STATE UNIVERSITY OF NEW YORK AT BUFFALO

The Realization of Tele-Operated Rover for NASA RASC – AL Robo –Ops 2011

Pramod Chembrammel
Dipen Harish Dave
Ravikiran Chollangi
Shailaja Nagarajan
Vishnusudhan Raghupathy
Kumar Viswajeet

May 2, 2011

Faculty Advisor

Dr. Puneet Singla

Assistant Professor,

Mechanical and Aerospace Engineering Dept.,

State University of New York at Buffalo

Abstract

Tele-operated rovers are the future of space exploration as we intend to land astronauts on Mars in the immediate future. Astronauts will study the planets by tele-operating these rovers from their controlled bases. NASA/NIA RASC-AL ROBO-OPS 2011 is a competition aimed in this direction whose primary goal is to make a rover mounted with a robotic arm to pick up and collect rock samples in a mock outer-planetary environment. Here we present the realization of rover by Spacebulls, a University at Buffalo team. The rover is a 6 wheeled rover with a rocker-bogie suspension. All six wheels are driven independently with the four corner wheels steerable. A 7 DOF serial link manipulator is mounted in front of the rover with a four-jaw gripper. The rover has a monocular color camera for video streaming and a monochrome stereo camera for path planning and visual odometry. The rover communicates with the home campus via a Verizon 3G dongle. The report covers design, challenges and realization of the entire system along with Education and Public Outreach program of the team in detail.

Co – Opted Members

Two more members we co-opted to realize the much specialized areas like navigation

1. Chetan Ramaiah
2. Dan Snitzer

Acknowledgment

We, the SpaceBulls as a team express our gratitude and thanks to our faculty advisor Dr. Puneet Singla who inculcated hard work and promptness in us and for pushing us forward through the thick and thin during the course of the project.

We also would like to thank our volunteers Sehwan Jun, Sagar Keer and Robin Sachdev for their steadfast work without which this project would not have been a success.

We would like to thank Mr. Ken Peebles, In-Charge, Engineering Machine Shop, UB, Mr. Gary Olson, Mr. Roger Teagarden and Mr. William for their help in designing and the fabrication of the elements of the rover.

We thank UB SEDS and UB ASME for involving us in their programs to make our Education and Public Outreach a grand success. We also would like to thank UB Spectrum and other campus publications in playing a major role in our EPO program.

Contents

1.0 Introduction

Astronomy has ever been man's inspiration to think big. The onset of the space exploration gave it an impetus to study not just our neighbors in the solar system but also distant heavenly bodies like comets. The purpose of all these explorations is manifold. To understand the origin of the universe and hence the origin of man has been one among them. But the most important has been to find a new home for our future generations or to find new sources of energy like the Helium-3[1] which is rare on earth but available in abundance on Moon. All these endeavors are very promising but with associated risks. Lack of amicable environment is one of those. Man has built machines to improve his work efficiency, with some having their own intelligence. With the advent of computers those machines got a facelift making them capable of taking intelligent decisions. These automatons or robots also have been helping us in the space explorations where a human factor was involved. Canadarm is one such robotic arm which is helping the astronauts during space walks and other extra-vehicular activities on International Space Station. But what about the other planetary surface missions? Lunakhod was the first mobile robot sent to Moon by the erstwhile USSR in 1969. In 1996 and more recently in 2004 NASA had sent 3 mobile robots to Mars for various scientific experimentations and studies which have given us a plethora of information and scientific data about the red planet. The challenges involved in building such a mission and making it a success are numerous. Each challenge is a technological marvel. NASA has given an opportunity to the students in the universities around the globe to find innovative solutions to such challenges. The challenge is to realize a tele-operated planetary rover capable of traversing an uneven and unstructured terrain. SpaceBulls from State University of New York at Buffalo (UB), is one the 7 teams participating in that challenge called Revolutionary Aerospace Systems Concepts Academic Linkage (RASC-AL) Exploration Robo-Ops jointly conducted by NASA and National Institute of Aerospace (NIA). This report contains the evolution of such a rover at UB. The report discusses the project requirements, the design of the rover and its subsystems, implementation and realization of such systems, testing and results.

2.0 Project Requirements

The requirements for the project have been chalked out to realize a rover that will emulate a real rover for interplanetary missions. The maximum mass of the rover is 45kg and the overall dimensions are 1m x 1m x 0.5m. The rover is expected to be tele-operated using a communication link over internet provided by Verizon Wireless. It has to identify and collect 5 colored stones of sizes varying from 2cm to 8cm while doing so it has to navigate over terrain terrains of various kinds and strewn with obstacles of size 10cm. The terrain could be rocky, loose or gravel filled.

The most challenging of these requirements is the navigation of the rover on the Mars-like terrain. This demands a highly efficient suspension mechanism and a high performance navigation software.

The design of the locomotion is designed in the next section.

3.0 Locomotion System

For an autonomous rover, the choice of a mobility system for locomotion is of the utmost importance. Since one of the primary goals is to have this rover survive independently for an extended period of time in such harsh conditions, reliability and adaptability are key. Clearly there are options to choose from, and certainly each has certain advantages and disadvantages over another. The prime objective in this case is to decide on a system that will provide the most effective means of locomotion for the rover without compromising reliability.

3.1 Legged systems

Legged locomotion[2] has long been an attractive alternative to wheels or tracks for mobile robots. Legged animals, for example, have the ability to negotiate rough terrain and obstacles far more easily than wheeled vehicles of similar size. However, current legged robots enjoy neither the simplicity of wheels nor the versatility of legged animals. Legged robot systems have been developed most successfully in a hexa-pedal configuration for stability and their movement modeled after that of insects.

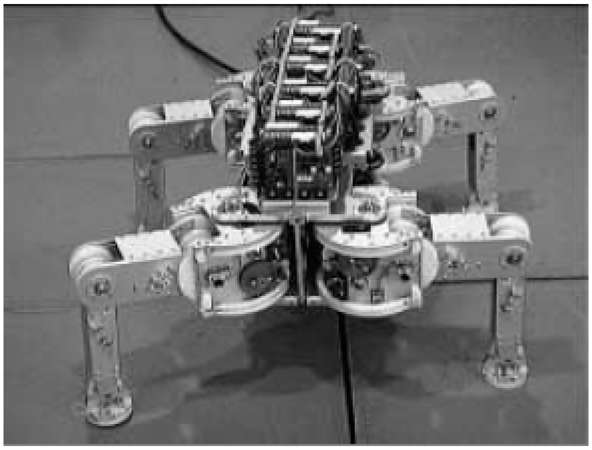


Figure 1 Legged Walker(Courtesy: Biomimetic Intelligent Mechatronics Laboratory)

Advantages

Ideally, legged robot systems will mimic the movements of animals and provide a locomotion option that is comparable in terms of speed and stability to more conventional methods. While most of the work in this area is still experimental, small legged walkers have been developed that are capable of speeds of 2.5 body lengths per second and have proved proficient in quickly traverse large, hip- height obstacles. The distinctive goal of legged walkers will be their ability to negotiate variously structured terrain more quickly and successfully than their wheeled counterparts and push the limits of robotic exploration even further.

Disadvantages

The current state of the art in legged walkers is very small in scale (about 16 centimeters long) and remains very experimental in terms of feasible locomotion. This lack of reliability and need for constant observation could prove devastating in an autonomous setting. Should a legged walker happen to fail, the entire project would suffer long, if not indefinite, delays. While a legged walker may be more capable of traversing rough terrain, there is a question in this case of necessity. Mars-like surfaces do provide the distinct advantage of being fairly uniform in its terrain. It is unknown at this time whether or not a legged walker of sufficient size to support all of the computer systems would be able to keep them stable enough for ideal operation since each leg joint allows for up to three degrees of freedom in movement. Legged locomotion mechanisms demand power even in its static condition and a higher power during plane terrain travel.

3.2 Tracks

Figure 2 Tracked Robot

Flexible tracks, usually made from either steel or steel belted rubber, are most commonly found on tanks, construction equipment such as bulldozers, or large farm machines and tractors. The tracks are installed on assemblies of wheels that provide both the driving power as well as support, and are situated on each side of the vehicle. Each side of the treads are allowed to be driven separately, allowing for skid steering, or the moving of the treads on one side at a faster rate than on the other side, thereby causing the vehicle to turn. To travel straight, forward or backward, the treads are simply powered by the wheels at the same rate.

Advantages

Treaded vehicles tend to be much larger and heavier than their wheeled counterparts. The treads provide more contact area with the ground, thus distributing the weight over a larger area. This greater amount of contact area also results in more friction and better traction, especially in loose terrain, such as soft ground, sand, or snow. Since each set of treads is allowed to be driven separately, steering is relatively simple, and is mobile enough to turn in a circle while stationary. Tracks also provide a smooth ride across flat or uneven terrain, allowing the integrity of the observational equipment to perform without compromise.

Disadvantages

In their conventional form, treaded vehicles tend to require considerable more power to move than wheeled vehicles and therefore run on large gasoline or diesel-powered engines. A large part of this is a natural consequence of the sheer size and weight of the machines to which they are applicable. In addition, however, the increased friction of a larger footprint as well as the fact that treads cannot be pointed in the direction of a turn will cause a larger power requirement to the wheel motors than would a wheeled machine of similar size. In addition to the natural complication of various drive wheels and suspension, treads also require the use of tensioning devices to keep the treads both on the drive wheels and in firm contact with the ground at all times.

3.3 Wheels

Wheeled vehicles currently provide the most common method of locomotion, found in modern cars, motorcycles, trains, and airplanes, not to mention the current state of the art in robots. The NASA rover on the moon, the small Sojourner that was part of the Mars Pathfinder mission, FIDO, one of the current prototypes for future Mars missions, and Nomad, the large autonomous vehicle designed for a variety of terrain mediums, all use wheels as their means of locomotion. Wheels provide design options that are comfortable both to visualize and apply as well as presenting a mobility system that is efficient and stable. Many logistical variations are available in the design of wheeled vehicles.

Advantages

Quite possibly the greatest advantage to wheels is their range of possibilities for specific application. As shown in the various examples above, there are many configurations that can help specialize a rover to fit its specific terrain requirements. For programming simplicity and greater reliability, each wheel can be independently driven. With all wheel steering, the rover can become virtually as nimble as a treaded machine, but without the added weight. Suspension can also be configured independently for each wheel, adding to the simplicity and reliability of the design and aiding in the integrity of the observational equipment that the rover will transport.

Disadvantages

Unfortunately, no design option is without some disadvantages. Wheels lack some of the traction offered by treads, and should a wheel become stuck, the required troubleshooting would obviously cost valuable observation time. Steering of only two of the wheels, like a modern car, significantly limits the rover's ability to make sharp movements and can add considerable difficulty to programming tasks. This result from the different lengths traveled by the inside and outside sets of wheels.

3.4 The Selected system

Considering the lack of reliability of the legged systems, the immensity of the weight and the huge power requirement of the tracked systems, wheeled system shall be used for the rover.

The disadvantages of the wheeled systems can be over come by using an adaptable suspension that can shape itself to the terrain, making the vehicle more attractive in terms of dynamic loading. A more sophisticated approach to the steering of the vehicle would be to use a four-wheeled steering or all-wheeled steering, if the number of wheels is more than four, thus enabling a crab maneuver or omni directionality.

4.0 Wheeled Locomotion systems

The exploration missions will require the robot to perform difficult mobility tasks in rough terrain. Such tasks can result in the loss of wheel traction, leading to entrapment, loss of stability, and even power. The primary consideration in the selection of the locomotion system of the lunar rover is the selection of the suspension mechanism.

The factors to be taken into account in the design of the suspension system are:

1.equal traction on all wheels on all terrains

2.tip over stability

The suspension mechanism must keep all the wheels on the ground at all times so as to ensure equal traction on all wheels. Else the wheels may slip, leading to more power demand (or wastage). The mechanism must limit the body excursions (tilting of the body) on an uneven terrain.

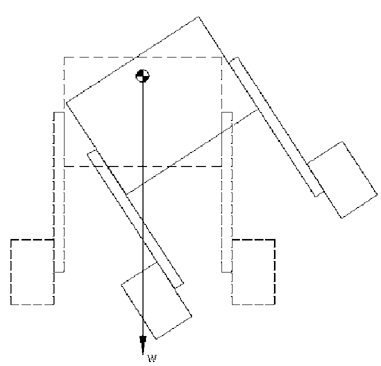


Figure 3 Static Stability

The suspension systems can be bifurcated into fixed suspension and articulated suspension.

4.1 Fixed suspension

The suspension is rigidly connected with body. Any deviation in the suspension orientation will alter the orientation of the body, which will affect the stability of the vehicle. As can be seen from the above figure, the CG gets shifted and the line of action of the total weight may go out of the footprint of the vehicle. This tip-over instability of the vehicle can result in rover damage and total mission failure. This may also lift the one or more wheels from the ground leading to loss of traction, consuming more power.

Figure 4 Fixed Suspension (Courtesy: NASA)

4.2 Articulated Suspension

The suspension mechanism can reorient itself with respect to the body to eliminate any tip over instability. Robots with articulated suspension sometimes called the "re-configurable robots", can improve the rough terrain mobility by modifying their suspension configuration and thus repositioning their center of mass. The reorientation of the links will keep all the wheels on the ground providing equal traction on all wheels.

Figure 5Articualated Suspension (Courtesy: NASA)

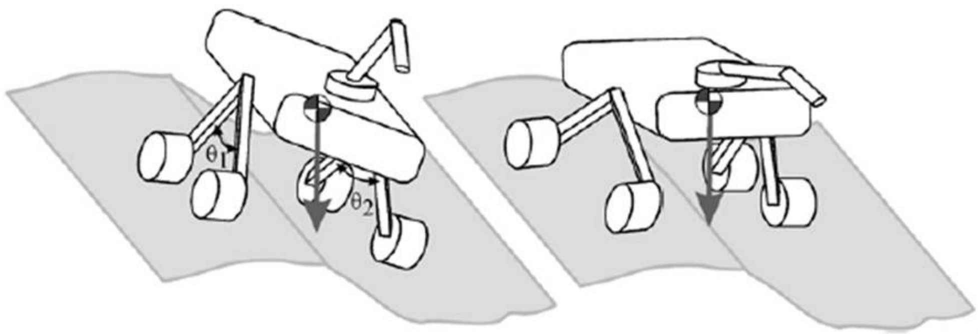


Figure 6 Articulated suspension robot improving stability by adjusting shoulder joints

4.3 The Selection of the wheel System

The selection of the mechanism shall be based on the design considerations.

1.Equal traction on all wheels

Since the links of the suspension mechanism reorients to keep all the wheels on the ground, it will ensure equal traction on all wheels

2.Tip over stability

The performance index [1] of the rover suspension mechanism is given by the form

$$\phi = \sum_{i=1}^{n} \left(\frac{K_i}{\eta_i} + K_{n+i} \left(\theta_i - \theta_i' \right)^2 \right) \qquad (4.3.1)$$

Where η_i are the stability angles defined by $\eta_i = \sigma_i \cos^{-1}\left(\hat{f}_g . \hat{I}_i\right)$, i= [3], number of wheels, with

$$\sigma = \begin{cases} +1 & \left(\hat{I}_i x \hat{f}_g\right) . \hat{a}_i < 0 \\ -1 & \text{otherwise} \end{cases}$$

$\hat{f}_g$ is the gravitational force vector,

$\hat{a}_i$ is the tip over axis which is the line joining the wheel-terrain contact points,

$\hat{I}_i$ is the tipover axis normals that intersect the centre of mass.

θ_i is the joint angles of the links of the suspension mechanism

θ_i' is the nominal values of the i[th] joint variables(i.e. the values of θ_i when the robot is at a user-specified configuration)

K_i are constant weighting factors selected to control the relative importance of vehicle stability and joint excursions.

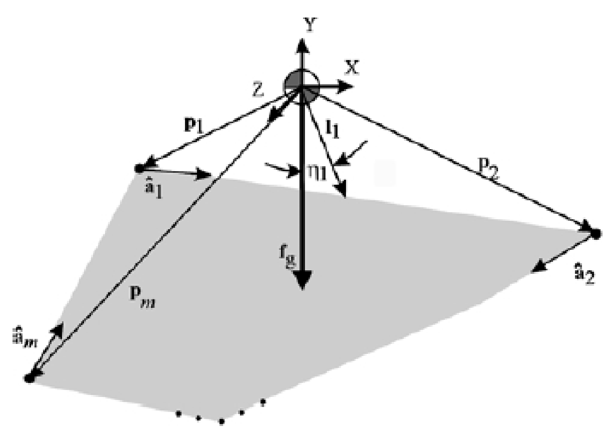


Figure 7 Stability definition diagram

For the tip over stability to be maximum, the performance index should be a minimum. The first term of the equation (4.3.1) tends to infinity as the stability angle at any tip-over axis tends to zero. The second term penalizes the deviation from the standard configuration. For a fixed suspension the stability angle is considerably lower than that of the articulated suspension of comparable configuration. Hence the performance index is higher than that of the articulated suspension. Studies conducted at Massachusetts Institute of technology have found out that the average stability of the articulated systems is about 50% more than the fixed suspension systems.

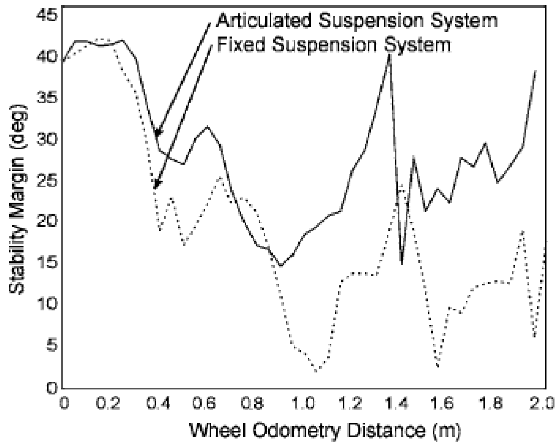


Figure 8 Stability margin for articulated suspension

Clearly, articulated suspension control results in greatly improved stability in rough terrain.

5.0 Articulated Suspension Systems

The articulated suspension systems are again bifurcated into two; active suspension and passive suspension

5.1 Active Suspension

Active suspension systems can be defined as the driven suspension systems. To reconfigure the suspension linkages during motion over an uneven terrain, the links are driven using actuators (rotary or linear), to shift the CG for the tip-over stability or equal traction. It implies a close

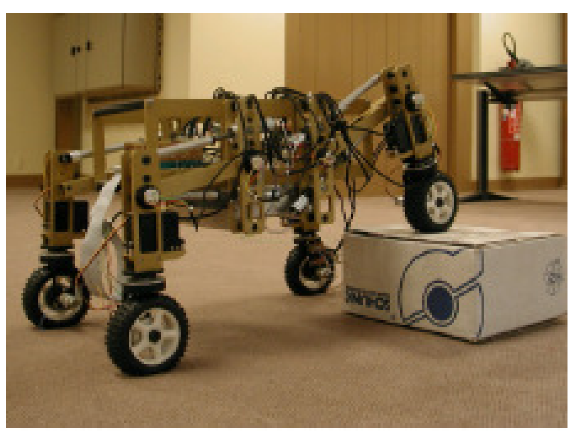


Figure 9 Active Suspension

control loop to keep the stability of the system during the motion.

Advantages

It can reconfigure itself with the help of motors present.

Disadvantages

In order to hold the linkage system in a particular configuration power must be supplied constantly. This consumption of power is avoidable while working with a shoestring power budget. Also, the terrain conditions may be so demanding that the control of these actuators become too much involved. The weight of actuators add on to the weight of the rover

5.2 Passive Suspension

In this type of suspension the linkages are not driven and are reconfigured owing to the forces developing from the wheel-terrain interaction. It means no sensors or additional actuators to guarantee stable movement. The forces involved in the actuation of the linkages of the passive suspension systems are the frictional force at the wheel-terrain contact point, the reaction force at point of contact of the wheel with an obstacle, which will produce a moment about the pivot to actuate the linkages.

5.3 The Selected system

Passive suspension would be the better choice with respect to power consumption, complexity of the control system and payload weight.

6.0 Passive Suspension Systems

Ample of passive suspension systems are available, but only of them worth mentioning that can be put to scrutiny.

6.1 Parallel Bogie System

Using a rhombus configuration [4], the rover has one wheel mounted on a fork in the front, one wheel in the rear and two bogies on each side to provide lateral stability. The position of the parallel-linkage bogie is passively articulated from the reaction of the terrain. Although the bogies have a special geometry, it is the same basic principle as used for a train suspension: a couple of two wheels mounted on a support which can freely rotate around a central pivot.

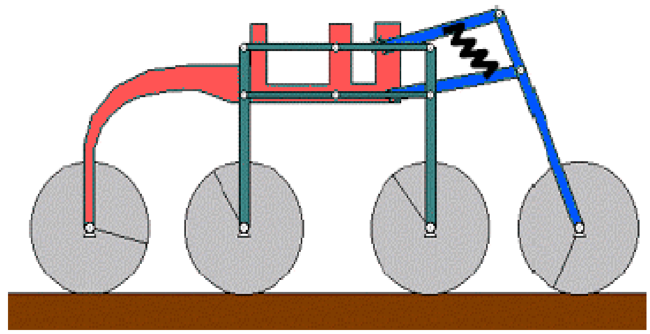


Figure 10 Parallel Bogie

The front fork [5] has two roles: its spring suspension guarantees optimal ground contact of all wheels at any time and its particular parallel mechanism produce an elevation of the front wheel if an obstacle is encountered.

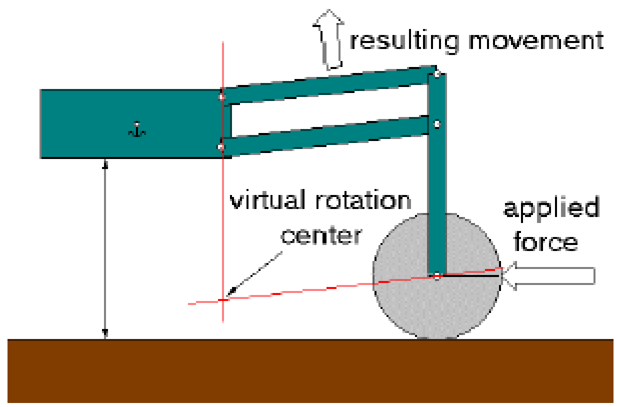


Figure 11 Front Fork gets lifted due to reaction from the obstacle

The parallel architecture of the bogies and the spring suspended fork provides a non-hyperstatic configuration for the 6 motorized wheels while maintaining a high ground clearance. This insures stability and adaptability as well as excellent climbing abilities.

6.2 Marsokhod Mechanism

The Marsokhod [6-7] is an extremely flexible and capable system built around an articulated, three-part chassis with the body/payload being mounted in a distributed fashion on the various chassis elements. The front and rear wheels are mounted on chassis sections capable of lateral rotation (roll) relative to the central portion and relative to one another, giving the robot high obstacle traversabilty capacities. The wheelbase is not fixed, but can be shortened or extended by means of hinge mechanisms incorporated in the front and rear chassis sections. Each of the six conical wheels is individually powered.

Unlike in the basic mechanism the central chassis is not rigid, but consists of articulated

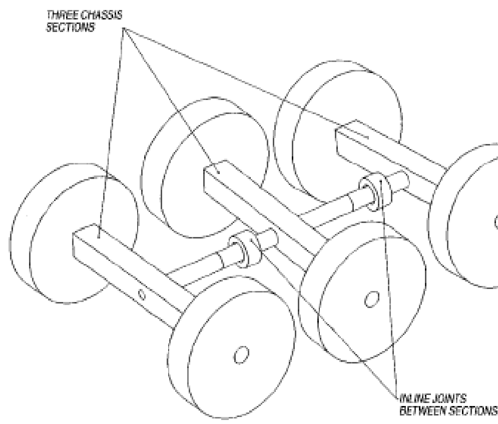


Figure 12 Basic mechanism ogf Marsokhod

joints. The conical wheels being non-orientable, the robot turns in a skid steering way: a differential of speeds must be applied to the right and left wheels of the center axle.

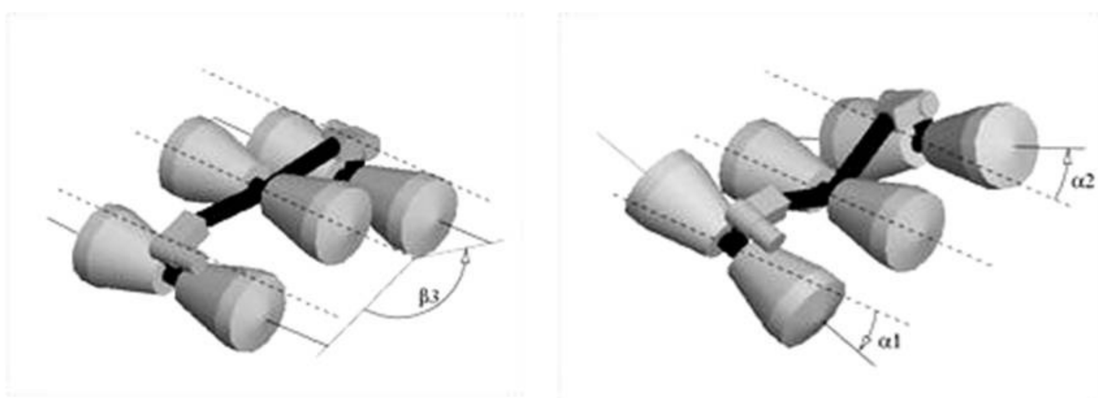


Figure 13 The articulated chassis

6.3 Rocker-Bogie Suspension

The mobility system [7-9] consists of a set of six wheels on mobile links, as shown in the figures. The front and center wheels are joined on each side to form bogies. These bogies pivot freely at the front of the rocker links. The rockers each have a rear wheel at the other end, and are pivoted freely at a point near the rover's CG. The rockers are connected to the main body with a differential mechanism so that the pitch angle of the body is the average of the pitch angles of the rockers. The bogie passes on only a portion of the wheel displacement to the rocker and hence to the body.

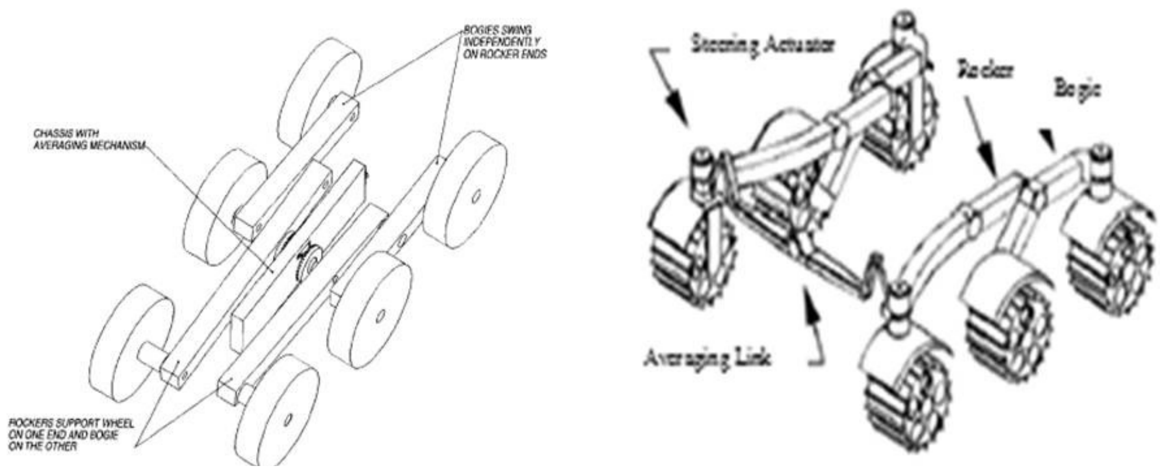


Figure 14 Rocker- Bogie suspension

In a rover with rocker bogie configuration, the vehicle maintains a substantially constant weight, and therefore traction, on all wheels, despite one wheel moving considerably higher or lower than others, while avoiding soft spring suspension as in a parallel bogie mechanism[10].

The obstacle size limit in most suspension is something less than half the diameter of the wheel. If a driven wheel is pushed against a wall that is taller than the wheel diameter with sufficient forward force relative to the vertical load on it, it will roll up the wall. This is the basis for the design of rocker bogie system. This mechanism works well in the low speed range where quasi-static force analysis is sufficient.

6.4 The Selected System

Six wheels are generally the best compromise for high mobility wheeled vehicles. Six wheels put enough ground pressure, traction, steering, steering mobility and obstacle negotiating ability on a vehicle without much complexity.

Springs do seem to be important to mobility, but are only suitable for vehicles that travel more than 8m/s. Below that speed they are actually a hindrance to mobility because they change the force each wheel exerts on the ground as bumps are negotiated. A 4-wheeled conventional independent suspension vehicle appears to keep all wheels equally on the ground, but the wheel that are on the bumps, being lifted, are carrying more weight than the other wheels. This reduces the traction of the lightly loaded wheels. The better solution is to allow some of the wheels to rise, relative to the chassis, over bumps without changing the wheel distributions or changing it as little as possible. This is precisely what happens in rocker bogie suspensions.

The parallel bogie suspension uses a spring and damper to maintain wheels and ground contact with enough normal force. The magnitude of normal force depends on the roughness of the ground.Where as in rocker bogie suspension, the articulated mechanism makes all wheel contact with the ground when travelling across rugged terrain. Normal force depends on angle of contact, not the surface roughness.

Independent steering is preferred to skid steering because of comparably high power consumption and making the dead reckoning difficult since the wheels must slip against the ground. The marsokhod suspension uses skid steering and rocker bogie uses independent steering system.

On the basis of Graph Theory [11], any linkage whose interchange graph is a spanning tree is not robust to kinematic or mechanical faults. The interchange graph of the marsokhod mechanism is a spanning tree. Whereas the interchange graph of rocker bogie mechanism contains two fundamental cycles, as a result mechanically more robust.

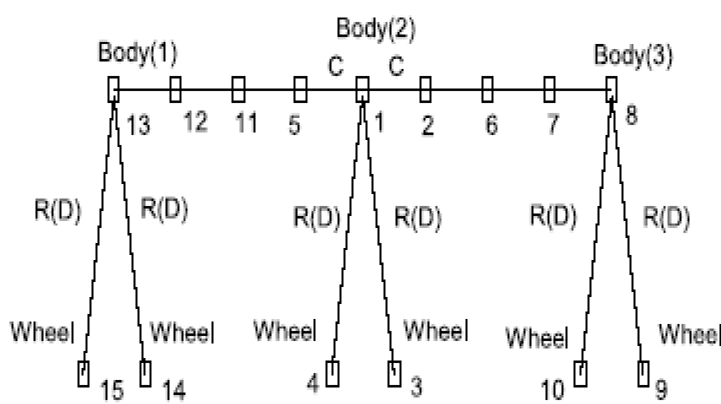


Figure 15 Marsokhod Interchange graph

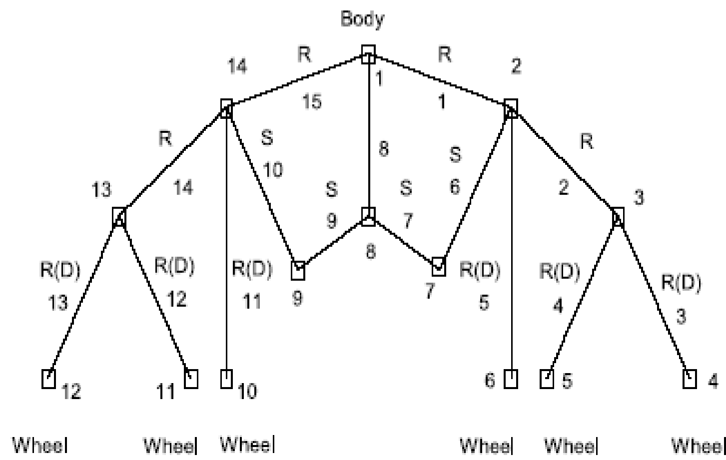


Figure 16 Generic Rocker Bogie Interchange graph

So, the rocker bogie suspension mechanism has been selected.

7.0 Configuration Design

The configuration design involves the determination of the wheel diameter, the wheel width and the size of the linkages of the rocker-bogie configuration. In the basic mechanism of the rocker-bogie, equal traction is ensured at all the wheels if the length of the bogie is half that of the rocker and the rocker is attached to the chassis one third of its length from the bogie end. The wheel size and the link length are determined with the above assumption.

7.1 Wheel sizing

There are two factors which contribute to the sizing of the wheels. The first of these factors is the stability [12] of the rover over an inclined surface. The wheelbase is taken as the distance between the centers of the rear and front wheels. A maximum acceleration vector is added as a transformation to a dynamic case. The vehicle tips over when the resultant of the gravity and acceleration vectors passes over the contact point of the rear wheel with the ground.

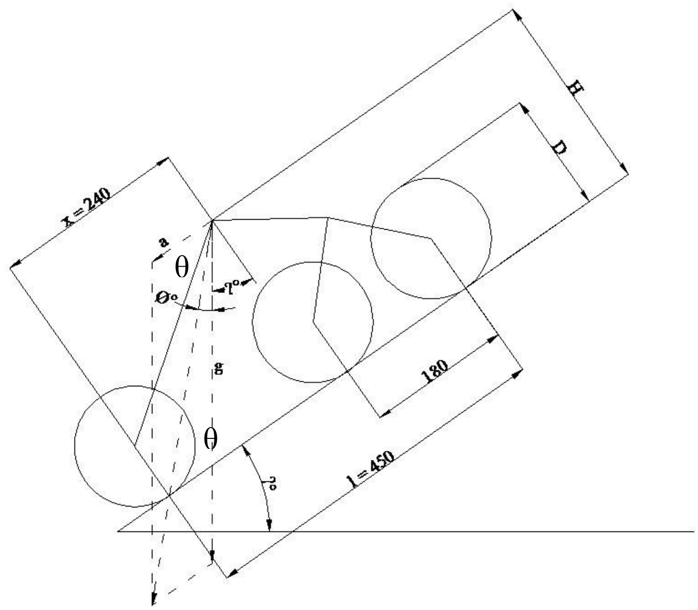


Figure 17 Stability Diagram

$$\phi + \theta = \tan^{-1}\left(\frac{2x}{2H - D}\right)$$

$$a = 9.81\frac{\sin\left[\tan^{-1}\left(\frac{2x}{2H - D}\right) - \theta\right]}{\sin\left[90 - \tan^{-1}\left(\frac{2x}{2H - D}\right)\right]} \quad \rightarrow (7.1.1)$$

Plotting acceleration as function of wheel diameter and slope,

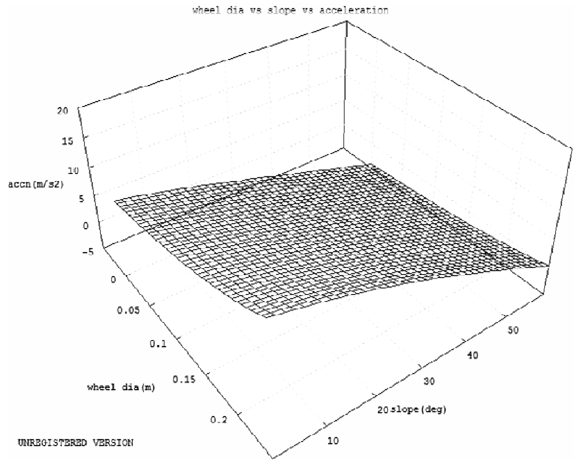


Figure 18 Wheel diameter vs slope vs acceleration

for a wheel diameter of 0.15m the rover can achieve a maximum acceleration of 4.5m/s2 on a 35^{o} slope a maximum acceleration of 1m/s2 on 48o slope. The wheel diameter of 0.15m is selected because, decreasing the wheel diameter below 0.1m will result in more sinkage of the wheel into the soil as predicted by Bekker's theory [13] on terra-mechanics, shown in the following fig.19 and wheel diameter above 0.15m is not selected since a higher value of wheel diameter would require higher drive motor torque.

$$\therefore D = \underline{\underline{0.15}}\,\text{m}$$

The cohesion of the lunar soil is too low that the wheels sink into soil under its own weight. The sinkage as predicted by Bekker's on soil mechanics is given by the following relation,

$$z = \left[\frac{3W}{(3-n)\left[k_c + b.k_\phi\right]\sqrt{D}} \right]^{\frac{2}{2n+1}} \rightarrow (7.1.2)$$

Where n, exponent of soil deformation = 1,

kc, cohesive modulus of soil = 0.14 kN/m^{n+1}

kφ, frictional modulus of soil = 0.82 kN/m^{n+2}

W, normal weight acting at the wheel-terrain contact point = (55/2)*1.63/2= 22.4125N (the worst case is assumed as the total weight acting on the two wheels),

b = width of the wheel (cm),

D = wheel diameter (cm)

The sinkage is plotted as a function of wheel diameter and wheel width, which is as shown in Fig.19.

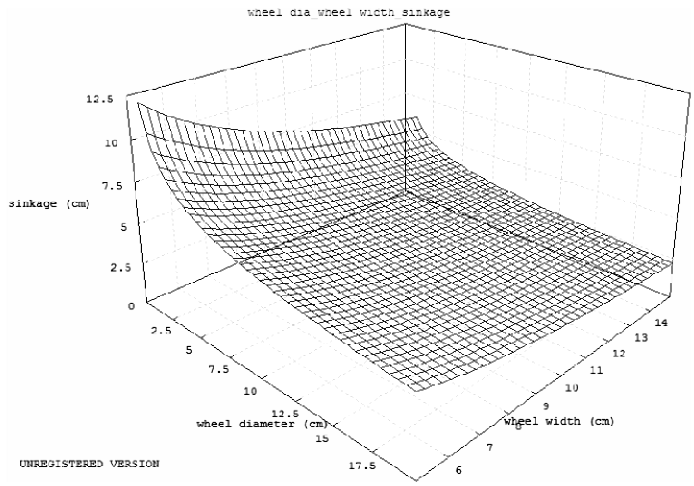


Figure 19 Wheel diameter vs wheel width vs sinkage

For a wheel diameter of 0.15m and wheel width of 0.1m the wheel will sink into the soil through a depth of 3.3cm. The ground which the wheels exert is a direct function of the sinkage. The ground pressure on terrestrial conditions is found to be 9.5kPa as obtained from the Fig.20 which is based on equation 7.1.3, which is acceptable to the standards of off-road automobiles (the ground pressure exerted by a tracked vehicle is 80kPa). In the case of terrestrial rover the sinkage is considerable only for calculating the torques of steering and driving wheels.

The pressure exerted by the wheel on the ground given by the relation,

$$P = \frac{\frac{W}{m}}{b.D\sin\left[\cos^{-1}\left(1-\frac{2z}{D}\right)\right]} \quad \rightarrow (7.1.3)$$

Where m is the number of wheels. The ground pressure is plotted as a function of wheel diameter and wheel width.

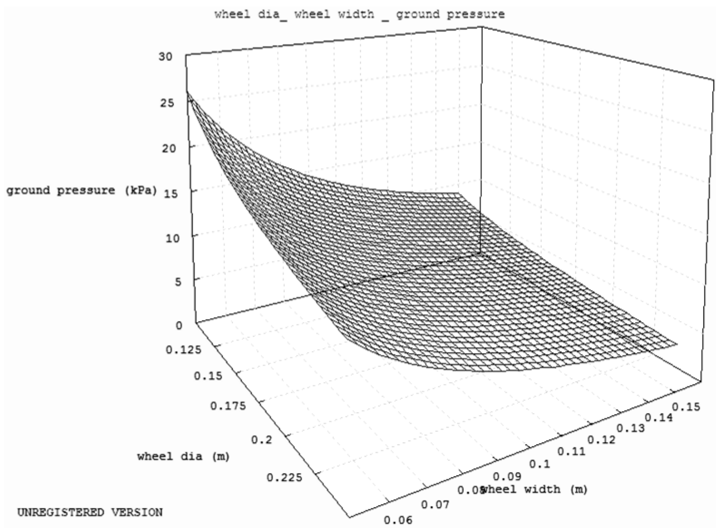


Figure 20 wheel diameter vs wheel width vs ground pressure

In order that the normal reaction at the wheel terrain contact point should pass through the wheel-axle fixing point during the vehicle roll, the shape of the wheel should be a part of a sphere of diameter 150mm.

7.2 Determination of Link Lengths

The link lengths are determined on the basis of the step-overcoming function of the suspension system [14]. The forces which resist the motion of the wheel in loose soil are the soil compaction resistance (Rc) [13] and the force (Rb)[13] due to bull-dozing effect of the soil infront of the wheel. The force Rc acts at height z from the wheel-terrain contact point, where z is the sinkage of the wheel into the soil. And the force Rb acts at a depth of 2z/3 from the soil surface.

Compaction resistance is given by the relation,

$$R_c = \left[\frac{3W}{(3-n)\sqrt{D}}\right]^{\frac{2n+2}{2n+1}} \cdot \frac{1}{(n+1)(k_c + b.k_\phi)^{\frac{1}{2n+1}}} \rightarrow (4)$$

Where, W, weight shared by one wheel = 55*9.81/6 = 89.925N

$$\therefore R_c = \underline{\underline{46.2N}}$$

Force due to bull-dozing effect is given by,

$$R_b = b\left(0.67.c.z.k'_{pc} + 0.5.z^2.\gamma_s.k'_{p\gamma}\right) \quad \rightarrow (7.2.1)$$

Where,

γ_s is the soil density, 1.5g/cc [5]

c = cohesion, 2.45 kPa

$$k'_{pc} = \left(N'_c - \tan\phi'\right)\cos^2\phi',$$

$$k'_{pc} = \left[\frac{2N'_\gamma}{\tan\phi'} + 1\right]\cos^2\phi',$$

$$\tan\phi' = \frac{2}{3}\tan\phi, \quad \rightarrow (7.2.2)$$

ϕ =angle of internal friction of soil, 20°[13]

N'_c and N'_γ are bearing capacity factors of loose soil with values 12 and 2 [15] respectively.

$$\therefore \tan\phi' = 0.2426$$

$$\Rightarrow k'_{pc} = 11.085 \ \& \ k'_{pc} = 16.488$$

$$\therefore R_b = \underline{\underline{73.2N}}$$

Since the links of the rocker-bogie are constrained to move only in one plane, the linkage can be analysed as a planar mechanism. When the vehicle passes over an obstacle the moments are generated as shown in fig no.2. During the forward motion, when the vehicle encounters an obstacle, moments are generated in the bogie and the rocker part is under equilibrium.

The reaction at the contact point of the front wheel with obstacle is given by the relation,

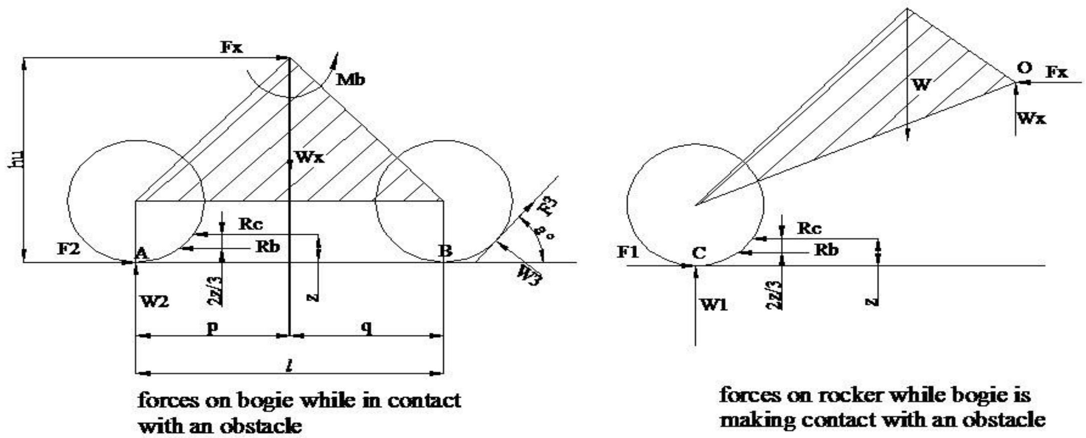


Figure 21 forces and moments in the forward motion

$$M_b = W_3\left[\begin{matrix}(\cos\alpha + \mu_3 \sin\alpha)(l + r\sin\alpha) + (\sin\alpha - \mu_3\cos\alpha)(r - r\cos\alpha) - \\ 2p(\cos\alpha + \mu_3\sin\alpha) - \{\mu_2(\cos + \mu_3\sin\alpha) - (\sin\alpha - \mu_3\cos\alpha)\}hu\end{matrix}\right] + \left(R_c + \frac{R_b}{3}\right)z + (R_c + R_b hu)$$

$$W_3 = \frac{\mu_2 W - 2(R_c + R_b)}{\sin\alpha(1 + \mu_2\mu_3) - \cos\alpha(\mu_3 - \mu_2)} \rightarrow (7)$$

The moment generated by the forces by the relation,

→ (7.2.3)

Where,

l = 0.225m

$\mu_2 = 0.36397, \mu_3 = 0.8$

are the coefficient of friction for middle wheel and front wheel respectively.

These relations are obtained with the assumption that all the wheels equally share the load(W). The moment as a function of p and h_u is plotted for $\alpha = 90^o$, which corresponds to a vertical wall

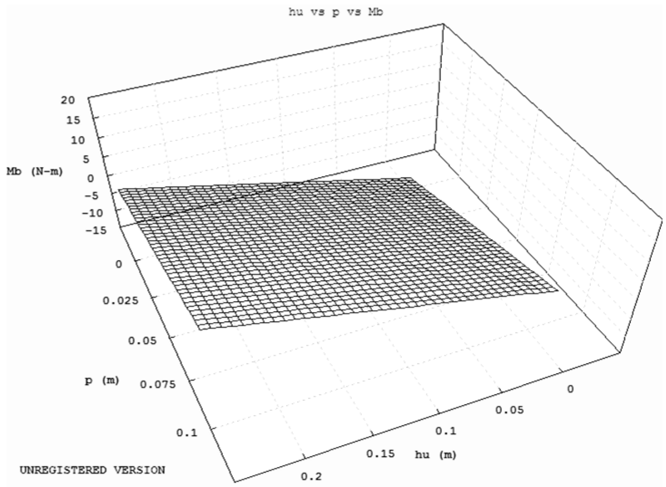


Figure 22 hu and p vs Mb(see fig no.21 for the quantities)

It is found from the Fig.22 that Mb is positive above 0.16m of h_u and below 0.1m of p. The maximum obstacle height to be climbed depends on the relative values of hu and p, which can be judiciously selected from the plot for a given obstacle height.

It is proposed to pass over an obstacle of height equal to wheel diameter. It obvious from the fig.no.3that the value for hu is 0.17m and that for p is 0.095m so that the bogie will not topple when it comes to a standstill condition with the front wheel on an obstacle since the weight,W, acting at the hinge point (defined by the coordinate (p,hu)) will generate a clockwise moment(w.r.to the diagram) which will hold the vehicle in a stable condition. For these values, it is obtained from the fig.22 that a positive moment of 10.5 N-m in the bogie is generated enabling it to climb a vertical wall of height 0.15m.

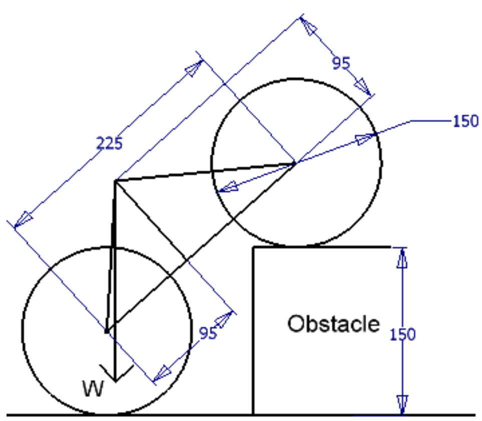


Figure 23 Stability of bogie on an obstacle

Now, the motion in the backward direction is considered. The forces and moments generated are as in the fig.no.24

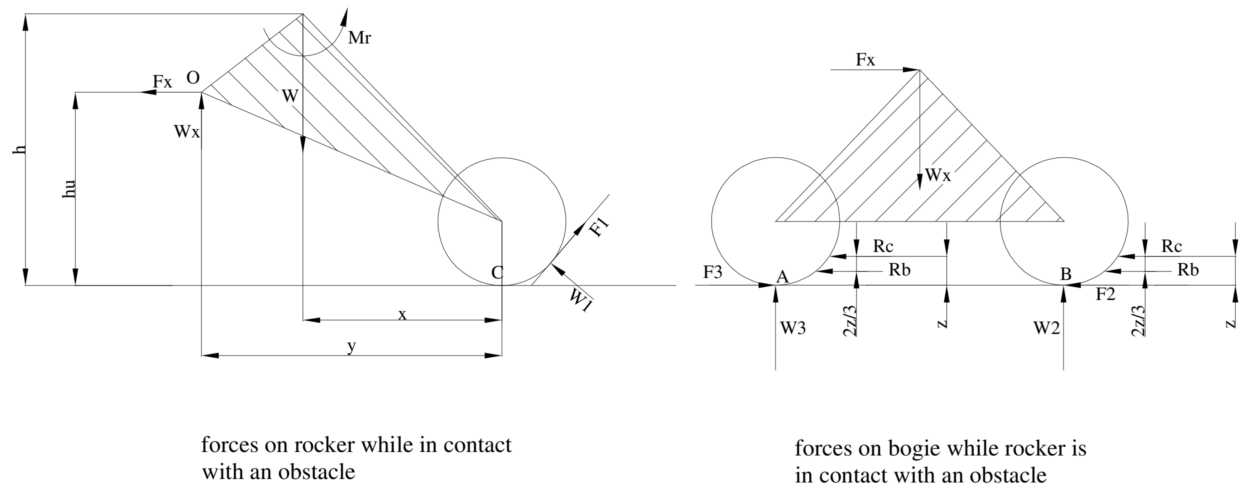


Figure 24 forces and moments in the backward motion

$$W_1 = \frac{\mu_1 . W - 2(R_c + R_b)}{\mu_2(\cos\alpha + \mu_1 \sin\alpha) - (\sin\alpha - \mu_1 \cos\alpha)} \quad \rightarrow (7.2.4)$$

Since the middle wheel fixed at the middle of the foot-print of the vehicle,

$$y = l + p = 0.225 + 0.095 = \underline{\underline{0.32m}} \quad \rightarrow (7.2.5)$$

$$M_r = W_1[(\cos\alpha + \mu_1 \sin\alpha)(y + r.\sin\alpha) - (\sin\alpha - \mu_1 \cos\alpha)(h_u - r + r\cos\alpha)] - W(y - x) \quad \rightarrow (7.2.6)$$

Where, μ_1 = 0.8, the coefficient of friction for the rear wheel w.r.to an obstacle, $\mu_2 = \mu_3 = 0.36397$ coefficients of friction of middle and front wheels.

With h_u obtained from the forward motion conditions, M_r can be plotted as function of x with α = 90°, which corresponds to a vertical wall.

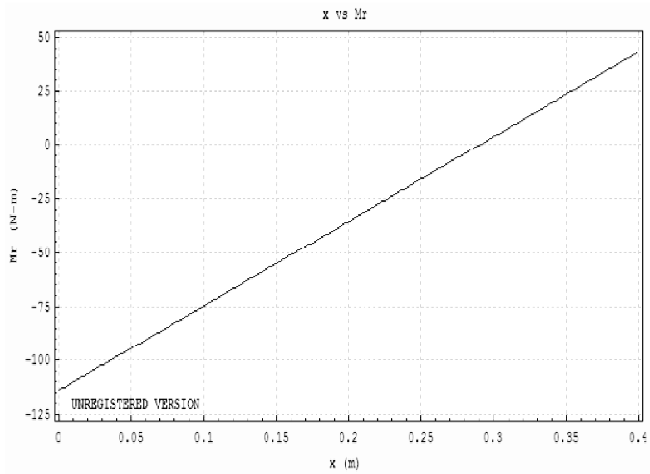


Figure 25 X vs Mr (see fig no.24 for the quantities)

It is found out from the fig.25 that Mr is positive above 0.285m of x. This value is not acceptable because of the following two reasons; (1) the gravity line will pass beyond the rocker – to – bogie pivot point while the rover is running down a slope, producing an over turning moment. (2) The normal reaction at the rear is found to be negative with this value of x. So it is required to select a value less than 0.285. The selection criterion is to choose the dimension which will generate equal normal reactions at all the six wheels. Since the middle wheel is fixed at the middle of the foot print of the rover, the weights are equally shared by the wheels when the body hinge point (defined by the coordinate (x,h)) is above the middle wheel axle. A value of 0.225m for x is selected. And it has been decided to run the rover backwards, if necessary, using enhanced kinematic control. The final configuration is as shown in the fig.no.5

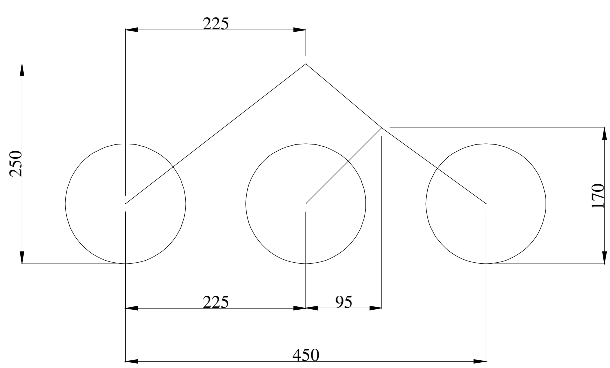


Figure 26 Final configuration

All these dimensions were obtained on the assumption that during the forward motion, the vertical components of the tractive effort (F3) and normal reaction (W3) share equal load with the normal reactions at middle and rear wheels, which is not the actual case. But it is sufficient to verify that a positive moment is generated with these dimensions for the linkage. It has been found out that positive value for Mb is generated till the front wheel reaches the obstacle height of 0.16m, beyond which the front wheel loses traction.

7.3 Determination of Lateral Dimensions

The only lateral dimension to be determined is the width of the vehicle. Since the transverse slope (slope in the direction of the motion of the vehicle) is fixed at 35°, the vehicle may be required to traverse the same slope in the lateral direction also. This condition defines the criterion for the determination of the width of the vehicle. There are two forces that act on the vehicle on a lateral slope, viz, the centripetal force and the gravity. The centripetal force comes into play only in the curved slopes such as that of craters. The centripetal force given by mv^2/r, can be neglected since the radii of the craters are very large of the order of 1-2 km, and the velocity of the vehicle less than 0.1m/s. The only considerable force is then the weight of the rover. For the rover to be stable on a lateral slope, the CG of the vehicle being fixed at the middle of the width of the vehicle, the gravity line should pass through the wheel-terrain contact point. For a CG height of 250mm from the ground and wheel diameter of 150mm, the width shall be 350mm (see fig.no.6), beyond which the gravity line falls beyond the foot-print of the vehicle. So the width has been conclusively fixed at 400mm.

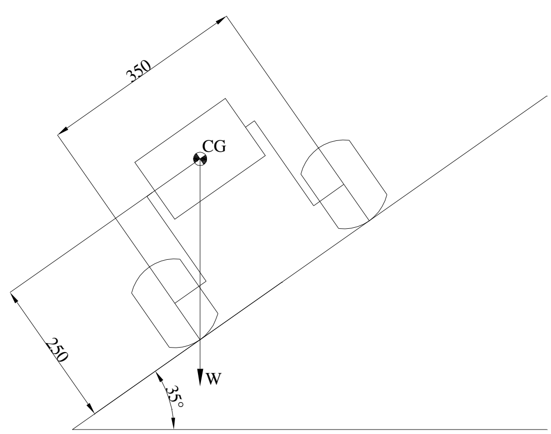


Figure 27 Stability on lateral slope

8.0 Steering and drive motor torques

8.1 Steering motor torque

Explicit steering has been selected for the rover. So it is required to find out the torque required for the steering motor. While steering in loose soil, the force encountered is the compaction resistance of the soil while turning the wheel. The resistance encountered by the wheel from the soil shall be considered as when a blade [13] is pushed against the soil. The soil in front of the blade will be brought into a state of passive failure. The problem may be considered as two dimensional, since the central section of the wheel gives the maximum area of coverage. The following assumptions are made to calculate the soil resistance:

1. the soil is homogeneous, offering same resistance in all directions
2. soil is dry
3. no adhesion between wheel and soil
4. no surcharge on the soil surface

The resistance offered is given by,

$$F_p = \frac{1}{2}\gamma_s.z^2.N_\phi + 2.c.z.\sqrt{N_\phi} \quad \text{(kN/m)}$$

Where,

$N_\phi = \tan^2(45 + \phi/2)$, is the bearing capacity factor of the soil, 2.0396

ϕ = internal friction angle of the loose soil, 20^o

γ_s is the soil density, 1.5g/cc

c = cohesion, 2.45 kPa

z = sinkage of the wheel into the soil, 3.3cm when supported on all the six wheels (steering is carried out when all the wheels are on ground)

$$\therefore F_p = 247.27 N/m$$

The torque arm is given by $w = 2\sqrt{2zr - z^2}$, r is the radius of the wheel.

$\therefore w = 0.124m$

F_p shall be considered as uniformly distributed load, acting on the two sides of the midsection of the wheel as shown in the fig. 28

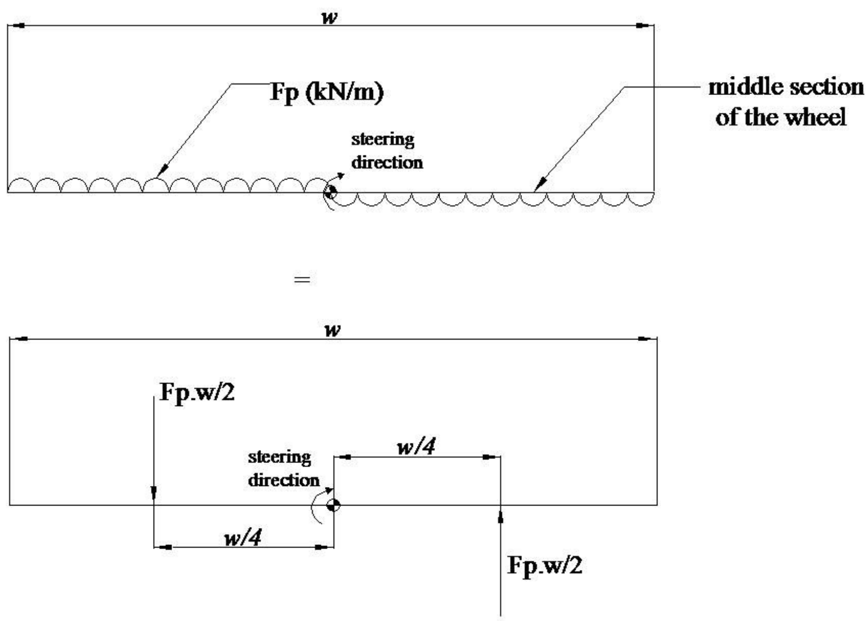


Figure 28 Soil resistance during turning is assumed act at the middle section of the wheel

The torque required to overcome the resistance is

$$M_s = F_p.(w/2).(w/2)$$

$$\therefore M_s = 0.95Nm = 950mN - m$$

In addition to this there will be friction at the steering column mounting point in the bogie. Since the steering column is supported using a thrust bearing, the following equation[16] is valid to calculate the frictional torque.

$$M_f = \frac{2}{3}\mu P \frac{R_o^3 - R_i^3}{R_o^2 - R_i^2},$$

Where, P is the axial load, $45*9.81/6$, Ro is the outer radius, 0.04m, Ri is the inner radius, 0.035m and μ is the coefficient of friction, 0.2(using thrust bearings).

$$\therefore M_f = 0.9156N - m = \underline{\underline{915.6mN - m}}$$

Therefore, torque required by the motor for steering is given by,

$$M_T = M_f + M_s$$

$$\therefore M_T = \underline{\underline{1.866N - m}}$$

Assuming a factor of safety of 2, $M_T = \underline{\underline{3.8N - m}}$

For straight motion or for the movement in any desired direction the wheel should be held at a particular angle against the soil resistance, otherwise the soil resistance will generate moment about the steering axis leading to unprecedented rotation of the steered wheels. The torque required to hold the wheels against the soil resistance is the holding torque of the motor. The worst case occurs when the total load is shared by the two wheels of a rocker-bogie. In that case the sinkage is 1.51cm. Correspondingly, the compaction resistance, Rc, is 46.2N and the resistance due to bulldozing effect is 73.2N.

So, the total soil resistance is given by $\underline{\underline{R_s = R_c + R_b \Rightarrow 119.4N}}$

The torque arm is the half of the wheel width, b/2 = 0.05m

$\therefore$ Holding torque, $\underline{\underline{M_H = R_s.b/2 = 2.985N - m}}$.

Assuming a factor of safety of 2, $\underline{\underline{M_H = 6N - m}}$

The motor to be selected shall have a stall torque of 6N-m and an operating torque of 3.6N-m at 10rpm

8.2 Drive motor torque

The maximum load is found to be exerted on the middle wheel of the rocker-bogie when the front wheel climbs an obstacle of 0.1625m beyond which the front wheel loses traction. Hence the maximum obstacle height of the obstacle that can be climbed is limited to 0.15m which is equal to the wheel diameter. Since the torque requirement is direct function of the load on the wheel, maximum torque has to be supplied by the middle wheel. The maximum torque is found to be 10N-m while the wheel runs at 3rpm and the normal operating torque is 7N-m at 13rpm

9.0 Pitch averaging mechanism

This mechanism is used to lock the body from swinging when the rocker-bogies follow the undulations of the terrain. The body will locked at an angle which is the average of the pitching angle of the rocker-bogies on two sides. Two kinds of pitch averaging mechanisms are available, viz. a differential attached to the CG of the rover and an averaging link mechanism. Since the construction of the averaging link mechanism is easier, it has been adopted for use. The simulation results of mechanism are shown below.

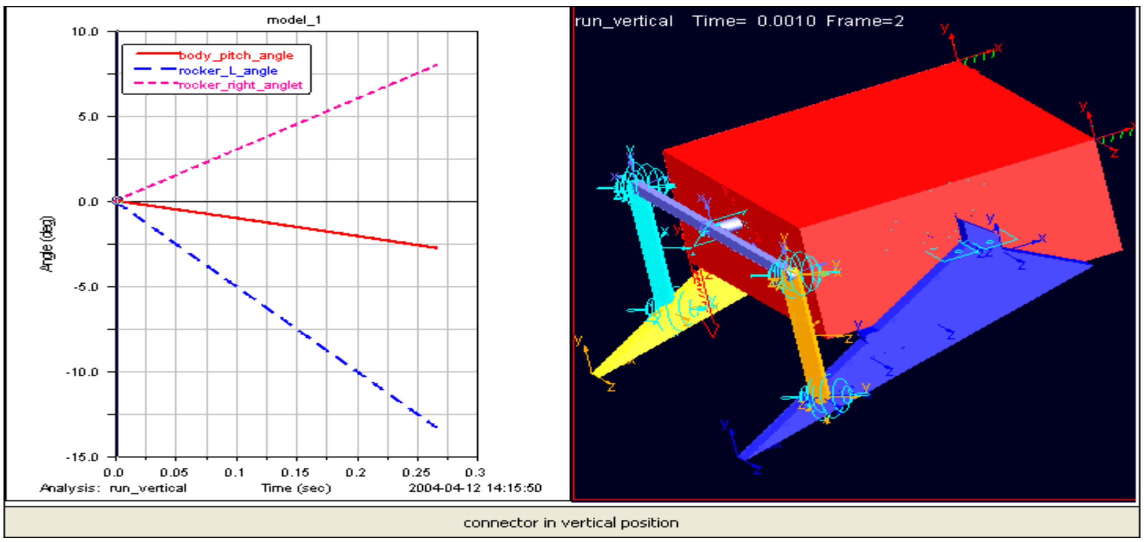


Figure 29 MSC.ADAMS Simulation of Averaging Mechanism. The dotted lines show the rotation of the rockers and the solid line shows the pitching of the body which the average of the rotation of eh rockers

10.0 Manufacturing

10.1 Requirements

1. Weight - One of the most important requirements of a rover to be sent on another planet is the weight. The advantage of reducing the weight is twofold; firstly it reduces the launch cost and secondly it reduces the operating power requirements for locomotion. Hence, selection of a light weight material for all the parts is a must.
2. Strength - The material selected has to be strong enough to withstand the impact loading caused by an uneven terrain. Also, for the success of a mission like this, it is important that the material can withstand numerous loading cycles without failure.
3. Cost - A tradeoff has to be made between having a material which meets the requirements and an inexpensive material as the budget is limited.

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.4-0.8	Max. 0.7	0.15-0.40	Max. 0.15	0.8-1.2	0.04-0.35	Max. 0.25	0.15	95.85-98.56

Table 1 Chemical composition of 6061T6 Aluminum Alloy (unit: Wt/%)

Taking all the requirements into consideration, we selected AA6061T6 Aluminum Alloy.

Aluminum alloy is widely used in many cases of the applications because of its ease of fabrication, non-toxicity, strength, and resistance to the corrosive atmospheres. 6061 combines most of the good qualities of aluminum. It possesses high strength, high resistance to corrosion, good workability, excellent joining characteristics, and a wide range of mechanical properties. It is the least expensive and most versatile of the heat treatable alloys. 6061 in the annealed condition offers excellent weldabilty and formability, and is readily disposed to furnace brazing. It can be clad to offer higher corrosion resistance. By adding the process of solution heat-treated and artificially aged, 6061T6 aluminum alloy gives more improvement of the aluminum's strength and hardness [3].

For the aerospace applications, the material needs to satisfy the requirements of having high strength combined with high fracture toughness, high corrosion resistance, and high modulus. The 6061T6 aluminum alloy has been proven to meet those requirements. At that same time, it is suitable to use joining method for space application, which will provide the extra higher durability of fracture of the body, and is good for the acceptance of applied coatings, which provide the higher resistance of corrosion of the parts.

Density	2.7 g/cm^3
Elastic Modulus	69500 MPa
Linear thermal expansion coefficient(20˚~100˚C)	23.6 x 10^{-6} C^{-1}。

Thermal conductivity	167 W/mc˚
Electrical conductivity	43 MS/m

Table 2 Physical Properties of 6061T6 Aluminum Alloy (unit: metric)

Thickness (mm)	Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	HB
0.4-0.5 0.5-6.5	310 MPa	275 MPa	8 10	95 ~ 100

Table 3 Mechanical Properties of 6061T6 Aluminum Alloy (unit: metric)

10.2 Machining

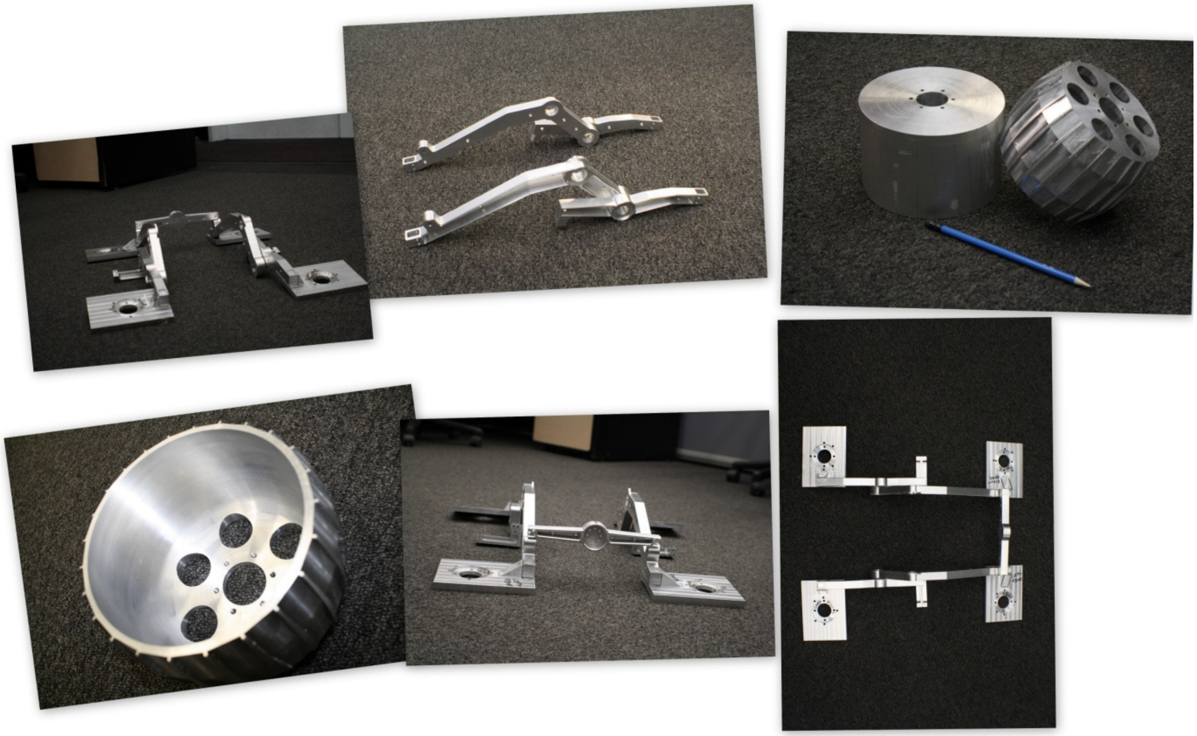
The mechanical design was customized to suit our needs, and hence almost all of the parts were manufactured. We had limited resources in terms of time and availability of CNC Mill and lathe. Hence, we decided to manufacture most of the parts manually while only using the CNC for intricate parts. The parts machined on the CNC are: rockers, bogies, averaging link and the six wheels. Rest of the parts were machined manually. DelcamFeatureCAM 2010 was used for CNC coding.

10.2.1 Estimated man-hours

We had three members assigned to manufacturing and we tried to manage the schedule in the most efficient manner so as to avoid downtimes. Here is a list of parts and number of man-hours that were put in.

N0.	Part name	# of parts	Hrs/Unit	Total Hrs/parts
1	Arm	4	4.5	18
2	Middle Wheel Strut	2	4.5	9

3	Steering Mount Bracket		4.8	0
4	Top			0
5	Wheel Mount			0
6	Body	1	10	10
7	Bearing Holder	10	4.2	42
8	Wheel	6	6	36
9	Average Link	1	2.5	2.5
10	Rocker (Right)	1	3	3
11	Rocker (Left)	1	3	3
12	Bogie (Right)	1	3	3
13	Bogie (Left)	1	3	3
14	Bearing Shaft			0
15	Rocker Bogie Shaft	2		0
16	Shaft Extender Rod			0
			Total Hours	***129.5***



11.0 Power and Electronics Systems

11.1 Battery

The power to rover is pumped through a 25.9V Ah 21 Ah High Power Polymer Li-Ion Battery [17]. This battery weighing 8.3 lbs. is used because of its high power to weight ratio compared to a regular lead acid/gel sealed batteries. It comes with a power control module (PCM) which enhances its life. It protects battery from over charge, over-discharge, over drain and short circuit.

Li-ion Battery

11.2 Power Distribution

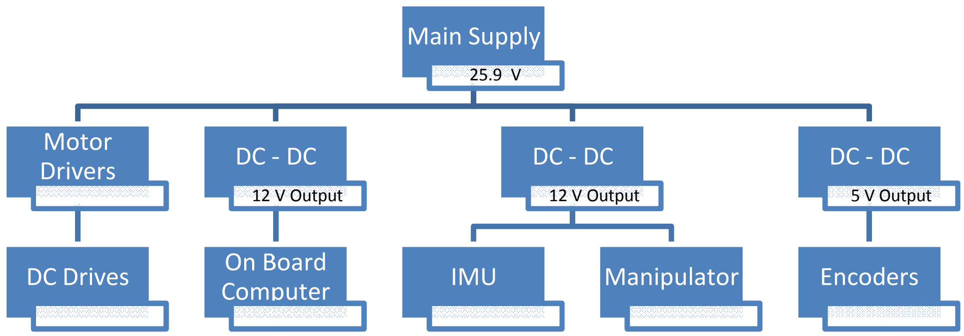


Figure 30 Power distribution chart

11.2.1 Power Splitters and Connectors

Figure 31 Professional RIGrunner 4008 for 24V

It offers a convenient and safest way to split the power from main battery. Each circuit has a fuse with a buzzer for out of normal range indication. [18]

Figure 32 Sub splitter

This is used to split the power down further from the RIG runner to the sub systems of rover.

11.2.2 DC-DC Regulators[19]

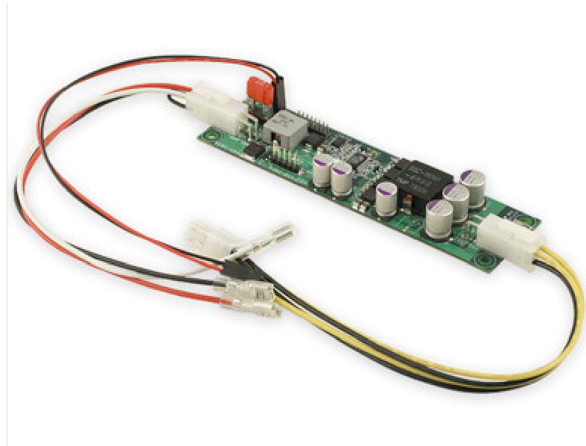


Figure 33 Intelligent DC-DC converter with USB interface

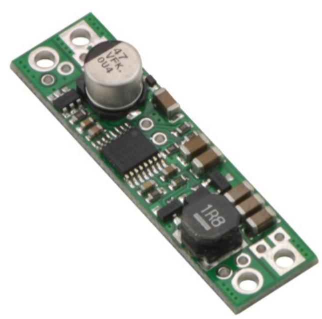


Figure 34 Pololu step-down voltage regulator

This regulator bought from pololu.com is used to power up the optical encoders on board [20].

11.3 Computer

The brain of the rover is a Pentium M single on-board computer by Versalogic. It was taken from a P3-DX mobile robot available in the LIARS lab.

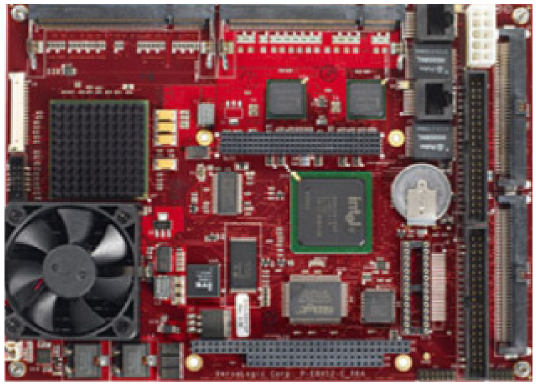


Figure 35 Rover Computer

11.4 Motor Drives and Control

The rover has six independent wheels with two steering motors in the front and back.The BDPG-60-110 24V[21] permanent magnet DC geared motors from Anaheim automation was selected based on budget and time constraints for the project.

Figure 36 Brushless DC Motor for drive and steering

The planetary gear box with 168:1 reduction ratio provides us enough torque for the rover design guidelines. Since the motor does not have a double ended shaft, we were not able to mount the encoder directly to the motor shaft. So we came up with a timer belt arrangement to drive the encoder. The encoder used is ENC-A5DI encoder [22] with a 1250 CPR which provides digital quadrature outputs.

Each motor will have its own controller and driver for independent control. These motors are arranged in the form of a master slave control as shown in the below figure through I^2C bus interface. This interface was chosen over SPI interface also available on the controller due to less wiring and reduced communication computation between master-slave.

I^2C requires just two lines compared to four lines used by SPI interface

SDL – Serial Data Line

SCL –Serial Clock Line

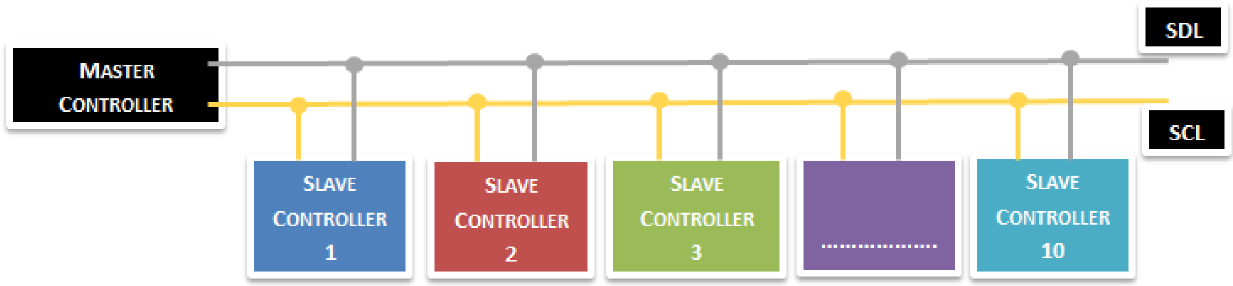


Figure 37 Master-Slave Control arrangement

11.4.1 Motor Driver and Controller

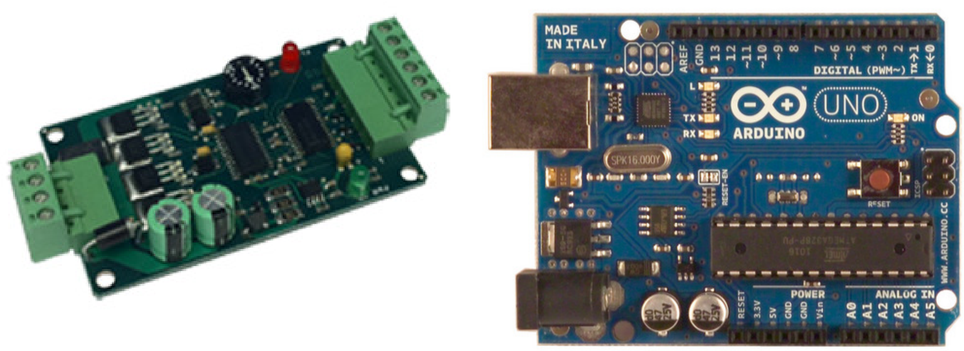


Figure 38 Motor Drive Electronics (Driver and Controller)

Manufactured by Anaheim Automation this controller is designed to drive a DC brush motor at currents up to 10A peak. The potentiometer on board allows us to current limit between 1-10A.It can be easily bolted to the aluminum chassis for heat dissipation if needed. The main controller provides a PWM signal to this driver which drives the motor. We are using a PID controller for motor control loop. The motor controller used is an Arduino Uno open source development board. This was chosen to reduce the development time needed to develop our own controller boards.

11.4.2.1 Safety

The motor drivers have a safety feature by restricting the maximum current available to the motor. Except for the power supply to the motherboard power to the other systems can be controlled through the digital i/o ports available on the motherboard itself.

12.0 Communication

Communication plays a pivotal role for a tele-operated robot. The robot is commandeered over an internet link form a remote location which demands a wireless connection. There are two modules of communication that connect the robot to the college computer.

1. Radio Frequency Module – This takes care of the connection between the robots and the internet wirelessly from the remote site.
2. Networking Communication Module – This takes care of the communication that takes place over the internet

12.1 Radio Frequency Module

The Rover is connected to the Internet through the VERIZON broadband dongle. The dongle gives the Rover access to the Internet. The college computer is connected to the internet through the college Internet Service Provider. The Rover is connected to the Internet through the Verizon dongle network; this causes the IP address to change dynamically if the system is restarted. Since we are controlling the Rover, making use of the IP address, knowing the new IP address of the Rover computer is critical. So we have written a module in Perl and Shell scripting that runs in the Rover in its background. This code returns the IP Address of the Rover computer to us each time the system is restarted.

12.2 Network Communication Module

The Network Communication Module used to communicate between the rover and the College Computer is that of a Server-Client Model. A packet based system is used to communicate between the client and the server. The College Computer (Client) is the Master and passes the commands to the Rover (Server) which acts as the Slave. The commands sent by the client are executed in the server and the result is given back to the client. The network interface uses sockets to connect the applications between client and the server. The communication model is implemented in Linux platform by using C/C++ for communicating over sockets. The flow of the socket program is shown in the diagram.

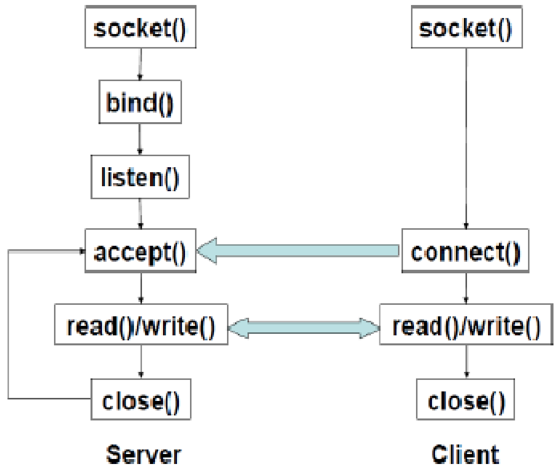


Figure 39 Interaction between client and the server

There are three separate tasks to be communicated from the rover to the College computer. Sensor Data, Video stream and Manipulator commands are to be constantly communicated between the Server and the Client. We have made use of three different sockets, one for sending the sensor data from the rover to the college computer, one for controlling the manipulator, and one for the video stream. For creating and assigning the sockets to the tasks we have made use of Berkeley sockets application programming Interface (API). The Type of connection used is TCP (Stream-Based) connection for passing the sensor data and the Manipulator commands, and UDP (Datagram –Based) for the video streaming. The overall flow is shown in the fig.40

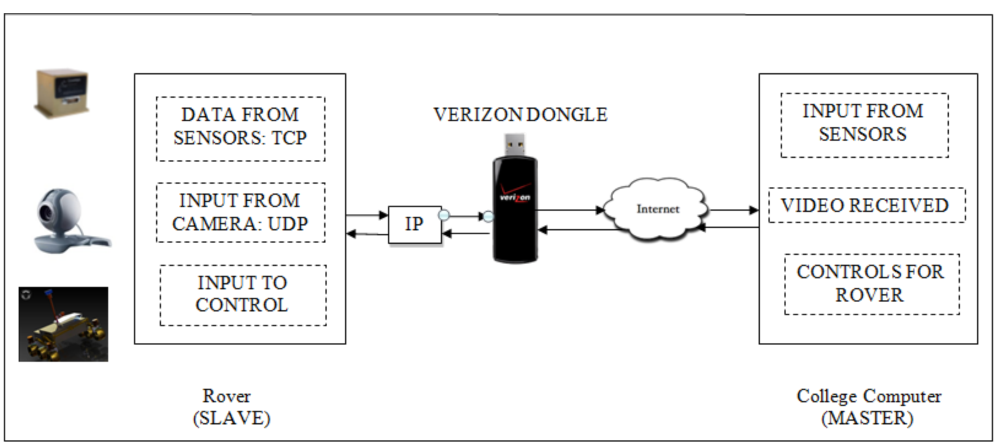


Figure 40 Communication Flow

13.0 Manipulator

One of the challenges in the competition is to collect and store all the stones present in the arena. The stones are of varying color and of sizes varying from 2cm to 8 cm. The manipulator should be able to pick up these stones and then place them on the rover. Since the time required to do this task is limited, one needs to consider the following criteria to ensure its smooth completion:

1. Workspace of manipulator

2. Manipulability

3. Its location on the rover

The reachable points in an n-dimensional space constitute the workspace of a manipulator while manipulability denotes its freedom of motion for a given configuration. Generally, a manipulator needs to have n degrees of freedom to map all the points of an n-dimensional space, but limitation imposed by the motors on the angle of rotation, and limitation on the length of the links reduce the number of reachable points in the given space. Redundant manipulators help in overcome this problem and they are an efficient tool to avoid any obstruction in the workspace. Thus workspace and manipulability is more for a redundant manipulator than for a non-redundant manipulator. In the context of this competition, a redundant manipulator will save time in the orientation of the rover while picking up the stones. Following table sums up the advantages and difficulties related with a redundant and a non-redundant manipulator:

Type	Advantages	Difficulties/Shortcomings
Non Redundant	Control is easy	Workspace, manipulability is limited
Redundant	Control is difficult	Better workspace and manipulability

Table 4

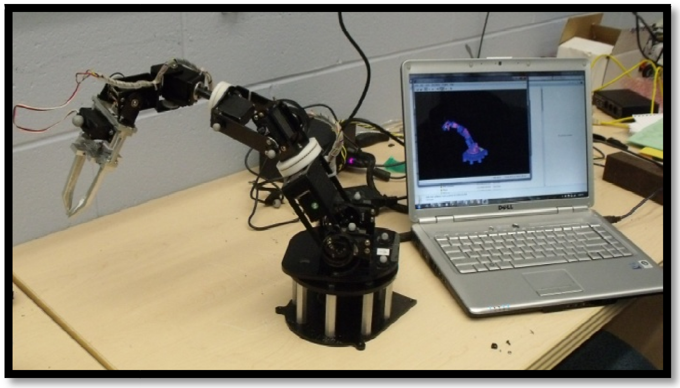


Figure 41- 7-DOF Manipulator

The location of the manipulator should be decided based on the stability of the vehicle and the storage of stones on the rover. The storage should be in the workspace of the manipulator and even though one can overcome any obstruction in the workspace of a redundant manipulator, it is advantageous to avoid them. Such obstruction may be offered by the camera mast or any other sensor being used on the rover.

Keeping in view all the issues discussed above, we chose Cyton Alpha 7 degree of freedom [23] (dof) manipulator for completing this task. Each joint can be rotated between -90^0 to 90^0, thus providing a range of 180^0.

13.1 Pick and Place

The manipulator is provided with a four jaw gripper to pick and place the stones. Normally there are two ways in which such tasks can be performed:

1. Autonomous

2. Semi-Autonomous

Autonomous – The camera locates and gives an estimated coordinates of the stones with respect to a fixed point on the rover. Since the ambient light may affect the estimation, there is possibility of some error in this method. However, one may use triangulation method to reduce the error in estimation. Since the camera provides an area rather than an exact location of the object, one may use three points on the boundary of the area to find its centroid. The centroid of the object can, then, be considered to be close to this point. The coordinates of this centroid can be given to the end effector of the manipulator. For a given position of the end effector, the orientation of a non-redundant manipulator is calculated using inverse kinematics. For a redundant manipulator, one can use numerical method like Newton Raphson or an analytical method in which some of the angles are fixed. Newton Raphson Method may take several iterations before convergence and since the time is limited, we used analytical method to find the orientation.

Semi-Autonomous – An input device is used to provide the coordinates to the end effector based on the visuals provided by the camera. The person using the input device looks at the image of the stone and the surrounding provided by the camera and provides an estimated coordinate of the stone.

Each of these methods has advantages and disadvantages which is summed up in the following table:

Mode	Advantage	Disadvantage
Autonomous	All the calculations are made on the server (Rover). Congestion due to data transmission over the network is reduced.	There may be error in estimation due to ambience. This error cannot be corrected without human intervention.
Semi-Autonomous	The human in the loop can see and rectify any error in the positioning of the end effector.	Data needs to be transmitted to the client (human) which increases the data congestion.

Another disadvantage of the autonomous mode is the difficulty in the translation of coordinates from the camera mast frame to end effector. It may not be easy on an uneven inclined plane. Since human intervention is allowed in this competition, we chose the semi-autonomous mode.

13.2 Control Input for Manipulator

1. **Requirements**

   The manipulator required an input device capable of providing position co-ordinates along the three axes.

2. **Available Options**

Logitech Attack 3 Joystick, Novint Falcon Haptic Device

3. **Description**

The Logitech Attack 3 Joystick has a control stick to control movement along the X and Y axes, and a lever to control movement along Z axis. Additionally, it also has 11 buttons.

Data is received as a byte-stream of 5 bytes through the USB port in the following format:

Byte	**Data**	**Description**
0	Time	The time represented as a 16-bit unsigned integer
1		
2	Value	Value of button/axis component
3	Type	Button(0x01) or Axis (0x02)
4	Number	Button/Axis number

4.

5. **Implementation**

The input from the Attack 3 joystick is read using a C++ code.

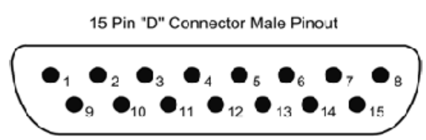
The Ubuntu OS recognizes the joystick port using the *joystick* package. A file descriptor is used to read the input. The joystick movements & button press/release act as events that fire the input. When an axis movement event is detected, the value component of input corresponding to the current axis position co-ordinate is obtained.

The position co-ordinates along all three axes range from -32767 to 32767 (integer range). These values are mapped to the range of the manipulator (-50 to 50).

14.0 Navigation

14.1 Inertial Measurement Unit (IMU)

The IMU is the main component of inertial navigation systems used in aircraft, spacecraft, watercraft, and guided missiles among others. In this capacity, the data collected from the IMU's sensors allows a computer to track a craft's position, using a method known as dead reckoning. The IMU has a 15 Pin "D" connector Male Pin out. We are making use of a 15 PIN "D" to USB convertor and passing the values of the IMU to the LINUX operating system. The IMU output is raw data contains all the required values but they are in plain hexadecimal format. We need to individually calculate the Acceleration Temperature Voltage, Roll Rate, Pitch Rate using the raw data and their corresponding formula.



The sensor data has to be sent from the server to the client. The IMU is connected to the Rover computer through the USB port. Since it is a Linux Operating System it sees all the ports as files. We open the USB port and read the values from the port just we use the system call functions for reading from files. A C code is used to convert the raw sensor values to acceleration and other useful data's automatically and then use the given values for navigation and controlling of the Rover. But the IMU is does not get activated automatically and requires a triggering signal for activating the IMU which is given by opening Cutecom software in one terminal and opening the USB port that the IMU is connected to. Then we run the C code that calculates the required sensor values from the raw data received.

14.2 Video Streaming

The project requirement specifies that the rover is to be tele-operated from our base at the university. To achieve this, it is necessary that we have a reliable video stream from the rover. The rover has 2 cameras, one of which is dedicated to streaming video. It is a high resolution web camera, and we intend to stream the video at a resolution of 1024x768 pixels and at 30 fps. If we find that the internet speed is not capable of delivering a smooth and real time stream, we will downgrade the resolution and/or frame speed to achieve a satisfactory quality of video.

Since video streaming is a critical aspect of the project, a reliable video stream is of paramount importance. There are a multitude of options to stream videos. Several products like Skype exist; they however are memory intensive and take up a lot of bandwidth as well. **FFmpeg** is a complete, cross-platform solution to record, convert and stream audio and video [24]. There are two specific components that we are interested in, namely:

ffmpeg is a command line tool to convert one video file format to another.

ffserver is an HTTP and RTSP multimedia streaming server for live broadcasts.

The ffmpeg is used in many streaming utilities such as the VideoLan, Xine etc. By operating at such a low level, we are eliminating the need for these utilities.

The quality of a 640x480 resolution video stream was tested at a 1-2Mbps speed internet service. It was found that that buffering of video for at least 2-3 seconds is needed to ensure a good quality of service. It was also found that using FFmpeg directly instead of products such as the VLC player slightly improves performance.

1.1 Visual Odometry

Odometry is a necessary component of any motorized vehicle. Traditional odometry methods are not suited to off road rovers due to the ruggedness of the terrain and the necessity for highly accurate results due to the autonomous or semi-autonomous navigation. Rotary encoders are error prone due to wheel slippage and sliding. Visual odometry is a camera based technique of ascertaining the rover's position. Visual odometry uses sequential images taken from a camera to estimate the distance and direction of travel. Visual odometry can be categorized using the orientation of camera. There are two major approaches:

(1) Downward facing camera: In this approach, the camera used to perform visual odometry is facing downward towards the terrain. The camera then captures images at regular intervals and features are extracted from each image. In each subsequent image, the features found in the previous image are located and the offset of the feature positions in successive images are used to estimate the distance traveled. This approach is dependent on identifying and locating reliable features. On uniform terrains, such as sand or roads, it is hard to identify distinguishable features. This approach also needs artificial lighting, as the camera is usually placed below the rover.
(2) Front Facing Camera: The forward facing camera overcomes the primary drawback of the previous method. Features obtained from these cameras are more desirable as the features obtained in this method are usually at a distance from the rover and hence are more likely to last through successive frames, giving more reliable results.

Kitt et al. [25] describe a stereoscopic camera based approach to perform visual odometry. Corner features are extracted and matched from successive stereo image pairs. Afterwards a subset is chosen by means of bucketing, that is, the image is divided into several non – overlapping rectangles. The smaller number of features reduces the computational complexity of the algorithm; as well as guaranteeing that the used image features are well distributed over the entire image. Feature points obtained from independently moving objects are eliminated by the means of a RANSAC based outlier rejection scheme [26]. Kalman Filtering is used to integrate the dynamic behavior of the rover. The Kalman Filter is a two-step estimator making use of a prediction step and an update step. It is used to estimate the current state of a dynamic system, which is assumed to be disturbed by zero-mean white noise. To estimate the instantaneous state, disturbed measurements are used. It is assumed, that the measurements and the state are related via a linear transform. It is also assumed that the given measurements are disturbed by zero-mean white noise.

The number of features that can be identified per frame in a real time application is dependent on the frames per second. It is estimated that at 30 fps, less than 10 features can be identified per image in order to maintain a real time process.

Visual odometry is but a step in our goal of fully autonomous navigation. We are currently in the process of building a autonomous navigation system based on the SLAM System [27]. Autonomous navigation will also include obstacle detection and avoidance and path planning.

15.0 Educational and Public Outreach

Any operation is deemed success only if it has a social commitment. To that end, we planned an extensive public and education outreach in the city of Buffalo, New York. We targeted not only the students in University at Buffalo, State University of New York but the general public as well. We set up Information booths in our University and in the Buffalo Museum of Science and explained the basic principles of the space related technologies. In addition to this, we sought the use and outreach of the social networks to spread the information on space exploration. The detailed report on EPO is as follows:

15.1 Information booths

We had set up information tables in our University's Student Union thrice. We explained the basic principle of the robotic that is being arm used in the International Space Station to secure the astronauts when they are outside the station to repair the damages to the ISS, by using our 7 DOF robotic manipulator. The students and staff were very much interested in knowing about the facts about space exploration and showed much enthusiasm in learning how to operate the Manipulator using a joystick.

We also explained the advantage of the modified Rocker-Bogie mechanism over a four wheel drive by building a model in LEGO® and driving it to show that they overcome the obstacles that are much bigger than their wheel size. We displayed the manufactured parts of our Rocker-Bogie structure and explained how the connections are made. Many students stopped by for tips on how to build their own Rocker-Bogies using LEGO®.

Last but not the least, we used the Erratic® rover that was available in our lab (LAIRS, UB) to demonstrate communication over the Internet. We encouraged the students and public to operate and drive the rover through an Ubuntu® platform.

Our team believes that it is not enough to enlighten just the students but the general public as a whole, specifically kids who are the pillars of the future world. With this task in hand, we tacked along with the SEDS chapter of UB to the Buffalo Museum of Science. We displayed and explained the above mentioned demonstration and SEDS demonstrated the underlying principle of rocket launch. Many kids listened to our explanation and demonstration about the Rocker-

Bogie & manipulator and were later seen explaining these concepts to their relatives. Kids enthusiastically walked around the museum lobby with our keyboard, driving our Erratic® rover over Internet. By all means, we strongly believe that we made a difference in their perception of space exploration.

15.2 Social Networks

In addition to setting up information booths, we used FaceBook to post updates on our rover and space related topics so as to kindle to desire to learn more about space exploration in the hearts of our followers and friends. People were excited to see the videos on manufacturing of our rover parts and other space related issues. We were able to send out a message that hard science need not be very much boring as everyone thinks. With right desire, vision and passion, hard sciences can be much more fun than the soft sciences.

15.2.1 Facebook for EPO campaign

Social networking is the best way to stay connected with our supporters and to keep them updated on our progress. We created a Facebook page for this very reason.

Our Facebook page was an instant hit with friends joining our page and sharing it. Our design and ideas got them interested and they wanted to know more about it. This was a very good beginning to our EPO campaign. We updated the page regularly with updates on our rover as well as articles/videos on space exploration.

Our 500 plus supporters come from 11 countries which served our purpose of reaching out to as many people from varied backgrounds and getting them excited about space exploration. Here is a snippet of our facebook page statistics.

15.2.2 Our Channels and websites EPO campaign

The complete information regarding this project can be had from our website 'spacebulls.buffalo.edu' and our Youtube channel 'ubspacebulls'.

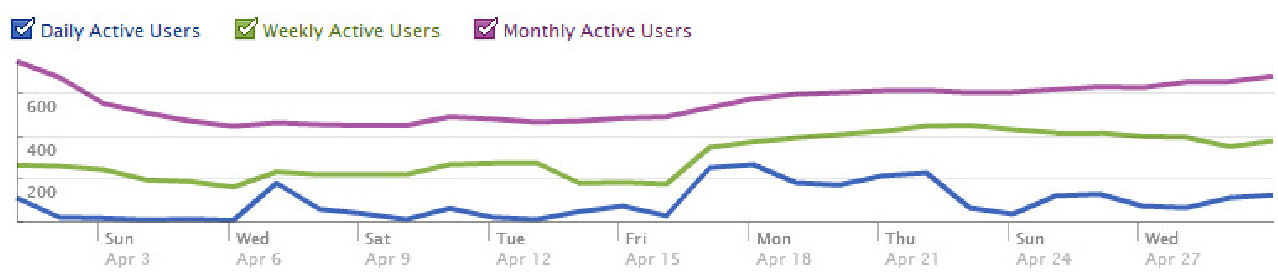


Figure 42 Statistics of Facebook activity

16.0 Budget

The following table shows the expenditure for the completion of the project. Some of the equipments onboard the rover was available in LIARS lab at UB. The project was also supported by the Mechanical & Aerospace Engineering (MAE) Department and Graduate Association of MAE Department.

Components	Cost (USD)
Motors, Drivers and Encoders	2542
Manufacturing Material	1100
Battery	900
Electrical Connectors	3423
Camera	40
On board Computer	NA
HDD	97.86
Encoder Mounts	200

Crossbow IMU	NA
Stereo Camera	NA
Motor Controllers	102
DC-DC regulators	166
TOTAL	4590

Table 5 Project Expenditure

17.0 Conclusion

A rocker-bogie suspension based six-wheeled tele – operated robot was realized in the project. The navigation systems and communication modules were successfully developed for the remote operation of the rover. The Education and Public outreach were planned and executed in an intense manner which is evident from the responses that the project team got from the public at the University at Buffalo and Buffalo Science Museum and also from the electronic media. At the time of the writing of the report the rover is yet to be test to its full functionality. The observations from the subsystem level tests are promising.

18.0 Scope for Future Work

The rover can be made lighter using lighter motors and using composite material for the chassis and other elements. A full-fledged navigation scheme can also be implemented to make the rover completely autonomous.

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