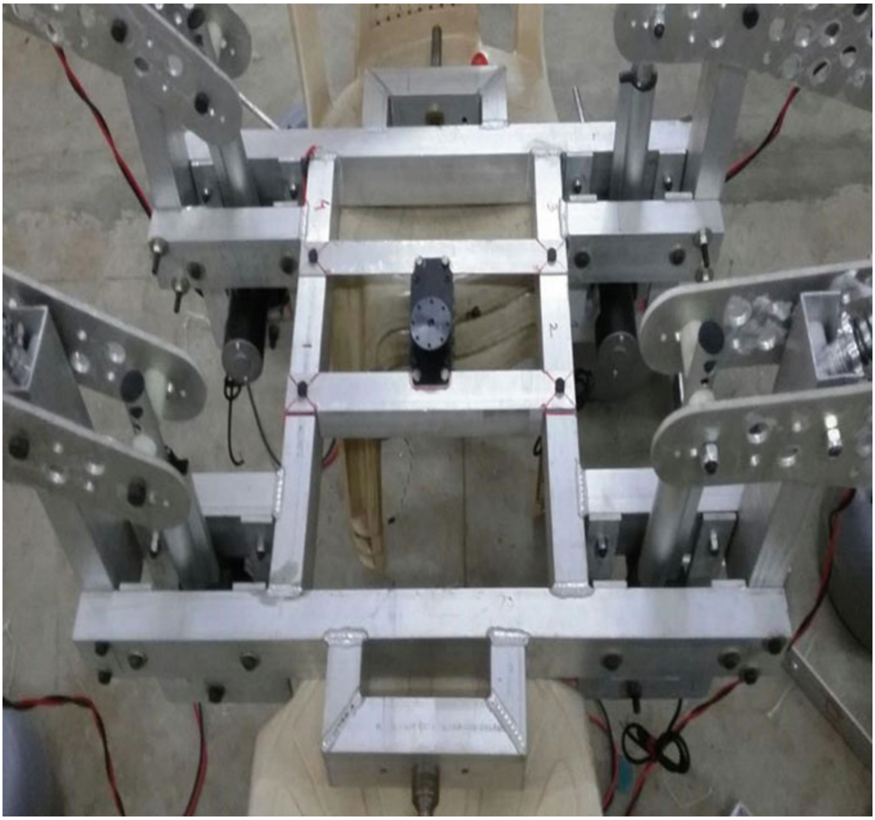


Fig. 8 Real-time chassis model

4.1 The Spider Mechanism

The spider-leg mechanism ensures that the vehicle can traverse over a height far greater than the chassis height. This could extend as far as thrice the diameter of the wheels. Additionally, since the mechanism is actuator-powered, the slope of the rover can be adjusted in such a way that it does not topple for a wide range of inclination and allows the rover to traverse over highly rugged or uneven terrain. It provides a large amount of traction with the ground even in terrains where there is a negative slope or vertical drop of around 1 m using a spring–damper suspension mechanism, and it achieves this without compromising on the strength of the chassis.

4.2 Line Diagram Depiction Showing Initial Position

Figures 9 and 10 depict how the spider legs help to support the load when all the wheels are in ground. Notice that initially, all the linkages are pivoted at the center point of Sl no 3 as shown in Fig. 9. This pivot point moves only when the rover encounters an unexpected terrain. The springs are mainly involved in traction control and in supporting the weight.

Figure 10 clearly depicts that the spider-leg, which is a combination of the four-bar linkage, spring–damper, and the linear actuator, provides assistance for the rover to traverse over small hindrances. As mentioned earlier, one link of the mechanism is hinged to the chassis. One end is pinned to the actuator and the other end to a four-bar linkage.

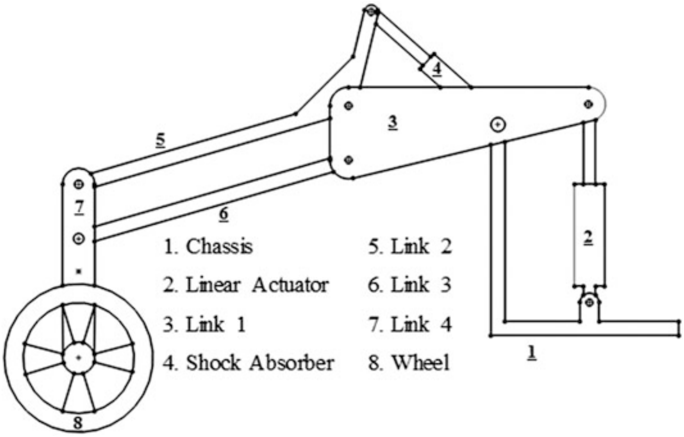


Fig. 9 Wheel in ground level

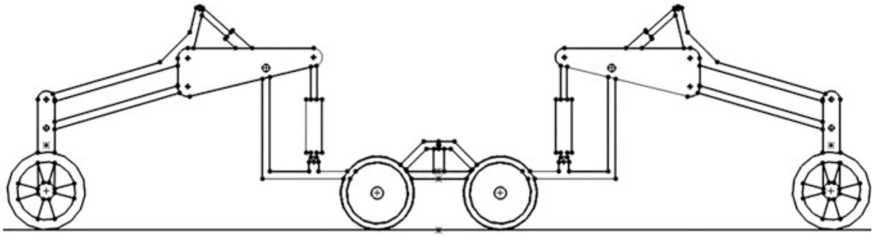


Fig. 10 The complete side view of the spider legs

4.3 Line Diagram Depictions Showing the Movements of the Rover

In Fig. 11, an example of the working of the spider-leg mechanism is shown at its mean position. At this position, the links are able to transmit the shocks of varying terrain to the shock absorber. When the wheels of the spider-leg mechanism encounter a small obstacle relative to its wheel size, it is able to easily overcome the obstacle as the shock absorber mounted on the top of the wheel's link gets compressed and the lift of the wheel is compensated this way.

In Fig. 12, as the spider-leg mechanism encounters a high obstacle, the linear actuator is retracted wirelessly, this causes the link mechanism to extend out and reach a greater height, and the shock on top of the mechanism is also compressed. However to get maximum reach and traction, there needs to be 2 spider legs in front of the vehicle. Therefore, 2 legs are raised. After this initial step, the vehicle rests on

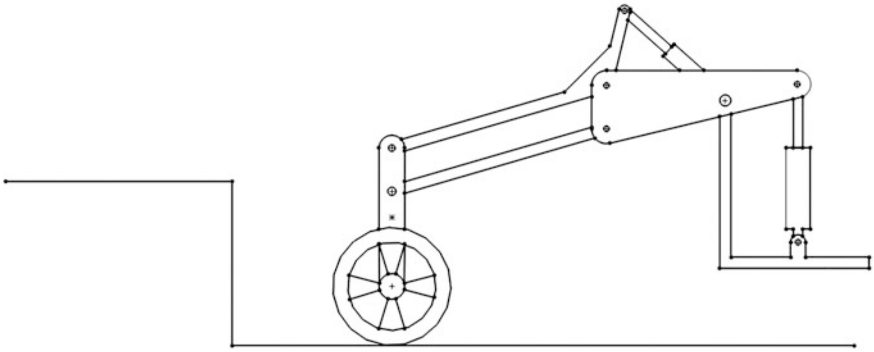


Fig. 11 An example of spider-leg mechanism approaching a stepped terrain

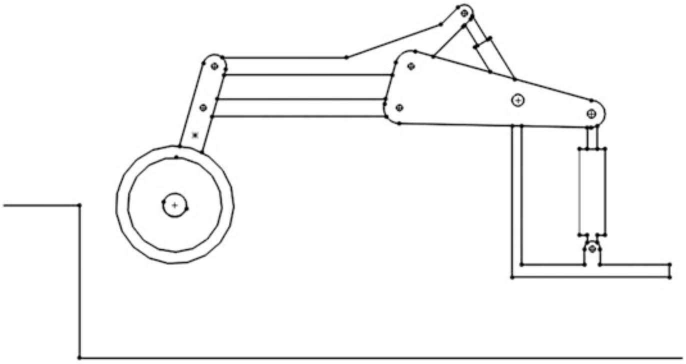


Fig. 12 An example of spider-leg mechanism raising itself

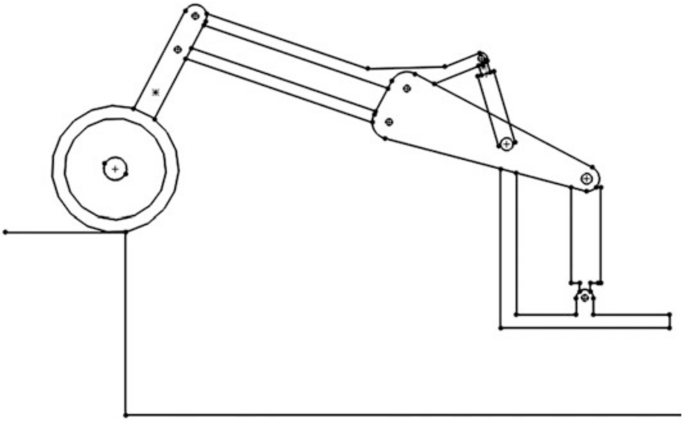


Fig. 13 An example of spider-leg mechanism overcoming a stepped terrain

the middle 4 wheels and the 2 rear spider legs. The lifting of the front spider legs allows the vehicle to reach terrain previously inaccessible and gain traction on top of the high terrain.

In Fig. 13, to effectively climb over a high obstacle, a total of 4 spider legs are required on a vehicle with individual drives, 2 spider legs at the front, which can be raised onto the high terrain and gain traction on the terrain, and 2 spider legs at the rear of the vehicle. The legs at the rear lower onto the ground effectively lifting the vehicle and giving a push to the entire vehicle, while the spider legs in front of the vehicle act to gain traction at the top of the obstacle and effectively pulls the entire vehicle up. This combination of the two forces allows the vehicle to overcome high stepped terrain.

4.4 Software Design Depiction

A SolidWorks model was designed, and the rover assembly was completed. This was essential for the manufacturing of the model. Figure 14 shows the solidWorks' rendered image of the mechanism, and Fig. 15 shows the isometric view of the entire rover making it easier to study the mechanism.

5 Kinematic Analysis of the Mechanism

The kinematic analysis is an integral part of the mechanism implementation. It helps us to study the trajectory of points, bodies (objects), and systems of bodies without considering the motion.

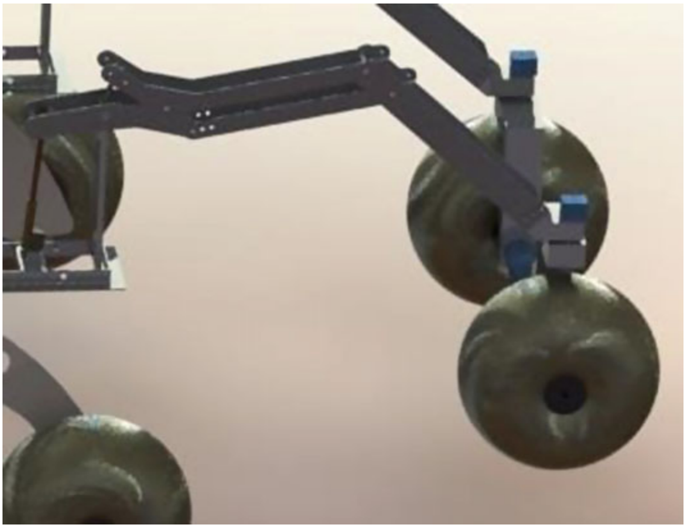


Fig. 14 SolidWorks' rendered image of the mechanism

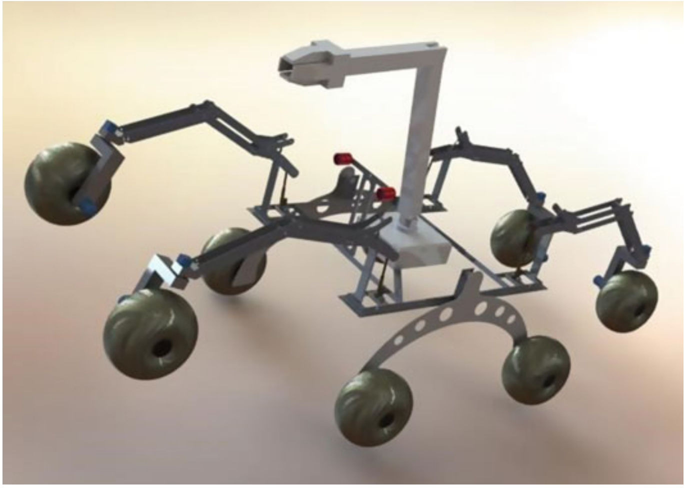


Fig. 15 An isometric view of the overall rover

5.1 Formulation of Velocity Polygon

If a number of bodies are assembled in such a way that the motion of one causes a constrained and predictable motion to others, it is known as a mechanism. The function of a mechanism is to transmit and modify the associated motion.

The leg of the rover moves according to motion which constitutes a planar mechanism. For planer mechanism, the degree of freedom of the mechanism can be calculated by Gruebler's criterion.

$$F = 3(N - 1) - 2j$$

where j = (1/2) (2N2 + 3N3)
where

N = the total number of joints, N2 = the number of binary joints, and N3 = the number of ternary joints.

According to the Grubeler's criterion if for a planar linkage the degree of freedom is one, then it is called a mechanism.

A spring in a mechanism can be converted to a turning pair. This is because the action of a spring is to elongate or shorten as it gets subjected to in tension or compression. A similar variation is obtained by two binary link joined by a turning pair.

The validation of the mechanism is done as shown below.

The mechanism consists of four binary links and two ternary links as shown in Fig. 16.

Hence, the total number of links is six.

$$\begin{aligned} F &= 3(N - 1) - 2J; \\ 2J &= 2 * n_2 + 3 * n_3 \\ &= 2 * 4 + 3 * 2 = 14 \end{aligned}$$

$$\begin{aligned} F &= 3(6 - 1) - 14 \\ &= 1 \end{aligned}$$

Hence, it is a mechanism.

The links move dependent of each other. Hence, the velocities of each link maintain a relation. So once we experimentally find a velocity of a link, we can find

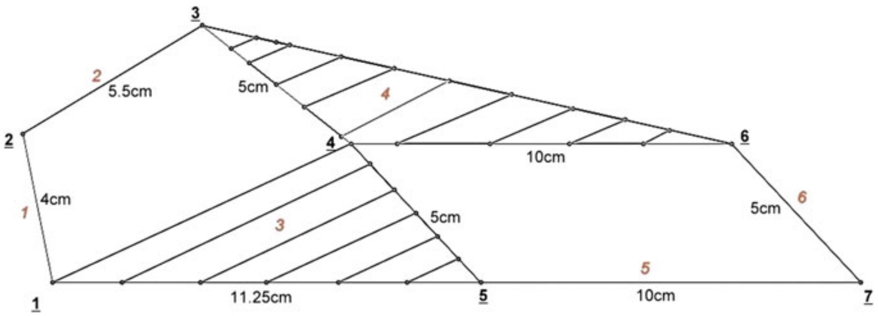


Fig. 16 Mechanism link diagram

out the absolute velocity as well as the relative velocity of other links with respect to reference links. To find out velocities this way, we must follow certain laws and constraints. They include laws like, the velocities of a joint are perpendicular to the direction of motion of a link and that the meeting points of line of action of velocity lines gives the velocity of the links with respect to ground.

Applying this method on the leg mechanism of the rover, the initial velocity given was found to be 7 cm/s. This velocity was given at the wheel of the rover. An assumption was made that the velocity of the wheel will be the same as that of the legs of the rover while traversing the terrain. From the velocity polygon, it was understood that the velocity with which the spring displaces is about one-tenth of the velocity with which the wheel moves up. Figures 17 and 18 show velocity diagram of links 5 and 7, and 6 and 7.

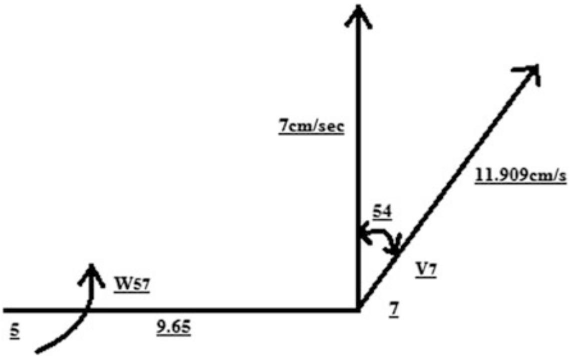


Fig. 17 Velocity diagram of links 5 and 7

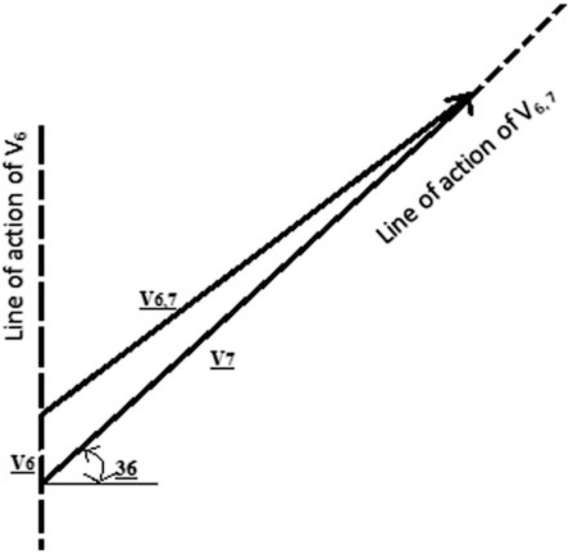


Fig. 18 Velocity diagram links 6 and 7

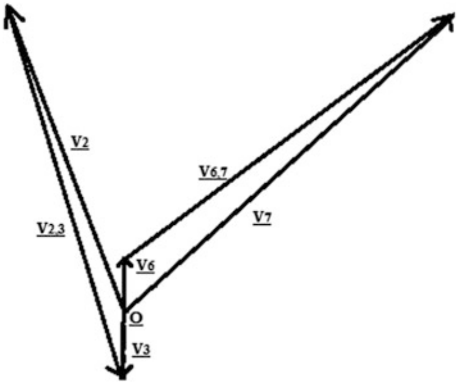


Fig. 19 Velocity polygon diagram

Initially, we assume the velocity of joint 7 to be 7 cm/s. Later, we have to find out the angular velocity of link 57 by the relation $V = r\,\omega$.

$W_{57} = V_7/L_{57}$

$W_{57} = 11.909/19.3 = 0.617$ rad/s

The known velocities are V_7 and the line of action of V_6 and line of action of $V_{6,\,7}$

$V_6 = 0.8$ cm/s and $V_{6,7} = 11.5$ cm/s

$W_6 = W_{6,7} = (V_{6,7}\ /L_{6,7}) = (11.5/7) = 1.15$ rad/s

$W_3 = V_6/L_{4,6} = (0.8/20) = 0.04$ rad/s

$V_3 = W_3 * L_{3,4} = 0.04 * 10 = 0.4$ cm/s

Now from the known $V_{3,}$ we find out V_2.

$V_2 = 5.7$ cm/s and $V_{3,2} = 6.3$ cm/s

Finally, velocity polygon is drawn showing all the absolute velocities and relative velocities of each link with respect to other links as shown in Fig. 19.

6 Dynamic Analysis Using Adams

The various parameters for the newly developed mechanism are found out with the help of ADAMS software. The parameters that were to be found out include velocity of every joints and links, acceleration of the links and joints, angular velocity, angular acceleration, force and torque acting on various parts, and finally the deformations of the spring, deformation velocity, and the forces that act on the spring. These are important for validating the new design. The basic governing equations that govern the kinematic analysis in ADAMS are based on the Eulerian and Lagrangian dynamics.

The mechanism of the leg of our rover was analyzed in ADAMS, and for the acceleration due to gravity 9.81, with the weight of the members, the graphs were plotted for each link. The results for each part that was analyzed are given below.

6.1 Simulation of the Spider Leg Using ADAMS

The leg mechanism was kinematically analyzed in ADAMS software as shown in Fig. 20 by giving the center of gravity for each specific links and specifically giving the connectors to each link. Afterward, motions were assigned to each of the joints. Later, graphs were plotted when simulated. Some of these are as shown below from Figs. 21, 22, 23, 24, and 25.

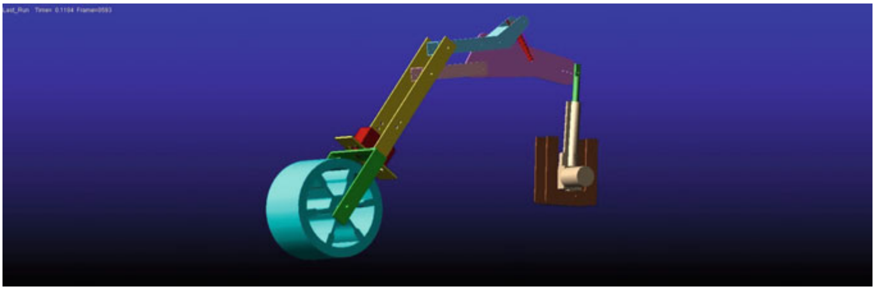


Fig. 20 Simulation in ADAMS

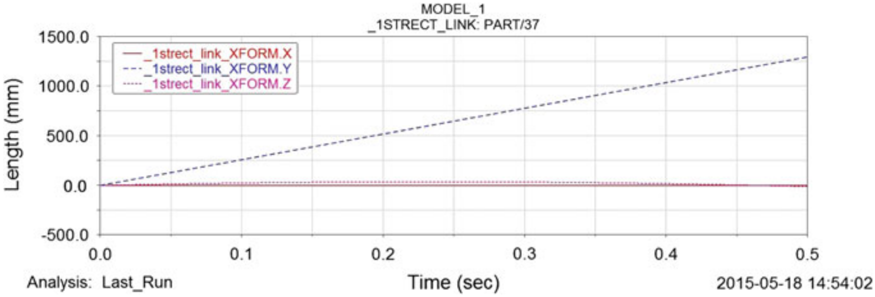


Fig. 21 Length versus time graph of rectangular link 1

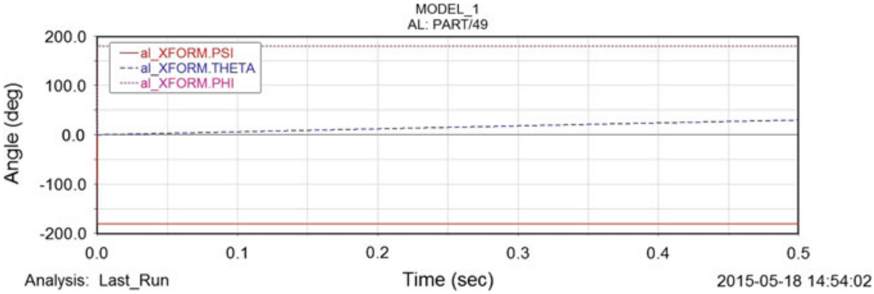


Fig. 22 Angle versus time graph for wheel

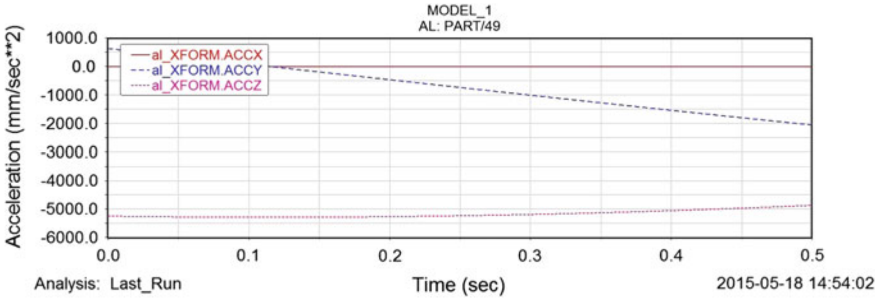


Fig. 23 Acceleration versus time graph for wheel

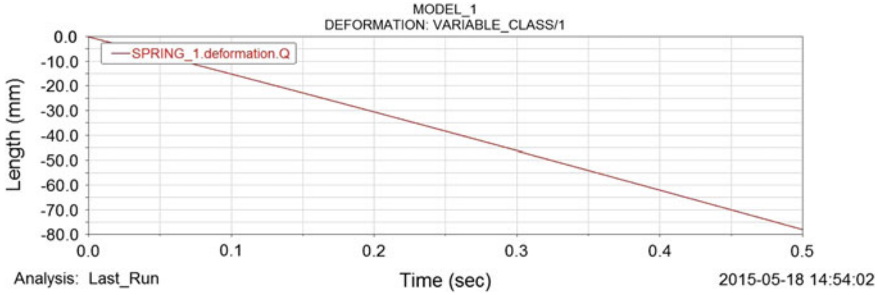


Fig. 24 Deformation versus time graph for spring

7 Linkage Spring Design

The linkage spring has to be carefully designed to support the weight while traversing a terrain in order in turn providing traction. For this, various parameters such as spring rate (spring constant), spring material, and free length have to be considered, and number of coils had to be fixed.

The cycle shock was the best available alternative for the shock absorption and maintaining traction. But the standard available cycle shocks have a very high stiffness rate. A spring has to be custom made for the specific purpose. So in order to do that, a spring had to be selected whose free length and the compressed length are known. Figure 26 shows the dimension of the spring used. But it is to be evaluated whether the spring can support prescribed weight. The load calculation for the spring is as follows.

To calculate the spring rate, we know that

Wire diameter = 4 mm;

Free length = 118 mm;

Compressed length = 80;

No of active coils = 13;

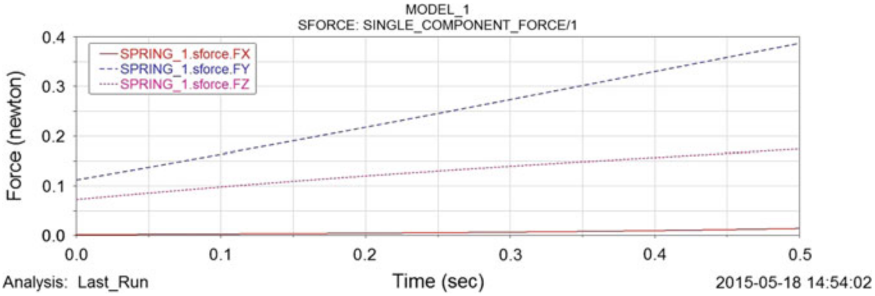


Fig. 25 Force versus time graph for spring

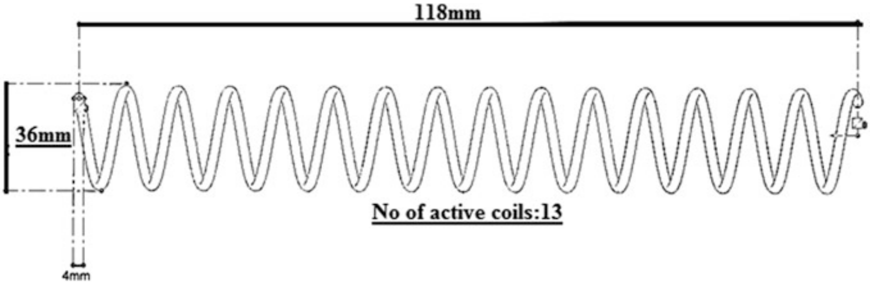


Fig. 26 Spring dimensions

Outer diameter = 36 mm;

$$\text{Deflection} = \text{Free length} - \text{Compressed length}$$
$$= 118 - 80 = 38 \text{ mm}$$

Spring rate = Spring rate/stiffness = (Modulus of spring steel * (wire diameter) ^{4})/ (8 * no of active coils*(mean coil diameter)^3

$$\text{Spring Rate} = \left(\left(209 * 10^9\right) * \left(4 * 10^{-3}\right)^4\right) / (8 * 13 * \left(36 * 10^{-3}\right)^3$$
$$= 5957 \text{ N/m}$$

$$\text{Force which can compress } 1'' = \text{spring rate} * \text{deflection}$$
$$= 5957 \text{ Nm} * \left(38 * 10^{-3}\right)$$
$$= 226 \text{ N}$$

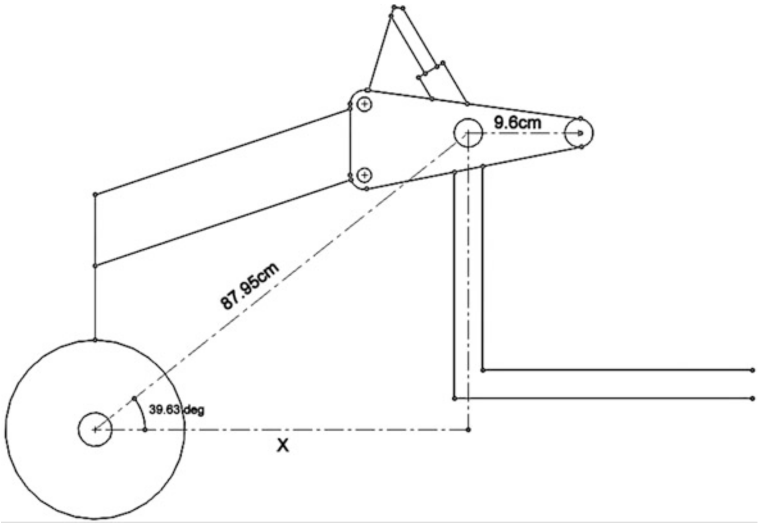
Hence, the load will be approx. 23 kgf required for the spring to compress “1” which is the desired value.

8 Calculation of Height Traversed by the Wheels Using the Mechanism

It is necessary that the calculation of height traversed by the wheel should be done for analyzing the mechanism. Here, the height traversed by the wheel is calculated when the actuator moves down 1 cm. The following figure shows the structural dimensions of the mechanism. Using this, the maximum height traversed when the actuator is at its maximum limit can also be found out.

Under a load of 200 lbf (90.7 kgf), the actuator speed is 0.90 in/s.

Under a load of 600 lbf (272 kgf), the actuator speed is 0.39 in/s.



$$\theta = 39.63^\circ$$

$$X = 87.95 \cos 39.63 = 68.34 \text{ cm}$$

$$\begin{aligned}\text{Ratio maintained} &= 68.34/9.61\\ &= 7.11134\end{aligned}$$

Hence, when the linear actuator moves 1 cm, the wheel moves 7.11 cm from the ground.

For a load of 200 lbf, the velocity of the wheel at x cm/s = ratio maintained * velocity of the linear actuator in cm/s. For a load of 600 lbf,

$$\begin{aligned}\text{The velocity of the wheel at } 0.39\ \text{in/s}(0.99\ \text{cm/s}) &= 7.1134 * 0.99\ \text{cm/s}\\ &= 7.04\ \text{cm/s}\\ \text{The velocity of the wheel at } 0.9\ \text{in/s}(2.286\ \text{cm/s}) &= 7.1134 * 2.286\ \text{cm/s}\end{aligned}$$

9 Weight Distribution

The weight distribution is the apportioning of weight within a vehicle. Typically, it is written in the form *x*: *y* where *x* is the percentage in front and *y* is the percentage in the back. In a vehicle which relies on gravity in some way, weight distribution directly affects a variety of the vehicle characteristics including handling, acceleration, and traction. For this reason, weight distribution varies with vehicle's intended usage. The following section shows how the weight is distributed when the Mars rover is in different positions.

9.1 The Rover Is in Normal Position

Figure 27 shows the rover in normal position with $X = 78$ cm, $Y = 396$ cm, and $Z = 714$ cm.

The calculation of weight distribution is as follows:

$$\text{Overall length} = 230\ \text{cm}$$

When four wheels are in ground, the weight distribution is

50: 50; that is, the center of gravity lies in the center as shown in Fig. 28. The vehicle is stable as the CG lies in the center of the rover.

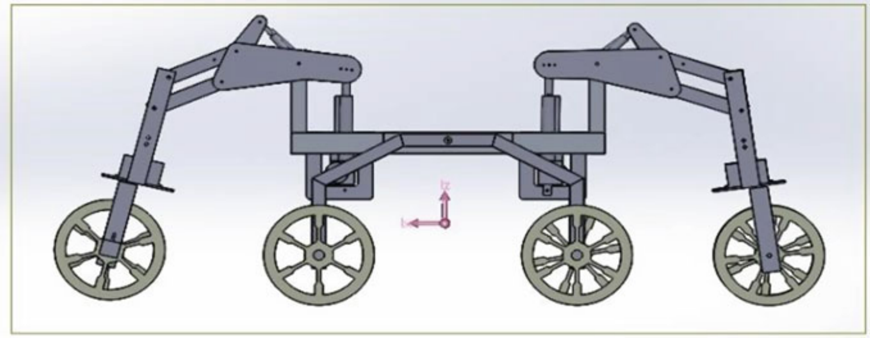


Fig. 27 Normal position

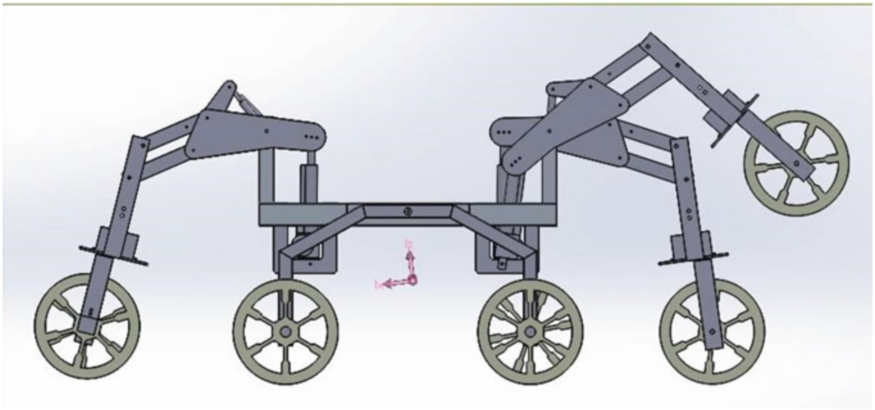


Fig. 28 Rover's one leg lifted position

9.2 The Rover's One Leg Is in the Lifted Position

Figure 28 shows the rover in one leg lifted position with $X = 78$ cm, $Y = 400$ cm, and $Z = 711$ cm.

The calculation of weight distribution is as follows:
Shift in length = 4 cm.
Ratio = 230/(115 + 4) = 1.932.
Overall weight distribution = 25 * 1.932 = 48.3.
Hence, the weight distribution is 51.7: 48.3.

9.3 The Rover's Both Legs Are Lifted

Figure 29 shows the rover in both legs' lifted position with $X = 78$ cm, $Y = 401$ cm, and $Z = 711$ cm.

The calculation of weight distribution is as follows:
Shift in length = 5 cm.
Ratio = 230/(115 + 5) = 1.9166.
Overall weight distribution = 25 * 1.9166 = 47.915.
Hence, the weight distribution is 52.1: 47.9.

The weight distribution was well optimized when compared to the previous versions. In the final model, there is a significant difference in the weight distribution and in the CG value. After optimization, the CG shift is very low which makes the rover stable with the proper working of the mechanism. Figure 30 below shows the final prototype of the Mars rover.

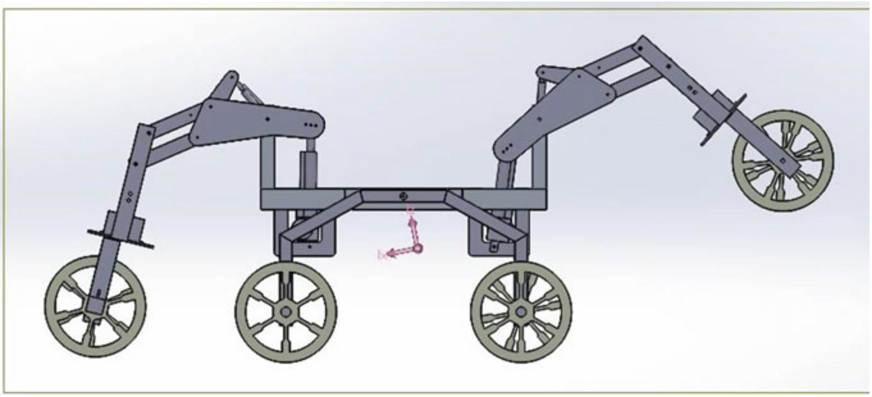


Fig. 29 Rover's both the legs are lifted

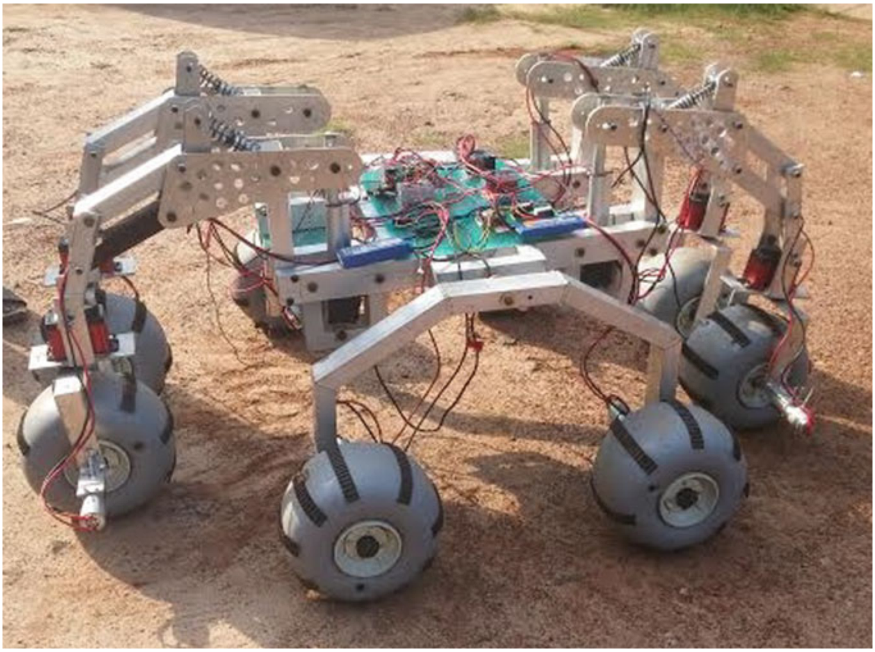


Fig. 30 Final prototype

10 Conclusion and Future Works

The Mars rover has been designed with an improved mechanism when compared to existing versions, and the final prototype has been built. The rover was built with aluminum 6061 and using various mechanical techniques such as water jet cutting, TIG welding, and drilling. The team's design had cleared the Critical Design Review of the University Rover Challenge 2015 conducted by Mars Society, USA. An innovative spider leg mechanism has been implemented in which suitable kinematic linkage analysis and dynamic analysis were conducted to analyze and verify whether it is capable of traversing all terrains. The prototype manufacturing helped us to experimentally test the mechanism, so that we could bring necessary changes to the design. The present mechanism enables the vehicle to traverse up steps/rocks while still being able to take the impacts of varying terrain. In currently used designs, the height which the wheels of a vehicle can traverse is limited, and it is extremely difficult for these vehicles to climb up high steps. However, a suspension mechanism with very soft shocks can cover rough and rocky terrain to an extent. Unfortunately, it is impossible for them to climb up huge steps and rocks. Study and analysis have been done on the design, and finally, an optimized design is obtained. The final design is again tested experimentally using a fully functional prototype.

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