Chapter 5

Design of A Six-Wheel Rover

In this chapter we discuss the design of the six wheel rover. The rover is designed to transverse a wide variety of terrain. We discuss different subsystems of the rover like frame, wheels, links, drive/steering and mechanism used.

5.1 Design Considerations and Constraints

The mobility system designed should meet the constraints imparted by the launcher, lander and the operating environment (terrain).

The overall envelope available for the rover inside the lunar lander is limited to 600 mm x 500 mm x 400 mm. Allowable mass of the rover is limited to 20 Kg. The rover should be able to climb and be stable on terrain of 35^0 slope (bidirectional) while accelerating at 0.1 m/s^2. The rover should be safely able to negotiate an obstacle of height 150 mm and the maximum velocity on any terrain is limited to 10 cm/s.

Limiting operating conditions:

a. Maximum longitudinal slope - 35^0

b. Maximum lateral slope - 35^0

c. Maximum obstacle height - 150 mm (vertical wall)

Kinematic Constraints:

a. Maximum steering angle - 45^0 from the forward position (corresponds to the turning radius of 425 mm)

b. Maximum body pitch - 20^0

c. Maximum body roll - 15^0

d. Maximum speed on normal terrain - 10 cm/s

e. Maximum acceleration - 0.1 m/s^2 on 35^0 slope

5.2 Configuration design of the rocker bogie system

The kinematic configuration of the rover can be arrived at by determining the various dimensions shown in the figure 5.1

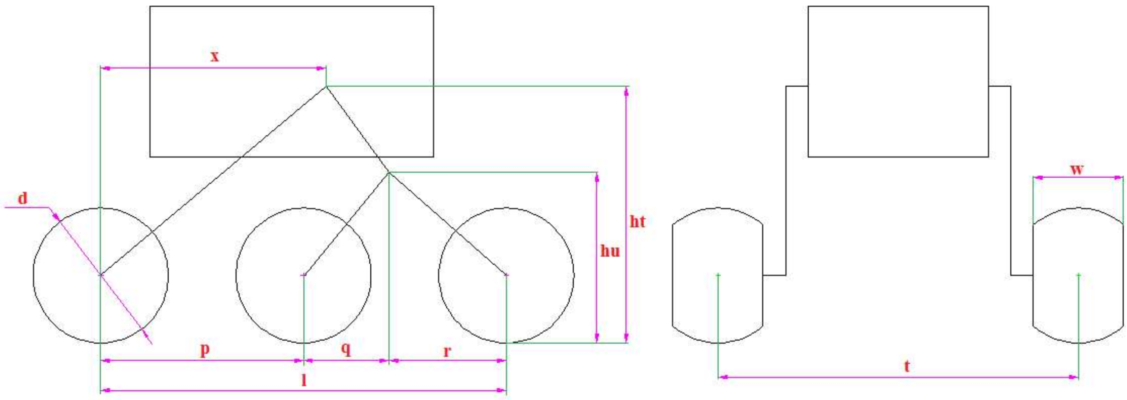


Figure 5.1: *Configuration of rocker bogie.*

Considering the overall envelope available for the rover (600 mm x 500 mm x 400 mm), the wheel-base is fixed as 450 mm (l) and the rocker-body pivot was fixed at a height of 285 mm (ht) from the ground. Calculations show that when the bogie wheels are equally spaced from the rocker-bogie pivot, fixing the rocker-body pivot at two-third the distance between the rear wheel centre and the rocker-bogie pivot distributes the total weight uniformly at the three wheels when the vehicle is on level ground. But for steering the vehicle about the centre, the middle wheels should lie at the centre of the wheel-base i.e. equidistant from wheels on either side. Hence the bogie wheels cannot be symmetric about the rocker-bogie pivot.

Sizing of the linkages is done in such a way that the rover is able to negotiate the worst expected terrain conditions (obstacles and slope) and at the same time maintain stability.

In order to finalize the bogie configuration, the height of the rocker-bogie pivot from the ground (hu) and the horizontal distance of the bogie wheel centres from the rocker-bogie pivot (q) need to be determined. In order for the bogie to climb an obstacle or slope by the action of the forces acting on it, the net moment generated about the rocker-bogie pivot should be positive (clockwise). The net moment is calculated for a range of values of hu, q. It is found that the moment is positive for values of hu greater than 100 mm and q less than 110 mm. Consistent with the overall geometry of the rover, a value of hu = 190 mm and q = 95 mm is fixed and a positive moment is verified. Hence r = 225-95 = 130 mm.

Now the position of rocker-body pivot has to be determined i.e. the horizontal distance from the rear wheel centre (x). The same principle as above is applied to the rocker as it climbs over a slope or obstacle in reverse movement. It is found that positive moment is generated for values of x greater than 245 mm. The value of x = 250 mm is fixed and a positive moment is verified.

The primary input to the design of the wheel is the lunar soil parameters. The wheel has to be designed to minimize sinkage of the wheels into the lunar soil as well as to maintain optimum ground pressure. Sinkage and ground pressure are functions of both wheel diameter and wheel width. Wheel diameter plays a part in the stability of the vehicle over a slope as well drive torque required. After optimization studies, the wheel diameter (d) was fixed as 150 mm and the wheel width (w) as 100 mm.

In order to determine the width between wheel centres, the stability of the rocker over a lateral slope of 35^0 is considered. It is found that for a lateral width (t) of 400 mm between wheel centres, the vehicle is stable. This dimension is also consistent with the overall width of 500 mm.

Fig. 5.2 shows the Kinematic configuration of the rover with overall dimensions.

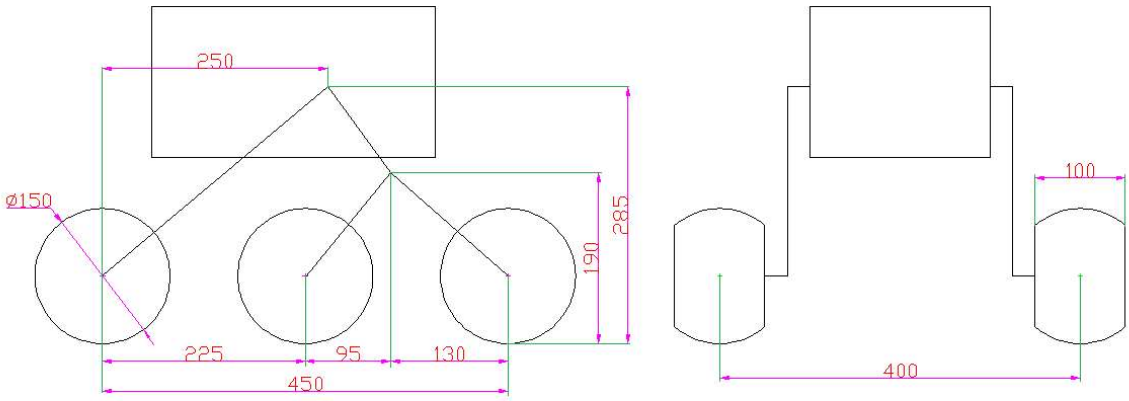


Figure 5.2: *Kinematic configuration of rocker bogie.*

5.3 Structure/Materials

Due to the uneven terrain, an optimal rover would be ideal for the design. This would allow for freedom of movement over a wide range of obstacles. One of the most suitable design will allow for the rover to move on most terrain it is likely to encounter and still be relatively small. The rover is divided into different section for increasing flexibility. Each wheel will have an independent clamp attaching it to the body of the rover with the help of the links. Articulated suspension system was chosen over fixed suspension systems as they could maintain contact of all the wheels with the ground over a wide range of terrain conditions and could climb obstacles significantly higher. Among articulated suspension systems, passive articulated system was chosen over active articulated system. This was because active systems would require actuators for articulations of the links, which in turn demands more power and computational requirement. Aluminium alloy are mostly used for different parts because of its strength/weight ratio and corrosion resistance properties.

Next section explains about structure and materials used for various parts.

5.3.1 Structural Design and Material Selection

The overall dimensions of the rover were set at a length of 550 mm, a width of 500 mm and a height of 350 mm. The maximum weight of the rover including equipment was set at 20 Kg. The under-body clearance was set at 190 mm from the ground. The wheel-base has been fixed at 450 mm and height of the CG is kept at 285 mm from ground. The track of the rover is 400 mm.

5.3.2 Frame

The primary requirement for the frame is that of a support structure for the rover. It must rigidly connect the links which attach to each of the six wheels, support the vehicle at rest and in motion over rough terrain, and supports the electronic parts. The main factors in designing were simplicity, lightweight, strength and rigidity. The frame consists of aluminium angles joined together. There is one cross tube going through the electronics enclosure connected to the links at rocker-body pivot. The main function of the electronic enclosure is to house, support and shield electronic components. The chosen design for electronic enclosure is a simple box structure. This makes design simple and yet functional. It has six sides of flat plates joined together on the exterior. The sides are connected to the outside of the frame angles.

The material should be lightweight and have good structural, electrical and thermal properties. The material chosen for the frame is aluminium angles.

5.3.3 Wheels

The wheels must support the vehicle and move it over rough terrain. They must have enough traction to move over uneven terrains but also be able to rotate freely for steering. Each wheel also has grousers, providing grip for climbing in soft sand and scrambling over rocks. The wheel itself must be a thermal sink for the drive motors to keep them cool during continuous operation. The critical design condition for the wheel is that two driving motors must be able to move the vehicle and one wheel must be able to support the entire weight of the vehicle. Driving wheel while driving must be able to climb obstacles of height equal to wheel diameter (150 mm). The chosen design of wheel has dimensions of 150 mm diameter and 100 mm width which forms the part of a sphere of diameter 150 mm. There are 24 numbers of grousers with maximum height of 5 mm at the centre width of the wheel and 2 mm at the edges of the wheel as shown in the figure 5.3. The base of the wheel faces away from the rover. Driving motor is clamped inside the wheel with the help of driving motor clamp. Wheel shields the motor and also dissipates heat generated from the motor during continuous running. Al6061-T6 aluminium alloy is used as material for wheel. It is precipitation hardening aluminium alloy, containing magnesium and silicon as its major alloying elements. It has good mechanical properties and exhibits good weldability. T6 temper 6061 has an ultimate tensile strength of at least 290 MPa and yield strength of at least 241 MPa. More typical values are 310 MPa and 275 MPa respectively.

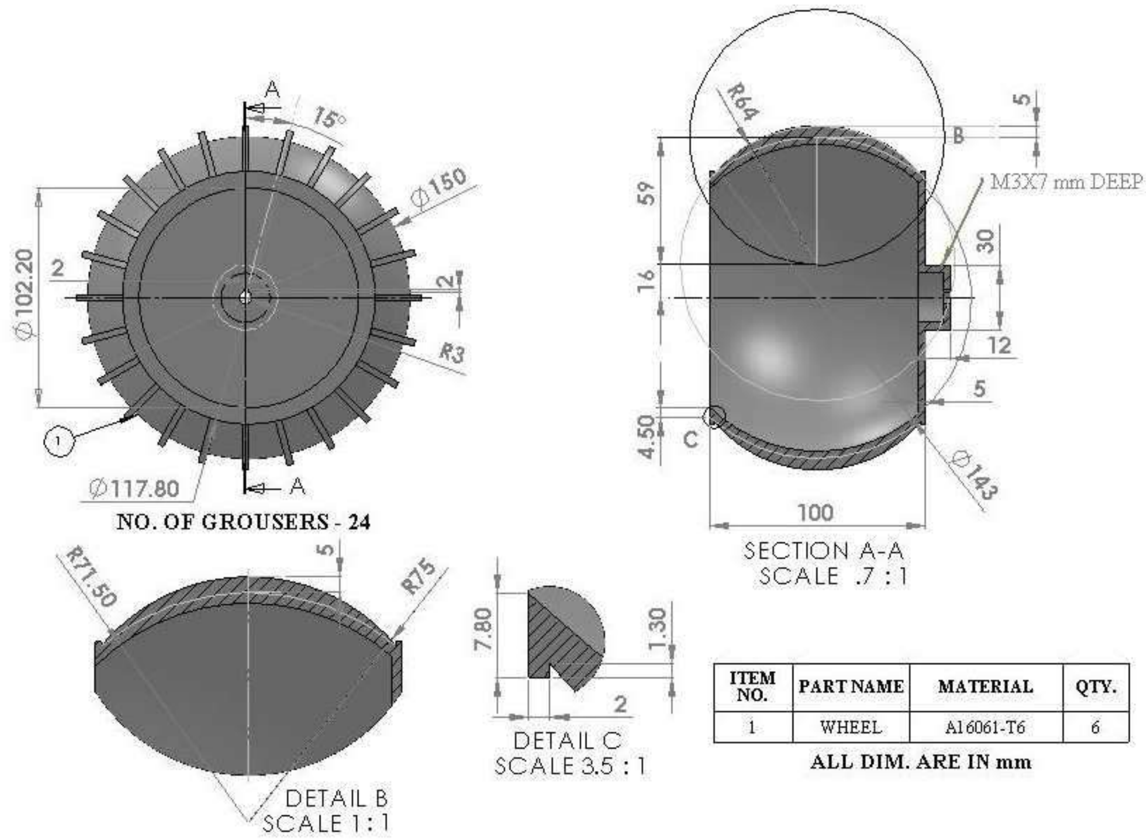


Figure 5.3: *Detail dimensional view of the wheel of the rover.*

Figure 5.4 shows the two views of wheel manufactured.

Figure 5.4: *Shows two views of the wheel of the rover.*

5.3.4 Links

The links connect the wheels to the body with the help of driving motor clamp. The maximum design force on the link is the weight of the entire vehicle in case of roving over flat terrain (neglecting forces caused due to acceleration) or the forces caused from a sudden impact. Analysis of rocker and bogie links was done in chapter 4. Results of analysis showed that box type link is best for the rocker and bogie link as it has less mass with stresses and displacement in limit.

5.3.5 Driving Motor Clamp

Driving motor drives the wheel, which is mounted inside the wheel with the help of the driving motor clamp. Aluminium alloy Al6061-T6 is used as material. Figure 5.5 shows the detail dimensional view of the driving motor clamp of the rover.

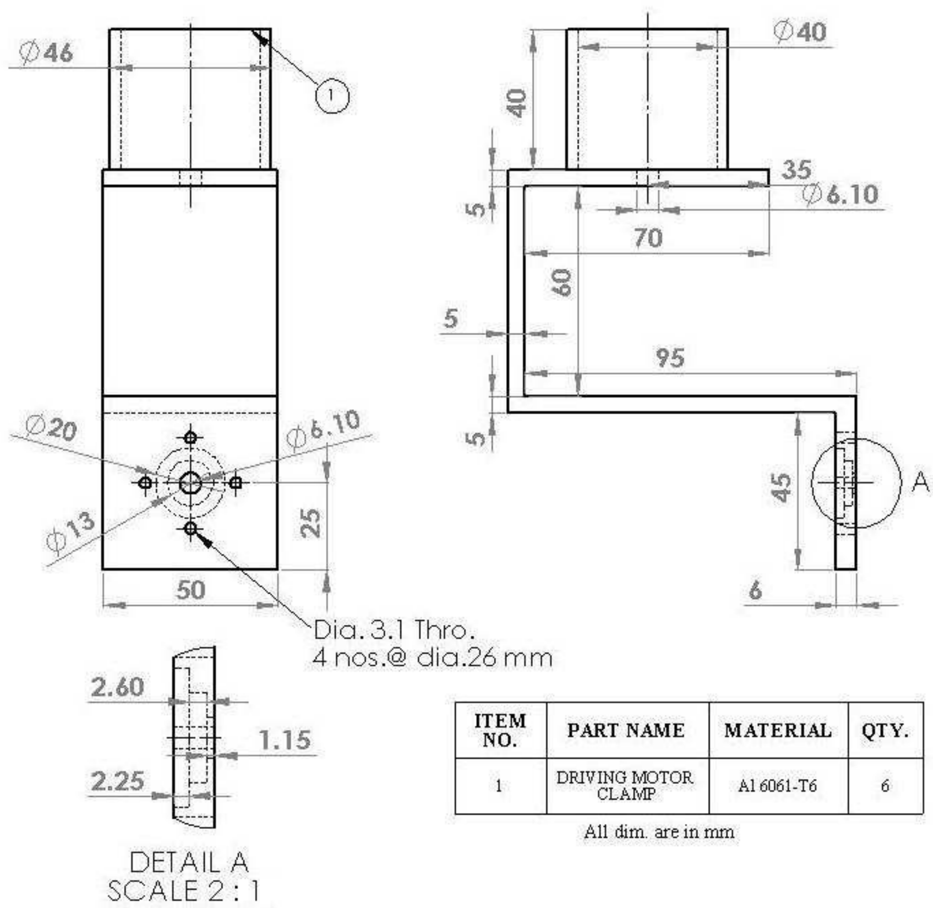


Figure 5.5: *Detail dimensional view of the driving motor clamp of the rover.*

5.4 Drive System

The two most important factors considered while choosing the driving and steering motors are mass and power. Motor with minimum power consumption with adequate torque will be the ideal choice. Each of the rover's six wheels has an independent motor. The use of six wheel drive will assure that the rover keeps contact with the ground every time, because the wheels are separately driven, the rover can rotate some wheels with the others locked so that a variety of tasks using the wheels can be accomplished. Driving motors are mounted inside the wheels. The maximum speed of the rover operated is limited to eliminate as many dynamic effects as possible so that the motors can be geared down, thus enabling each wheel to individually lift a large portion of the entire vehicle's mass. Permanent magnet DC brushless motors are used as this type of motor produces the required torque with minimal power and mass.

5.4.1 Driving Motor

To determine the requirements for the drive motor, several characteristics are considered. The maximum desired velocity of the rover is 10 cm/s. The following estimates were made to calculate the torque required:

a.) Rover weight is 196.2 N (considering mass of the rover = 20 Kg).

b.) Motor efficiency is 76 %.

c.) System acceleration time is 10 s.

d.) Coefficient for static friction & kinetic friction are 0.3 and 0.15 respectively.

Based on the mass, dimension and space availability, the Maxon motor assemblies were chosen for consideration. The EC-max 30 motor DC motor was the choice for the drive motor due to its relatively low power requirements and high torque. Gearhead with gear ratio of 318:1 is chosen to produce the desired velocity and reduce the input power required.

Total required torque given by T_{sys}

$T_{sys} = J_L \text{ X } \alpha + T_L$

Where,

T_{sys} = Total required torque

J_L = Moment of inertia of the load

α = Angular acceleration of the system

T_L = Torque required by the load

$$J_L = \frac{W_L}{E\ X\ g}\mathrm{R}^2$$

Where,

W_L = Weight of the rover (196.2 N) on moon surface

E = Efficiency of the motor (76 %)

g = Gravitational acceleration (1.63 m/s^2) on the moon surface

R = Radius of the wheel (75 mm)

α can be found from,

$$\alpha = \frac{V}{R\ X\ \mathrm{t}_a}$$

Where,

t_a = Time required to attain the desired velocity (est. 10 sec.)

V = Desired velocity of the rover (0.1 m/s)

T_L is found from,

$T_L = \mu_s$ X W_L X R

Where,

μ_s = Coefficient of static friction (est. 0.3)

$$\therefore \mathrm{T}_{sys} = \frac{W_L}{E\ X\ g}\mathrm{R}^2\ \mathrm{X}\ \ \frac{V}{R\ X\ t_a} + \mu_s\ \mathrm{X}\ W_L\ \mathrm{X}\ r$$

$$= \frac{196.2}{0.76\ X\ 1.63} X\ \ 75\mathrm{X}10^{-3}\ \mathrm{X}\ \frac{0.1}{10}\ +\ 0.3\ X\ 196.2\ X\ \ 75\mathrm{X}10^{-3}$$

$$= 0.1195 + 4.4145 = 4.534\ \mathrm{Nm}$$

Applying a safety factor of 2 & a factor of 3 considering only two drive motors are in operation.

$\therefore$ T_{sys} = 4.534 X 6 = 27.204 Nm

As all the wheels are independently driven, torque per wheel is 27.204/6 Nm

= 4.534 Nm

Considering the most extreme case to be encountered, the stall torque requirements for the rover can be obtained. Extreme case occur when rover has to lift its total weight while moving over bump or step. The required stall torque can be calculated from:

$T_{Total} = T_{sys} + T_{step}$

Where,

$T_{step} = W_L$ X h, (h = Height of the step)

$\therefore$ T_{Total} = 4.534 + 196.2 X 100X10^{-3} = 24.154 Nm

Using Gearbox efficiency (η_g) of 53 % & a gear ratio (GR) of 318:1, the input torque required from each motor is,

$$T_{in} = \frac{T_{Total}}{\eta_g\ X\ GR}$$

$$= \frac{24.154}{0.53\ X\ 318} = 143.31\ mNm$$

In order to find the operating point of the motor, the steady state condition is analyzed. Assuming Coefficient of kinetic friction (μ_k = 0.15)

$T_{ss} = \mu_k$ X W_L X R

= 0.15 X 196.2 X 75X10^{-3} = 2.207 Nm.

Applying a safety factor of 2 & a factor of 3 considering only two drive motors are in operation.

$\therefore$ T$_{ss}$ = 2.207 X 6 = 13.243 Nm

As all the wheels are independently driven, torque per wheel is 13.243/6 Nm

= 2.207 Nm

Again using gearbox efficiency (η_g) 53 % & a gear ratio (GR) of 318:1, the steady state input torque required from each motor is,

T_{ss} = 13.09 mNm

Using the speed/torque gradient ($\bigtriangledown$) from the data sheet of EC-max 30 motor, the operating speed is calculated to be

Operating speed (O.S.) = N.L.S. - ($\bigtriangledown$ X T$_{ss}$) = 8700 - (57.8 X 13.09)

$\therefore O.S. = 7944\ rpm$

This motor speed corresponds to a linear velocity of the wheel

$$= \frac{\pi X 150 X 10^{-3}\ X\ 7944}{60\ X\ 318}$$

= 0.196 m/s.

EC-max 30 motors are used for driving the wheels. To increase the required output torque of the motor, planetary gearbox are used. Details of the motor assemblies are given below.

a.) Driving Motor: EC-max 30, 40 W, 12 V

b.) Planetary Gearhead: GP 32 C, 1.0 - 6.0 Nm, Gear Ratio = 318:1

c.) Controller: EPOS P 24/5

Using EC-max 30 ϕ30 mm, brushless, 40 Watt. Table 5.1 shows specification of driving motor.

Motor Voltage	No Load Speed	Starting Current	Stall Torque	Continuous Torque
12 V	8700 rpm	11.80 A	153 mNm	35 mNm
Speed/Torque Gradient	Outer Diameter	Total Length	Weight	Gear Ratio
57.8 rpm/mNm	30 mm	91.8 mm	391 gms	318:1

Table 5.1: *Specification of driving motor.*

5.4.2 Steering Motor

The two front and rear wheels have individual steering motors which allow the vehicle to turn in place. Steering motor is required to steer the wheel is mounted vertically on the driving motor clamp with the help of the steering motor clamp. Trust bearing is used between the two clamps to have relative motion between them.

To find the requirement of the steering motor, the coefficient of kinetic friction (μ_k) was used and the radius of arm (R_a, measured from the axis of the motor shaft to the steering clamp) is 85 mm. The load torque can be found as

$T_{steer} = \mu_k$ X W_L X R_a

$= 0.15\ X\ 196.2\ X\ \ 85\mathrm{X}10^{-3} = 2.502$ Nm.

Gear ratio of 318:1 and gearbox efficiency 53 % are used, the overall steering torque reduces to

$$T_{steer} = \frac{2.502}{0.53\ X\ 318}$$

$= 14.845$ mNm.

Applying a safety factor of 2 and dividing by the number of steering motors produces the required steering torque T_s.

$\therefore \mathrm{T}_s = 14.845/2 = 7.42$ mNm.

EC 32 flat motors are used for steering the wheels. To increase the required output torque of the motor planetary gearbox are used. Details of the motor assemblies are given below.

a.) Steering Motor: EC 32 flat, 15 W, 12 V b.) Planetary Gearhead: GP 32 A, 0.75 - 4.5 Nm, Gear Ratio = 318:1

c.) Controller: EPOS 24/1

Using EC 32 flat ϕ32 mm, brushless, 15 Watt. Table 5.2 shows specification of steering motor.

Motor Voltage	No Load Speed	Starting Current	Stall Torque	Continuous Torque
12 V	4460 rpm	3.49 A	84.1 mNm	22.8 mNm
Speed/Torque Gradient	Outer Diameter	Total Length	Weight	Gear Ratio
54.9 rpm/mNm	32 mm	67.7 mm	272 gms	318:1

Table 5.2: *Specification of steering motor.*

5.4.3 Wheel Assembly

Front and rear wheels have two degrees of freedom provided by two motors namely driving motor and steering motor. Middle wheels have only one degree of freedom provided by driving motor. The driving motor is clamped inside the wheel with the help of the driving motor clamp. The steering motor is clamped on the driving motor clamp inside the cylinder. This provides protection for the motors. Figure 5.6 shows degrees of freedom provided by the driving and steering motor.

5.5 Mechanism

Rocker bogie system was chosen for the following advantages over the other systems:

a.) it has significant ability to climb obstacles in both directions.

b.) it can be explicitly steered.

c.) proven record in planetary missions.

The rocker bogie suspension system is a six wheeled system. On each side is a rocker, to one end of which a bogie is pivoted. One wheel is mounted to the other end of the rocker (rear wheel). Each end of the rocker carries a wheel. All the six wheels are driven by

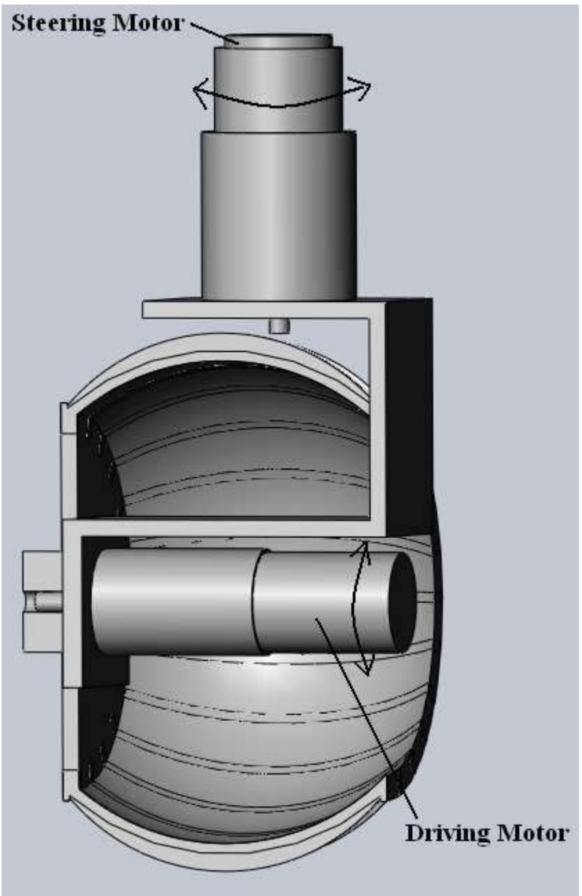


Figure 5.6: *Two degrees of freedom provide by driving and steering motors.*

servo motors. The four corner wheels are explicitly steered whereas the middle wheels are driven suitably (backward or forward) so that the vehicle turns about the centre of the axis connecting the middle wheels. The body of the rover is pivoted to the rocker on either side. The body is attached to the suspension at a third point through the pitch averaging mechanism. The pitch averaging mechanism consists of an averaging link which is pivoted on the body through revolute joint and two connecting rods which are attached to the rocker and the averaging link using revolute joints. At the centre of the averaging link (pivot on the body), the rocking motion of the two rockers is averaged and imparted to the body, which in turn executes pitching motion about the rocker-body pivot axis. Figure 5.7 shows detail dimensional view of averaging link and connecting rods assembly.

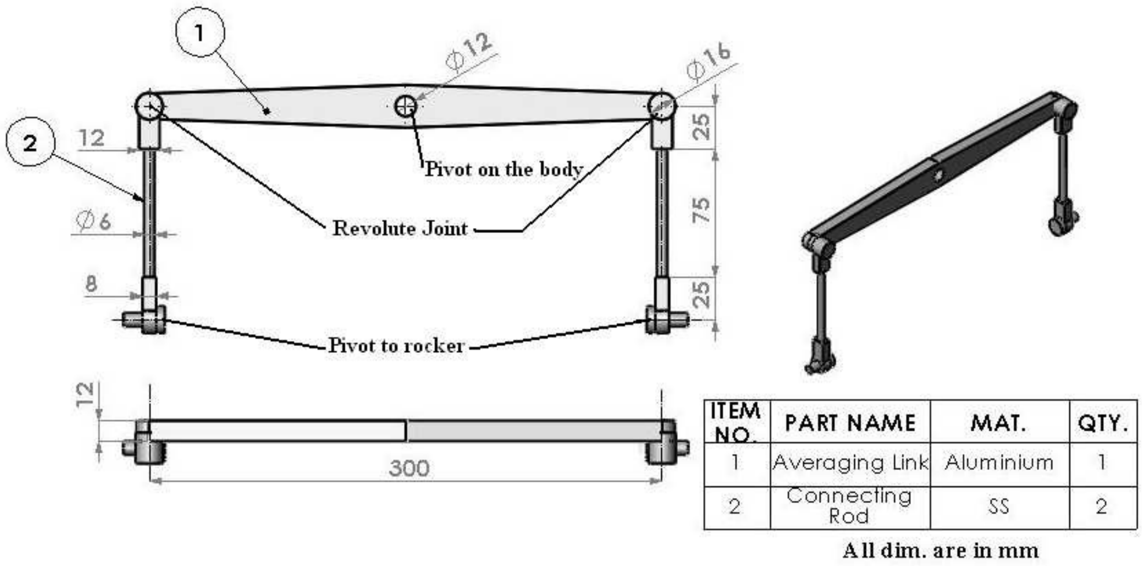


Figure 5.7: *Detail dimensional view of averaging link and connecting rods assembly.*

5.6 Six Wheel Rover Assembly

Final assembly of six-wheel rover contains following main parts. Table 5.3 shows detail of parts of six wheel rover with mass contribution.

Item No.	Part Name	Quantity	Part Mass (Kg)	Total Mass (Kg)
1	Large Link	2	0.383	0.766
2	Small Link	2	0.182	0.364
3	Averaging Link	1	0.20	0.20
4	Wheel	6	1.2	7.2
5	Driving Motor Clamp	6	0.182	1.092
6	Driving Motor	6	0.391	2.346
7	Steering Motor	4	0.272	1.088
8	Remaining	-	-	6.944
	Total			20.0

Table 5.3: *Different parts of six wheel rover with mass contribution.*

Rocker-Bogie suspension is used. All the six wheels are independently driven. Six motors are clamped inside the wheel with the help of the driving motor clamp. Both rear and front wheels are explicitly steered for turning the rover. Steering motors are mounted vertically on the driving motor clamp with the help of the steering motor clamp. Trust bearing is used between the two clamps to have relative motion between them. The body of the rover is pivoted to the rockers using cross bar. From the rear side, the body is pivoted through the pitch averaging mechanism. Figure 5.8 shows isometric view of six wheel rover.

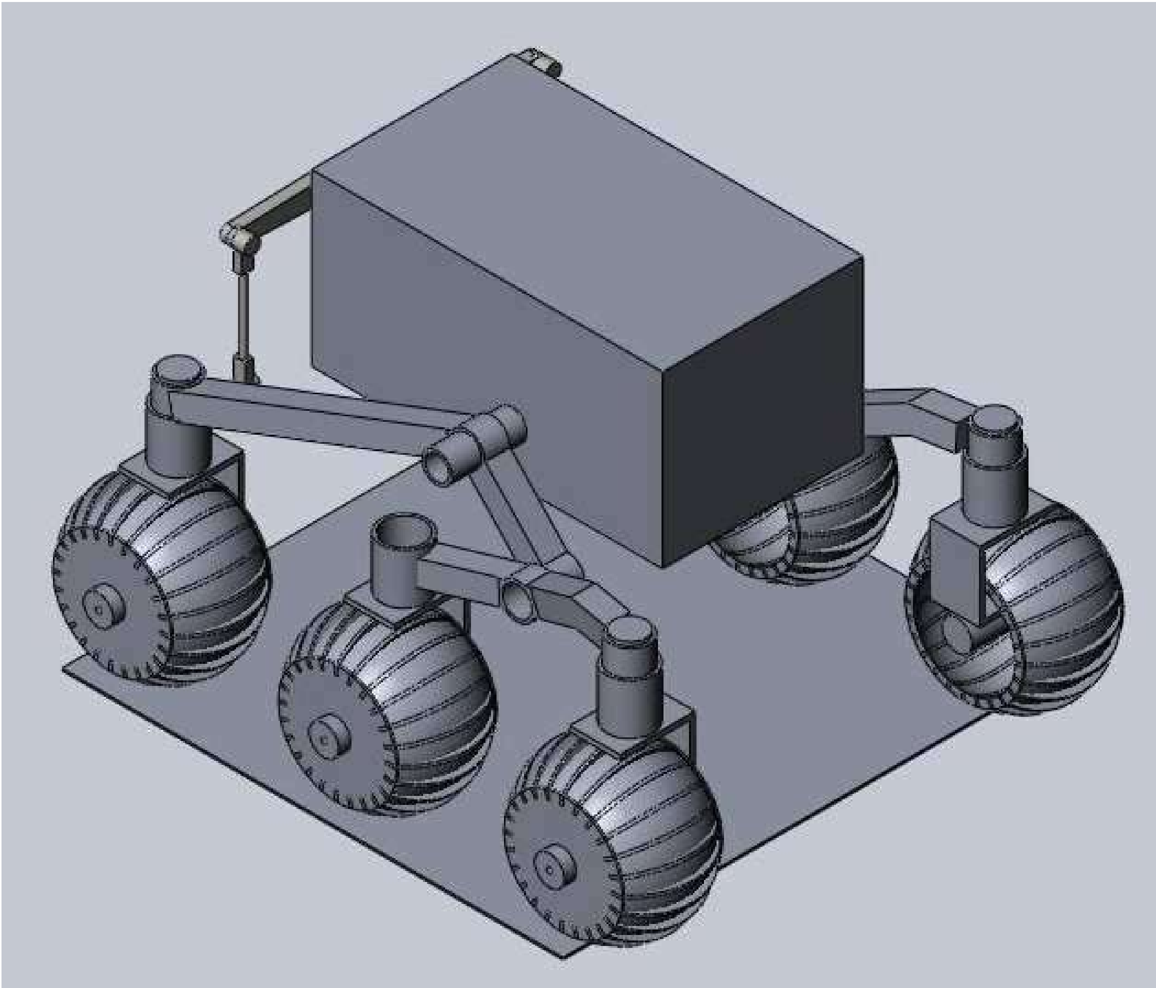
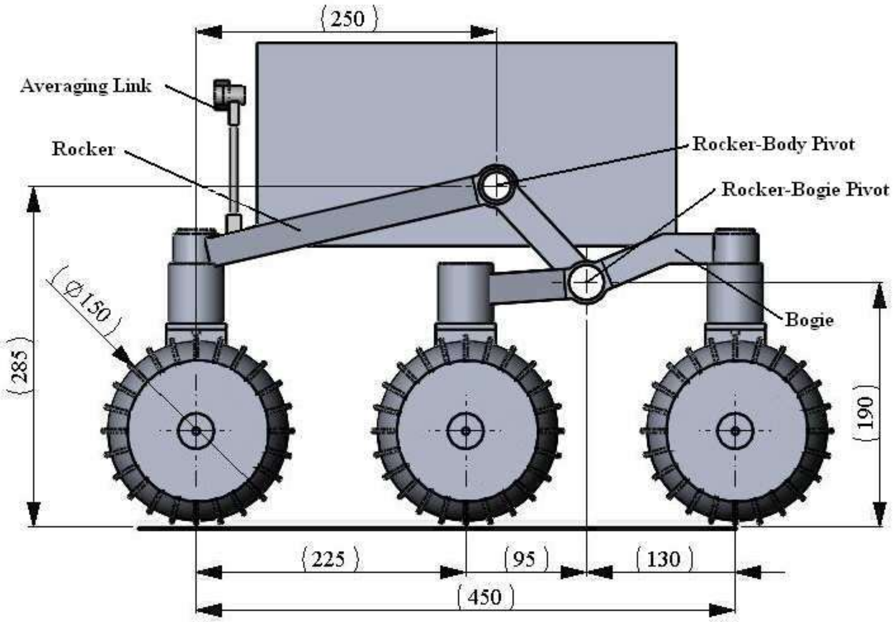
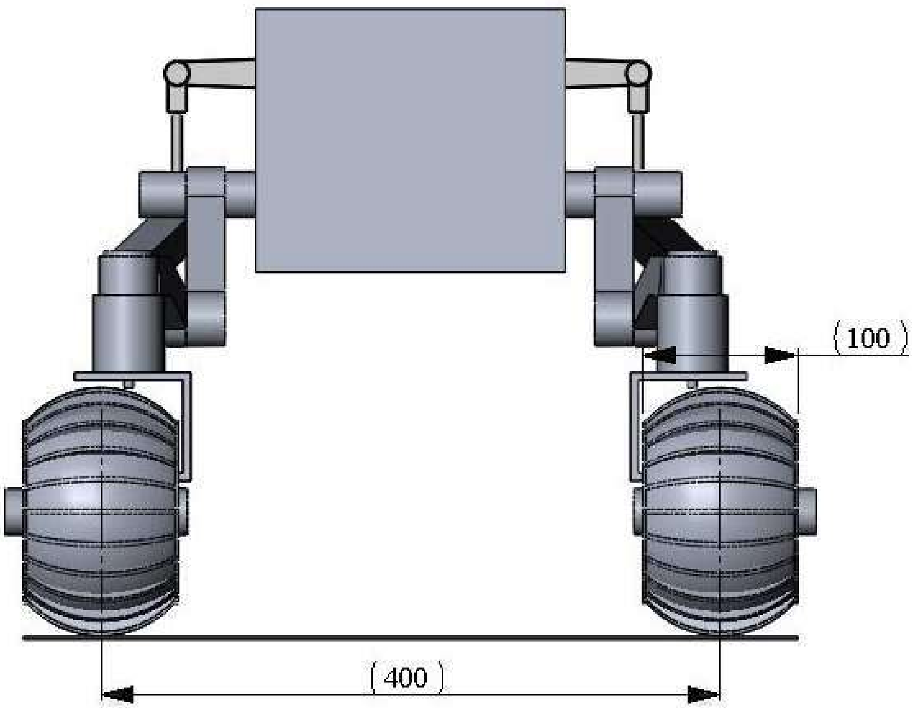


Figure 5.8: *Isometric view of six wheel rover.*

Figure 5.9 shows detail dimensional views of six wheel rover.



(a) *Right side view*



(b) *Front view*

Figure 5.9: *Detail dimensional (a) Right side view, (b) Front view of the six wheel rover*

Figure 5.10 shows rocker-bogie mechanism with wheels.

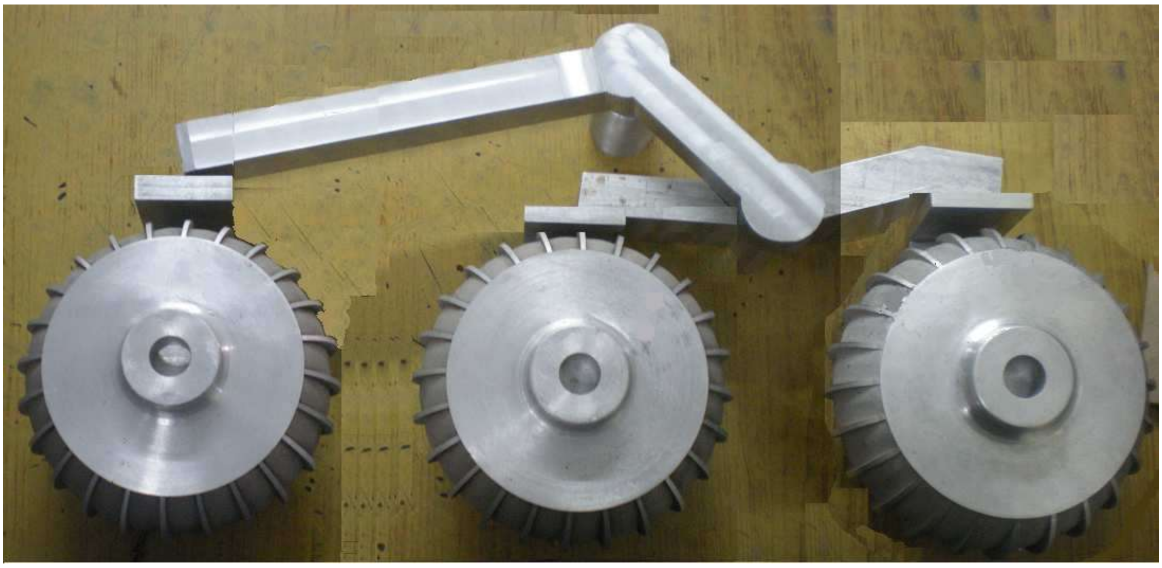


Figure 5.10: *Shows rocker-bogie mechanism with wheels.*

5.7 Closure

In this chapter we discussed the assembly of a six wheel rover. We discussed different subsystem of the rover. Overall configuration of the rover is also shown. Details of all the main parts are shown with dimensions.