# MODELLING AND DYNAMIC ANALYSIS OF ROCKER-BOGIE ROVER FOR SPACE EXPLORATION

**A DISSERTATION**

*Submitted in partial fulfillment of the requirements for the award of the degree*

*of*

MASTER OF TECHNOLOGY

*in*

MECHANICAL ENGINEERING

(With Specialization in CAD/CAM & Robotics)

*By*

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## CANDIDATE'S DECLARATION

I hereby declare that the work which is being presented in the dissertation entitled **"MODELLING AND DYNAMIC ANALYSIS OF ROCKER-BOGIE ROVER FOR SPACE EXPLORATION"** is presented on behalf of partial fulfillment for the award of the degree of **Master of Technology** in Mechanical Engineering with specialization in **CAD/CAM & Robotics**, submitted to the **Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee** under the supervision of **Dr. P.M. Pathak**, Assistant Professor, Department of Mechanical and Industrial Engineering, Indian Institute of Technology, Roorkee.

I have not submitted the record embodied in this report for the award of any other degree or diploma.

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## CERTIFICATION

This is to certify that the above statement made by the candidate is correct to the best of my knowledge and belief.

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*Roorkee* *Pushpendra Kumar*

*June 30, 2010*

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# ABSTRACT

We have entered a new phase of solar system exploration which has become increasingly necessary in order to answer questions about the origin and history of solar system bodies such as Mars, Moon, asteroids, and comets etc. It is very challenging task to land and collect the data from an unknown body whose environment may be unexpected. Space robotics has become the main area of research for many researcher and scientists all over the world, various research are going on in space robotics in different fields as mechanical, electrical, electronics, software etc.

In the present work the six wheeled rocker-bogie rover is described. The detailed kinematic modeling and the quasi-static force analysis is presented for the rocker-bogie rover. The dynamics of the system is presented based on the bond graph modeling and the motor dynamics is also integrated to the system. Simulation of the rover is performed and the performance of the rover is analyzed on different uneven surfaces.

# LIST OF ABBREVIATIONS

## Nomenclature:

| Notation | Definition |
|---|---|
| $V_{it}$ | Tangential velocity of wheel '*i*' |
| $V_{ix}$ | Linear velocity of wheel '*i*' in X direction |
| $V_{iy}$ | Linear velocity of wheel '*i*' in Y direction |
| $r$ | Radius of wheel |
| CoM | Centre of mass of body |
| $x_i$ | Position of point '*i*' in X direction |
| $y_i$ | Position of point '*i*' in Y direction |
| $T_i$ | Tangential force on wheel '*i*' |
| $N_i$ | Normal force on wheel '*i*' |
| $F_x$ | External force in X direction |
| $F_y$ | External force in Y direction |
| $M$ | External moment |
| $P_x, Q_x, R_x, S_x$ | Component of vectors P,Q,R and S in X direction |
| $P_y, Q_y, R_y, S_y$ | Component of vectors P,Q,R and S in Y direction |

## Greek symbols:

| | |
|---|---|
| $\alpha_i$ | Wheel '*i*' and ground contact angle |
| $\rho$ | Orientation of rocker |
| $\beta$ | Orientation of bogie |
| $\omega_i$ | Angular velocity of wheel '*i*' |
| $\varphi$ | Pitching of body |
| $\theta_1, \theta_2, \theta_3$ | Fixed angles of rover structure |

## Bond graph symbols:

| | |
|---|---|
| 0 | Common effort junction |
| 1 | Common flow junction |
| I | I element or Inertial elemwnt |
| C | C element or Compliant element |
| R | R element or Dissipative element |
| SE | Source of effort |
| SF | Source of flow |
| TF | Transformer |
| GY | Gyrator |

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# Chapter 1
# INTRODUCTION

## 1.1 Introduction to Space Robot

Robot is usually an electro-mechanical machine which is guided by computer or electronic programming, and is thus able to do tasks on its own.

Space Robots are the robots which are used for various space activities such as assembly, inspection, maintenance and planetary surface operations like mobility and exploration as surrogates for human explorers.

## 1.2 Types of Space Robotic systems

There are mainly two fields in space robotics:

1) Orbital robotic systems
2) Surface robotic systems

The Orbital robotic systems are used in orbital activities such as manipulation, assembling and servicing in orbit as assistants to astronauts while surface robotic systems are used in planetary operations like mobility and exploration.

In our study work we are going to deal with surface robotic systems for planetary exploration and sample collection from the planet.

## 1.3 Motivation

Sample collection from different planets is becoming increasingly necessary in order to answer questions about the origin and history of solar system bodies such as Mars, Moon, asteroids, and comets etc. It is very challenging task to land and collect the sample from an unknown body whose environment may be unexpected.

In the space we cannot predict about the environment; there are various key factors (Time delay, Gravity, Terrain, Temperature, Vacuum, Pressure, Radiation etc.)

which have to be considered while designing a space robot. In exploration robots (rovers) the ability of locomotion is very important factor to travel on a remote planet surface, because there may be unexpected terrain and may be rocky or sandy. In the deep space there is a big problem of time delay between robot and the operator so there is requirement of autonomous robotic system. The problem is of unexpected weather, which may be storms and high temperature variation whole the day.

## 1.4 Historical Development

The research on surface exploration rovers began in the mid-1960s, with an initiative (that never flew) for an unmanned rover for the Surveyor lunar landers and a manned rover (Moon buggy) for the human landers in the United States. In the same period, research and development began for a teleoperated rover named Lunokhod in the Soviet Union. Both the Apollo manned rover and the Lunokhod unmanned rover were successfully demonstrated in the early 1970s on the Moon. In the 1990s the exploration target had expanded to Mars and in 1997, the Mars Pathfinder mission successfully deployed a micro rover named Sojourner that safely traversed the rocky field adjacent to the landing site by autonomously avoiding obstacles. Following on from this success, today autonomous robotic vehicles are considered indispensable technology for planetary exploration. The twin Mars exploration rovers, Spirit and Opportunity, were launched in 2003 and have had remarkable success in terms of remaining operational in the harsh environment of Mars for over four years. In the future the Mars Science Laboratory (MSL) known as Curiosity is a NASA rover scheduled to be launched between October and December 2011 and perform the first-ever precision landing on Mars, and India's Chandrayaan-2 mission to land a motorized rover on the Moon likely in 2012, as a part of its second Chandrayaan mission. The wheeled rover will move on the lunar surface, to pick up soil or rock samples for onsite chemical analysis.

## 1.5 Types of Exploration Rover based on shape

These can be broadly classified into:

1) Mechanisms which utilize limitless rotational movement; (wheeled rover Fig. 1.1a)

2) Mechanisms which utilize leg motion; (legged robot Fig. 1.1b)

4) Mechanisms which utilize rotation and leg motion; (wheeled leg robot Fig. 1.1c)

3) Mechanisms which utilize articulated body motion.(snake type creeping propulsion motion Fig. 1.1d)

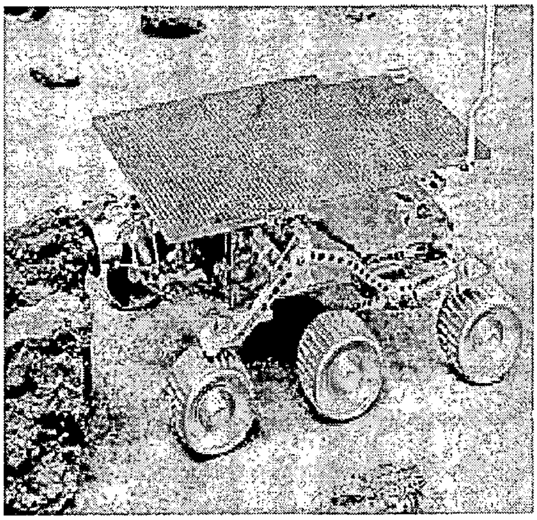


Fig. 1.1a. Sojourner

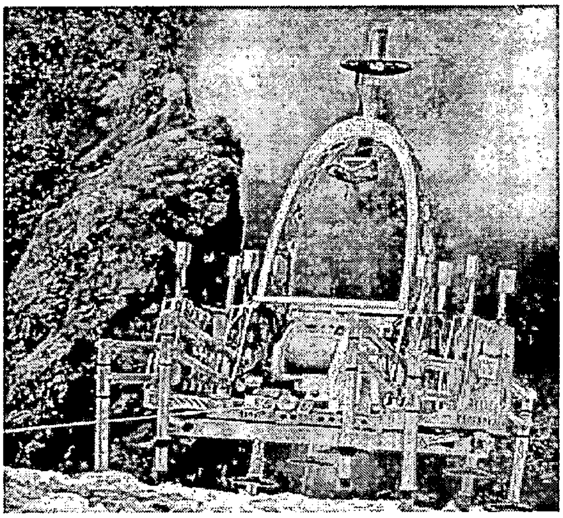


Fig. 1.1b. Dante-II

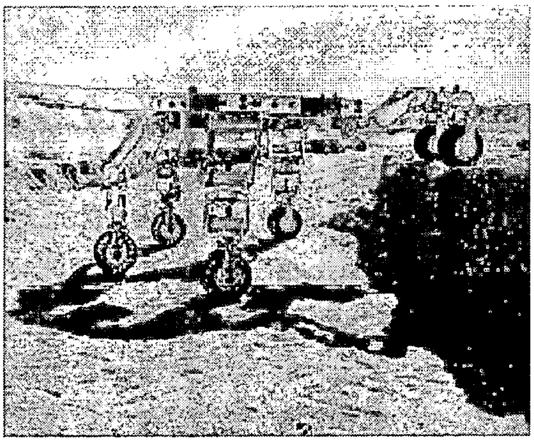


Fig. 1.1c. Athlete

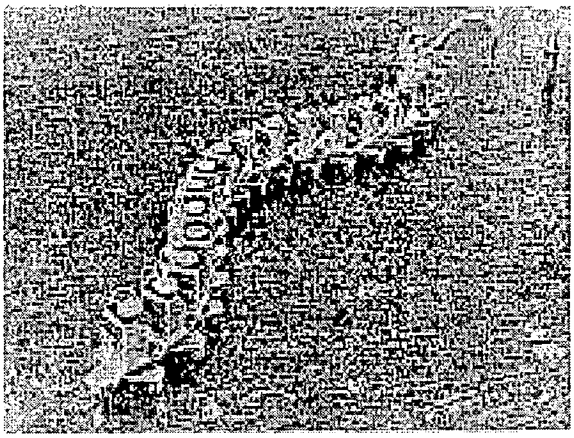


Fig. 1.1d. ACM-III

**Fig. 1.1.** Types of exploration rovers.

Many planetary exploration rovers have been developed since 1960s. According to the features of the mobile mechanism of robots, planetary exploration rovers have some types: wheeled, legged and tracked, etc. Wheeled mobile mechanisms have some excellent features, such as high speed on a relatively flat terrain and easily control, so many researchers trended to design their exploration rovers with wheeled structure. Currently, wheeled structure planetary rovers have 4-wheeled, 6-wheeled and 8-wheeled, etc. Among them, the 6-wheel mobile system with rocker bogie mechanism has superior adaptability and obstacle climbing capability, which had been applied in Rocky series and Sojourner Mars Rover.

## 1.6 Critical factors for Exploration Rover:

**Mobility** – For the remote planetary exploration the ability to travel is the most important for the rover as these surfaces are natural and rough, and thus challenging to traverse. Sensing and perception, traction mechanics, and vehicle dynamics, control, and navigation are all mobile robotics technologies that must be demonstrated in a natural untouched environment.

**Teleoperation and autonomy** – In deep space there is a significant time delay between a robotic system at a work site and a human operator in an operation room on the Earth. Telerobotics technology is therefore an indispensable ingredient in space robotics, and the introduction of autonomy is a reasonable consequence.

**Environment**– Issues such as extremely high or low temperatures, high vacuum or high pressure, corrosive atmospheres, ionizing radiation, and very fine dust. That environment affects natural and rough terrain that affects surface mobility, there are a number of issues related to extreme space environments that are challenging and must be solved in order to enable practical engineering applications.

## 1.7 Main requirements of the Exploration Rover:

**SUSPENSION SYSTEM:**

This is main consideration while designing an exploration rover as it has to be traversed on the rough terrain. The suspension system should be such that it can cope up with every situation as there may be various craters, boulders, ditch etc. So it should be stable while encounter with an obstacle and should not stuck or turn. The suspension system should be capable to traverse on rocky and soft terrain.

**DRIVE SYSTEM:**

The motors for driving the wheels should be of sufficient capacity and reliable so that can withstand in space environment. There should be gear mechanism for speed control of different wheels. The each wheel requires brake and disengagement mechanism and proper steering mechanism should also be considered while designing the exploration rover.

**POWER SYSTEM:**

The rover requires the power to operate its different subsystems so there should be sufficient arrangement for power in the rover.

**COMMUNICATION:**

There is requirement of communication between the rover and the operator on the earth so that the control commands can be received from the earth and the exploration data can be send to earth in least time delay.

**NAVIGATION AND CONTROL:**

There must be an excellent software and hardware architecture and cameras on the rover for the navigation of rover and control of different subsystems of the rover as the control commands received from the earth

**SCIENTIFIC INSTRUMENTS:**

The rover is required to carry various scientific instruments with it for doing some onsite tests.

## 1.8 The Rocker-Bogie structure:

The Rocker- Bogie system is the suspension arrangement used in the Mars rovers for both the Mars Pathfinder and Mars Exploration missions. It is currently NASA's favored design.

A 6-wheeled rover with rocker bogie structure is studied in this work. This has six independently driven wheels mounted on an articulated passive suspension system. The four corner wheels are steerable. With this design, while traversing rugged terrain, each wheel trends to contact with the ground. The principle of the 6-wheel mobile mechanism of planetary rover with rocker-bogie structure is shown in Fig. 1.2.

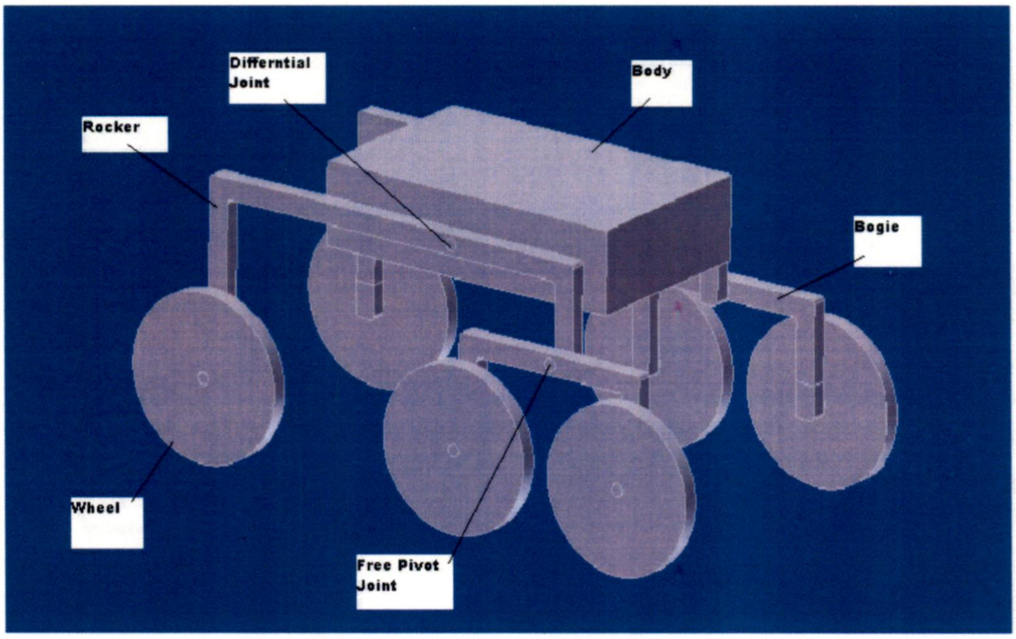



**Fig. 1.2**. Rocker-Bogie rover

Six wheels independently driven by the motors are mounted on an articulated frame. The frame has two rocker arms connected to the rover body. Each rocker has a rear wheel connected to one end and a bogie connected to the other end. The bogie is connected to the rocker with a free pivoting joint and at each end of the bogie there is a drive wheel, the rockers are connected to the rover body with the differential joint.

## 1.9 Contribution to Thesis

The issues that are presented in this thesis are, (i) Kinematic modelling and quasi-static force analysis of the rocker-bogie rover. (ii) Dynamic modelling of the rover using bond graph technique. (iii) Verification of model with simulation results and analysis of rover's performance on various uneven terrains.

## 1.10 Organization of the thesis:

The chapters of this dissertation are arranged as follow. Chapter 2 presents the literature survey for the space exploration rovers. The work done by the researchers in the field of space exploration rovers are briefly described. In chapter 3 detailed kinematic modeling for the rocker-bogie rover is presented. Chapter 4 describes the quasi-static force analysis for the rover. In Chapter 5 the bond graph model of the rocker-bogie rover is presented. Simulation and results for the rover are presented in chapter 6. The conclusion of the thesis and future scope is described in chapter 7.

# Chapter 2
# LITERATURE SURVEY

## 2.1 Existing literature on rocker-bogie modelling:

In year 1995 Shigeo Hirose *et al.* [1] outlined the fundamental considerations for a planetary rover. They compared the wheeled, legged and articulated body shapes, and it was found that the wheel type is currently the optimum for a planetary rover. Next they studied specific methods for configuring a planetary rover with one, two, three and four wheels.

In year 1996 Yangsheng Xu *et al.* [2] proposed the concept of mobile manipulator by the cooperation of a wheeled rover and a detachable manipulator called the Dual- Use Mobile Detachable Manipulator, or (DM)2 , for early construction and maintenance tasks in lunar stations. This system provides better flexibility of manipulation and exploration tasks such as collecting soil samples, surveying the lunar surface.

Pedersen *et al.* [3] at NASA have done a survey on space robotics and determine the state-of-the-art and future scenario in space robotics. They described the various issues like human-robot collaboration, planetary surface access, and surface investigation in the field of space robotics.

Yasutaka *et al.* [4] at Carnegie Mellon University discussed the configuration of robotic locomotion for the moon, and describe analysis and experimental results obtained through testing of a physical prototype. To achieve substantial climbing capability and mitigate body excursions they selected a six-wheeled configuration that utilizes pivot arm linkages for body suspension.

Miller and Lee [5] at NASA described a method of driving a rocker-bogie vehicle that can effectively step over most obstacles rather than impacting and climbing over them. They suggested some mechanical changes to gather the maximum benefit and to greatly increase the effective operational speed of future rovers. Most of the benefits of this method can be achieved without any mechanical modification to existing designs but a change in control strategy.

In year 2002 Yoshida and Hamano [6] investigated kinetic behavior of a planetary rover with attention to tire-soil traction mechanics and articulated body dynamics, and thereby study the control when the rover travels over natural rough terrain. They carried out experiments with a rover test bed using the tire slip ratio as a state variable to observe the physical phenomena of soils and to model the traction mechanics.

In year 2004 Lamon *et al.* [7] described quasi-static modeling considering the system constraints: maximal and minimal torques, positive normal forces of a six-wheeled robot with a passive suspension mechanism together with a method for selecting the optimal torques. The method is used to limit wheel slip and to improve climbing capabilities.

In year 2005 Tarokh and Dermott [8] described a general approach to the kinematics modeling and analyses of articulated rovers traversing uneven terrain for 6-DOF motion. Differential kinematics is derived for the individual wheel motions in contact with the terrain and then combined to form the composite equation for the rover motion. Three types of kinematics navigation, actuation, and slip kinematics are identified, and the equations and application of each are discussed.

In year 2005 Mann and Shiller [9] described the stability considering both static equilibrium and dynamic effects of a Rocker Bogie vehicle that accounts for the tendency to slide, tipover, or lose contact with the ground. The measure of stability is computed by solving for the range of acceptable velocities and accelerations that satisfy a set of dynamic constraints and the maximum acceptable velocity serves as a dynamic stability measure, whereas the maximum acceptable acceleration at zero velocity serves as a static stability measure.

In year 2005 Lindemann [10] described the Mars exploration rovers named Spirit and Opportunity which were landed on the mars surface in January 2004. In order to assess the mobility characteristics of the rovers in the Mars environment, an engineering model vehicle was tested before the mission launches in a representative environment of slopes, rock obstacles, and soft soil. In addition, to gain better insight into the rovers' capabilities, a dynamic model of the rovers was created in the software package

ADAMS. The rover model was then used to simulate many of the test cases, which provided a means for model correction and correlation.

In year 2006 Randel *et al.* [11] described the Mars Exploration Rover (MER) Project launched in mid-2000 to land on the Mars, and discussed the mission requirements, design architecture, mechanical mobility, hardware design, development and testing.

In year 2006 Thianwiboon and Sangveraphunsiri [12] proposed a method for kinematics modeling of a six-wheel Rocker Bogie mobile robot. The forward kinematics is derived by using wheel Jacobian matrices in conjunction with wheel-ground contact angle estimation. The inverse kinematics is to obtain the wheel velocities and steering angles from the desired forward velocity and turning rate of the robot. By comparing information from onboard sensors and wheel velocities traction control is also developed to improve traction to minimize wheel slip. Simulation is done with a rover has rocker bogie in two conditions of surfaces including climbing slope and travel over a ditch.

In year 2006 Xinyi Yu *et al.* [13] analyzed the motion of articulated lunar rover with six cylinder-conical wheels and force acting to wheels, according to the mechanical configuration of rover, operations pattern of wheel, and principle of speed matching of wheels they presented a control algorithm which can fit various uneven terrains and merge it into the whole locomotion control system.

In year 2007 Deng *et al.* [14] discussed the optimum control model of the motion, they done motion control of a lunar rover, the power optimum control was carried out for a lunar rover prototype with six cylinder-conical wheels in wheel walking motion mode in order to minimize the power consumption. The kinematics model of wheel-walking motion was built up and the simulation model was constituted based on Simulink.

In year 2007 Bai-chao *et. al.* [15] analyzed the structure of the new suspension and the kinematics of the levers, and to know the distortion capability of the suspension, relational equations of the suspension levers are established. In order to test the capability of suspension, they design a prototype rover with the new suspension and take a test of climbing obstacles, and the prototype rover with new type of suspension had excellent capability to climb up obstacles with keeping cab smooth in the results.

In year 2007 Kanfeng *et al.* [16] analyzed the external disturbances cause the lunar rover's unexpected move because rover may run on the uneven surface of the moon. They investigate the effects of external disturbance. The six wheeled- rocker-bogie lunar rover is considered as a six-wheeled vehicle with four steering wheels and the steering dynamic equation is built based on automotive theory. External disturbance is expressed as a force acted on the mass center of the rover and the Laplace transform is introduced. The research results show that the travel changes of the rovers will be different distinctly when the rovers with different steering characteristics are disturbed simultaneously.

In year 2007 Thueer *et al.* [17] presented the performance optimization tool (POT). The POT enables the comparison and optimization of a rover chassis in a quick and efficient way. The tool is based on a static approach including optimization of the wheel torques in order to maximize traction. Tests with real hardware were performed to validate the POT. Two different rovers, CRAB and RCL-E, were assessed in simulation and hardware with respect to specific, well defined metrics. In simulation, their performances were compared to the rocker-bogie-type rover MER.

In year 2007 Thueer *et al.* [18] Conducted a study of locomotion performance of different suspension types in order to find the rover that matches best any given mission requirements. A number of metrics were defined which precisely specify what qualifies as good or bad performance. These results were used to characterize the performance of each rover and put it in relation to the weighted mission requirements. This study has shown that a four wheeled rover can be a valuable alternative to the rocker bogie but only in very specific missions.

In 2008 Thueer and Siegwart [19] analyzed three different rovers from a kinematic point of view. The optimal velocities at the actual position were calculated for all wheels based on a kinematic model and used for characterization of the suspension of the different rovers. Simulation results show significant differences between the rovers and thus, the utility of the chosen metric. It is found that by integrating kinematics in a model-based velocity controller a substantial reduction of slip can be achieved.

In year 2008 Yuan *et al.* [20] presented a wheel-ground contact angle and slip estimation scheme for skid-steered lunar rover by combining drive and guidance system to form a closed control system, in which an observer will work out the slip values and wheel-terrain contact angle by using the measured datum of passed route of lunar rover's mass center. Simulation and experiment results show that the terrain and control parameters algorithms can accurately and efficiently be identified for loose sand.

In year 2008 Younse *et al.* [21] at the Jet Propulsion Laboratory used the Mars technology rover Sample Return Rover 2000 (SRR2K) for their experiment. They presented the Mars sample return missions technology to robotically acquire and cache multiple samples for delivery back to Earth. To prevent cross-contamination, individual detachable scoops and caching boxes were designed for use with a rover. They used a robotic arm on the rover to open and close the cache boxes. A clamping mechanism designed for the end effecter of the robotic arm attached and detached individual scoops and performed the scooping for sample collection.

In year 2008 Pathak *et al.* [22] presented the bond graph model of an autonomous vehicle, called RobuCar, with four independently driven wheels and two independently adjustable steering angles. The system bond graph is constructed for generating the Analytical Redundancy Relations (ARRs) which are evaluated with actual measurements to generate residuals and to perform structural fault isolation. The system is reconfigured to achieve given control objectives.

In year 2008 Suojun *et al.* [23] build the mobility performance indexes based on work conditions by summarizing the lunar surface terrain characteristics. The performance of overturning stability, load equalization of the wheels and trafficability are analyzed and established an optimization mathematical model of suspension parameters of rocker-bogie rover.

In 2009 Yongming *et al.* [24] presented a model based on force analysis of the differential joints and force analysis between the wheels and the ground; they established the quasi-static mathematical model of the 6-wheel mobile system of planetary exploration rover with rocker-bogie structure. Using the method of finding the wheels friction force solution space feasible region, obstacle-climbing capability of the mobile mechanism was analyzed by considering the constraint conditions. The simulation is done by giving the same obstacle heights and contact angles of wheel-ground.

Iagnemma and Dubowsky [25] at Massachusetts Institute of Technology addressed a rough-terrain control (RTC) methodology that exploits the actuator redundancy found in multi-wheeled mobile robot systems to improve ground traction and reduce power consumption. A key element of the method is to be able to estimate the wheel ground contact angles and an optimization criterion based on the local terrain profile is used. Kalman filter method is presented for estimating these angles using simple onboard sensors.

Hacot [26] at Massachusetts Institute of Technology presented the models of mechanics and method for solving the inverse kinematics of the rocker-bogie rover. The quasi-static force analysis was described for the rover. The simulation of the rover was done and compared with experimental results.

## 2.2 Gap identification from literature:

The existing literature shows that researchers have attempted kinematic analysis of rocker bogie rover and studied the behavior of the rover. This has been done with the assumption that rover moves with a very slow speed.

This work presents a dynamic model of rocker bogie rover using bond graph modeling and the force analysis has been performed. The model has been tested for various terrains.

# Chapter 3
# KINEMATIC MODELLING

In this section the rover kinematic modeling is explained. The rover consists of several rigid elements connected through joints. The rover is capable of locomotion over uneven terrain by rolling of the wheels and adjusting its joints, and the only contact with the terrain is at the wheel surfaces. In our analysis, each wheel is assumed to be represented by a rigid disc with a single point of contact with the terrain surface.

To establish the rover model rigid body kinematics is used and the model is simplified such that it has identical behavior as the real rovers Fig. 3.1.

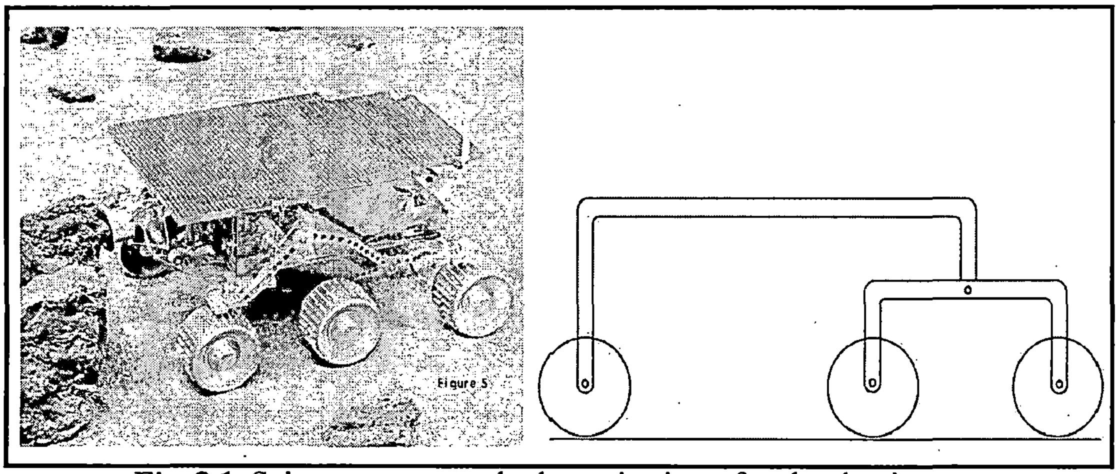


**Fig. 3.1.** Sojourner rover and schematic view of rocker-bogie rover

## 3.1 The Planar model:

The planar model of the rover is shown in the Fig. 3.2. A, B and C are the points on the centre of wheel axles and the point K represents the free pivot joint between rocker and bogie. Point D is the differential joint between rocker and body and G point is centre of mass (CoM) of the body. The system is defined by the vectors of constant lengths AK, BK, CK, KD and DG.

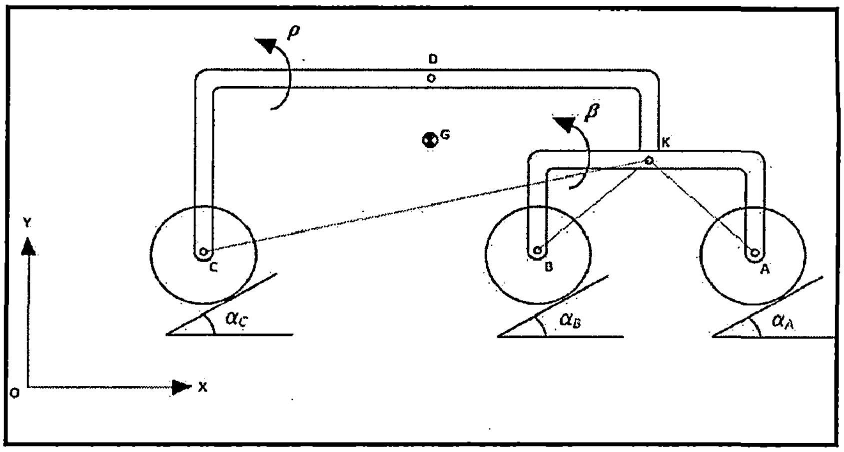



**Fig. 3.2.** Planar model of rover

The frame {O} is the reference frame. The orientation of rocker ($\rho$) and wheel-ground contact angles ($\alpha_A$, $\alpha_B$ and $\alpha_C$) are with respect to the reference frame and the orientation of bogie ($\beta$) is relative to the rocker.

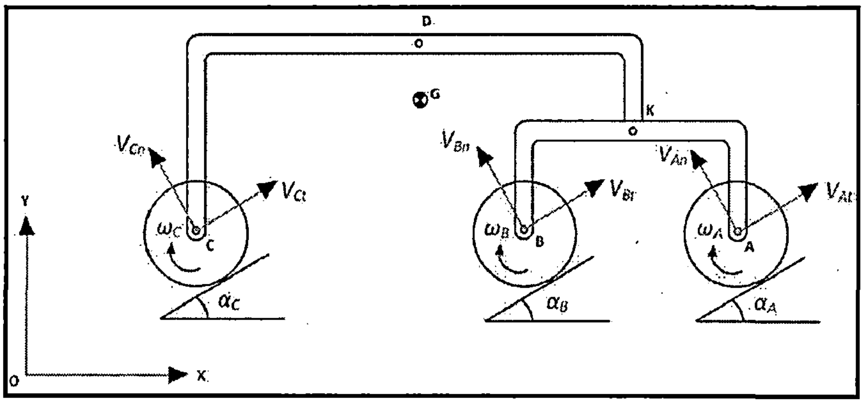



**Fig. 3.3.** Velocities description

The wheels at points A (front), B(middle), and C(rear) are actuated by the motors. If $\omega_A$, $\omega_B$, and $\omega_C$ are the angular velocities of the front, middle and rear wheel (Fig. 3.3), then the linear velocities of the centre of wheels are given by the following relations.

$$v_{At} = r.\omega_A \quad (3.1)$$

$$v_{Bt} = r.\omega_B \quad (3.2)$$

$$v_{Ct} = r.\omega_C \quad (3.3)$$

Where $r$ is the radius of wheel.

The positive X and Y directions of the reference frame {O} is shown in the Fig. 3.3. The components of linear velocities in X and Y directions are given below.

$$v_{Ax} = v_{At}.\,cos(\alpha_A) - v_{An}.\,sin(\alpha_A) \tag{3.4}$$

$$v_{Ay} = v_{At}.\,sin(\alpha_A) + v_{An}.\,cos(\alpha_A) \tag{3.5}$$

$$v_{Bx} = v_{Bt}.\,cos(\alpha_B) - v_{Bn}.\,sin(\alpha_B) \tag{3.6}$$

$$v_{By} = v_{Bt}.\,sin(\alpha_B) + v_{Bn}.\,cos(\alpha_B) \tag{3.7}$$

$$v_{Cx} = v_{Ct}.\,cos(\alpha_C) - v_{Cn}.\,sin(\alpha_C) \tag{3.8}$$

$$v_{Cy} = v_{Ct}.\,sin(\alpha_C) + v_{Cn}.\,cos(\alpha_C) \tag{3.9}$$

## 3.2 Frame assignment:

For further analysis first of all we assign frames at different points as shown in Fig. 3.4. Two frames are fixed on rocker at points C and D. Three frames are fixed on bogie at points A, B and K. One frame is fixed to the body at point G (CoM).

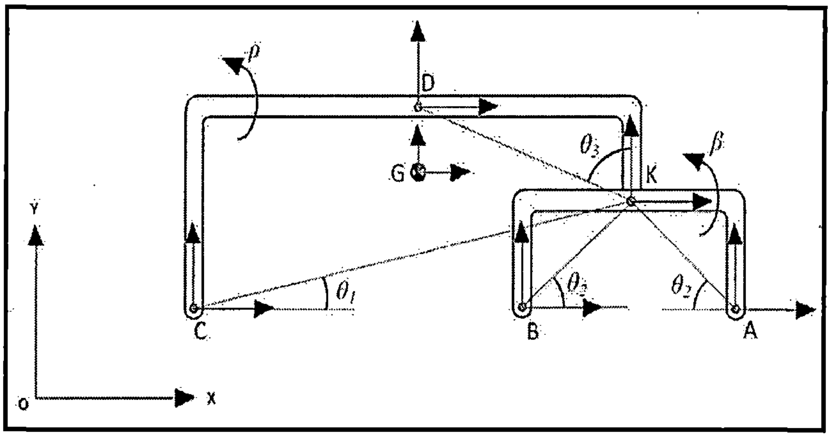



**Fig. 3.4.** Frame assignment

## 3.3 Kinematic Equations:

The angle '$\varphi$' represents the pitching motion of the body and the angles $\theta_1$, $\theta_2$ and $\theta_3$ are the fixed angles of the rover structure. Now we calculate the location of point K with respect to A, B and C in reference frame {O}.

-The location of point K with respect to A is:

$$x_K = x_A + AK.(-cos(\theta_2 - \rho - \beta)) \tag{3.10}$$

$$y_K = y_A + AK.sin(\theta_2 - \rho - \beta) \tag{3.11}$$

-The location of point K with respect to B is:

$$x_K = x_B + BK.cos(\theta_2 + \rho + \beta) \tag{3.12}$$

$$y_K = y_B + BK.sin(\theta_2 + \rho + \beta) \tag{3.13}$$

-The location of point K with respect to C is:

$$x_K = x_C + CK.cos(\theta_1 + \rho) \tag{3.14}$$

$$y_K = y_C + CK.sin(\theta_1 + \rho) \tag{3.15}$$

By differentiating above equations we can find the velocity relationships as follow:

$$v_{Kx} = v_{Ax} - (\dot{\rho} + \dot{\beta}) \times AK.sin(\theta_2 - \rho - \beta) \tag{3.16}$$

$$v_{Ky} = v_{Ay} - (\dot{\rho} + \dot{\beta}) \times AK.cos(\theta_2 - \rho - \beta) \tag{3.17}$$

$$v_{Kx} = v_{Bx} - (\dot{\rho} + \dot{\beta}) \times BK.sin(\theta_2 + \rho + \beta) \tag{3.18}$$

$$v_{Ky} = v_{By} + (\dot{\rho} + \dot{\beta}) \times BK.cos(\theta_2 + \rho + \beta) \tag{3.19}$$

$$v_{Kx} = v_{Cx} - (\dot{\rho}) \times CK.sin(\theta_1 + \rho) \tag{3.20}$$

$$v_{Ky} = v_{Cy} + (\dot{\rho}) \times CK.cos(\theta_1 + \rho) \tag{3.21}$$

Also the location of point D and G are given by:

$$x_D = x_K - KD.sin(\theta_3 + \rho) \tag{3.22}$$

$$y_D = y_K + KD.cos(\theta_3 + \rho) \tag{3.23}$$

$$x_G = x_D + DG.sin(\varphi) \tag{3.24}$$

$$y_G = y_D - DG.cos(\varphi) \tag{3.25}$$

By differentiating above expressions:

$$v_{Dx} = v_{Kx} - (\dot{\rho}) \times KD.cos(\theta_3 + \rho) \tag{3.26}$$

$$v_{Dy} = v_{Ky} - (\dot{\rho}) \times KD.sin(\theta_3 + \rho) \tag{3.27}$$

$$v_{Gx} = v_{Dx} + (\dot{\varphi}) \times DG.cos(\varphi) \tag{3.28}$$

$$v_{Gy} = v_{Dy} + (\dot{\varphi}) \times DG.sin(\varphi) \tag{3.29}$$

In this chapter we have developed the kinematic model of the rover considering the planar model.

# Chapter 4
# FORCE ANALYSIS

This section presents the planar quasi-static force analysis of the rocker-bogie rover. The rover travels at slow speed, therefore dynamic effects are small and a quasi-static model adequately describes its behavior.

## 4.1 Planar force analysis:

The different forces which act on the system are shown in Fig. 4.1. The forces $T_i$ and $N_i$ ($i$=A, B and C) are the tangential and normal forces respectively, which act at the wheel-ground contact point. The tangential forces act tangential to the ground, while the normal forces act normal to the ground. The forces $F_x$, $F_y$ and $M$ are the external forces which act on the CoM of the body. $F_x$ and $F_y$ are the external forces in X and Y direction respectively, while M is the external moment applied.

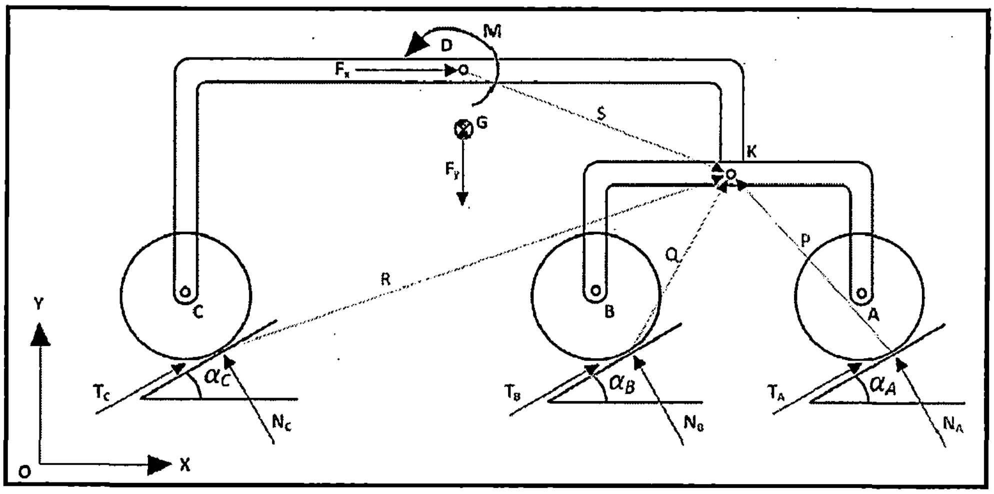



**Fig. 4.1.** Rover force analysis

## 4.2 Equilibrium equations:

There are four equilibrium equations for the system, two equilibrium equations for the forces in X and Y directions, and two moment equations on the rocker-bogie pivot joint. The moment equation must be zero at that point for both the rocker and the bogie.

The positions of the wheel contact points with respect to the rocker-bogie joint are required to perform the force analysis. The vectors P, Q and R connect the wheel-ground contact points to the rocker-bogie joint and the vector S connects the rocker-body joint to the rocker-bogie joint. The components of these vectors along X and Y are written below.

$$P_x = AK.cos(\theta_2) + r.sin(\alpha_A) \tag{4.1}$$

$$P_y = AK.sin(\theta_2) + r.cos(\alpha_A) \tag{4.2}$$

$$Q_x = BK.cos(\theta_2) - r.sin(\alpha_B) \tag{4.3}$$

$$Q_y = BK.sin(\theta_2) + r.cos(\alpha_B) \tag{4.4}$$

$$R_x = CK.cos(\theta_1) - r.sin(\alpha_C) \tag{4.5}$$

$$R_y = CK.sin(\theta_1) + r.cos(\alpha_C) \tag{4.6}$$

$$S_x = DK.sin(\theta_3) \tag{4.7}$$

$$S_y = DK.cos(\theta_3) \tag{4.8}$$

The force equilibrium equations in X and Y directions are given below.

$$T_A.cos(\alpha_A) + T_B.cos(\alpha_B) + T_C.cos(\alpha_C) - N_A.sin(\alpha_A) - N_B.sin(\alpha_B) - N_C.sin(\alpha_C) + F_x = 0 \tag{4.9}$$

$$T_A.sin(\alpha_A) + T_B.sin(\alpha_B) + T_C.sin(\alpha_C) + N_A.cos(\alpha_A) + N_B.cos(\alpha_B) + N_C.cos(\alpha_C) - F_y = 0 \tag{4.10}$$

The moment equilibrium equation of bogie about point K is:

$$T_A.cos(\alpha_A).P_y + T_A.sin(\alpha_A).P_x + N_A.cos(\alpha_A).P_x - N_A.sin(\alpha_A).P_y + T_B.cos(\alpha_B).Q_y$$
$$-T_B.sin(\alpha_B).Q_x - N_B.cos(\alpha_B).Q_x - N_B.sin(\alpha_B).Q_y = 0 \tag{4.11}$$

The moment equilibrium equation of rocker about point K is:

$$T_C.cos(\alpha_C).R_y - T_C.sin(\alpha_C).R_x - N_C.cos(\alpha_C).R_x - N_C.sin(\alpha_C).R_y + M$$
$$-F_x.S_y + F_y.S_x = 0 \tag{4.12}$$

In this chapter the quasi-static force analysis is done for the planar model of the rocker-bogie rover.

# Chapter 5
# BOND GRAPH MODELLING

In the previous chapters we have discussed the kinematics and force analysis for the rocker-bogie rover. The bond graph model of the rover is constructed directly from kinematical relationships. The dynamics is automatically represented correctly since the bond graph junction structure is power conservative.

## 5.1 Assumptions:

1. Wheels, Rocker and Bogie are assumed to be massless as compared to the body.
2. The mass of the body is assumed to be acted on CoM at point K
3. Each wheel is independently driven by the motors.

## 5.2 Word Bond Graph:

In Fig. 5.1 the word bond graph is shown for the system. The voltage supply is given as input to the motors and the motor output is applied to the wheels, the ground also influences the wheel motion. The effect of wheel motion is transferred to the body mass via suspension system and the weight of the body acts on the body centre of mass.

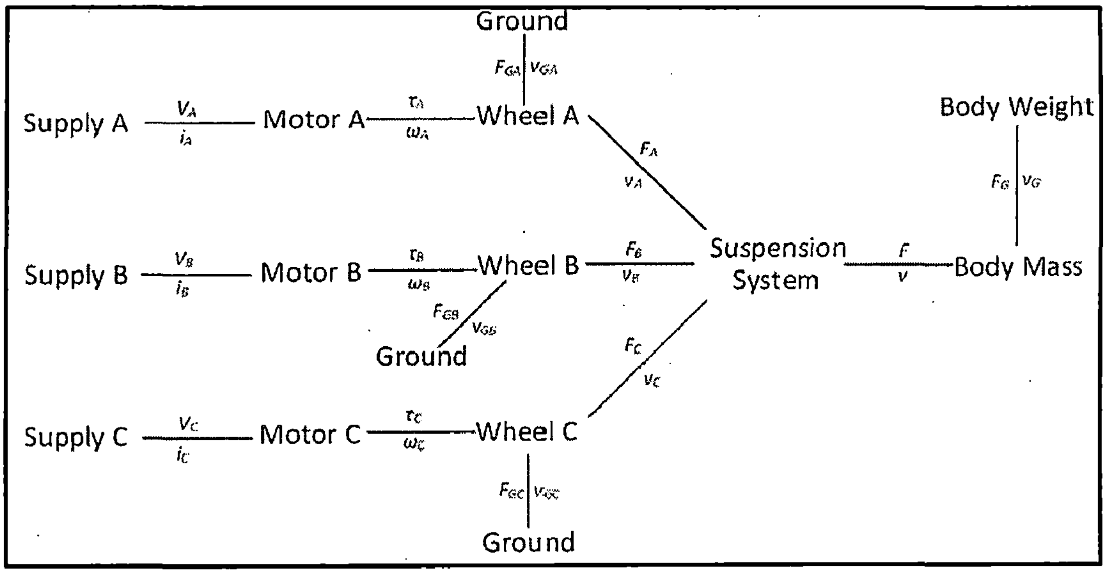



**Fig. 5.1.** Word bond graph

## 5.3 Suspension system and Body:

Refer Fig. 5.2, twenty one 1 –junctions are in the model corresponds to the velocity of different points. Three 1 –junctions ($1_{At}$, $1_{Bt}$ and $1_{Ct}$) for tangential velocity, three 1 –junctions ($1_{An}$, $1_{Bn}$ and $1_{Cn}$) for normal velocity, six 1 –junctions ($1_{Ax}$, $1_{Bx}$, $1_{Cx}$, $1_{Dx}$, $1_{Kx}$ and $1_{Gx}$) for velocity in X direction, six 1 –junctions ($1_{Ay}$, $1_{By}$, $1_{Cy}$, $1_{Dy}$, $1_{Ky}$ and $1_{Gy}$) for velocity in Y direction, three 1 –junctions ($1_{\rho}$, $1_{\beta}$ and $1_{\varphi}$) for angular velocity of rocker, bogie and body. The mass and the inertia of the body are modeled with I elements at CoM of the body.

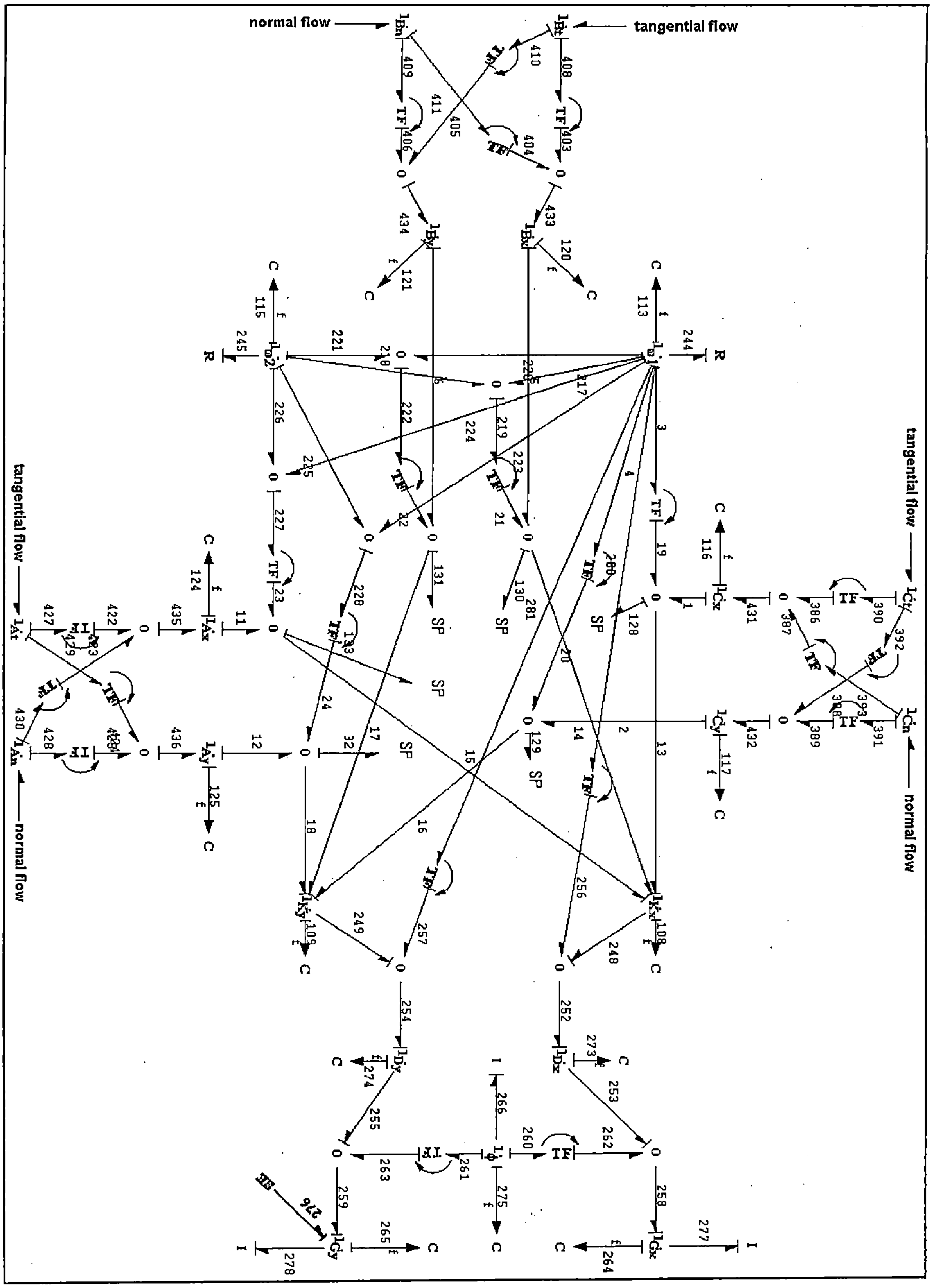



**Fig. 5.2.** Detailed bond graph of body and suspension system

## 5.4 Motor:

The three wheels are independently driven by the motors. In Fig. 5.3 the angular velocities of three motors are represented by three 1 –junctions ($1_{\omega A}$, $1_{\omega B}$ and $1_{\omega C}$). The angular velocity is multiplied by radius of wheel to get the tangential velocity represented by junctions ($1_{At}$, $1_{Bt}$ and $1_{Ct}$).

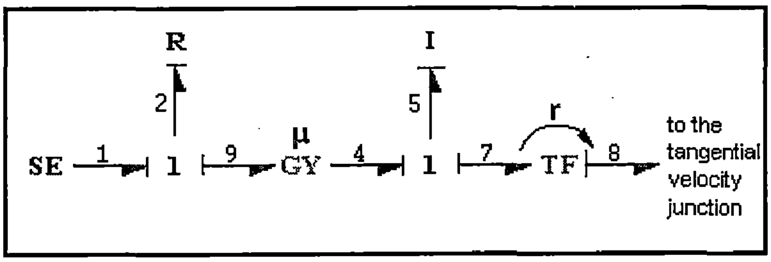



**Fig. 5.3.** Bond graph model of motor

## 5.5 Ground:

The ground is responsible for the flow in normal direction of the rover represented by junctions ($1_{An}$, $1_{Bn}$ and $1_{Cn}$). We have modeled the ground as spring damper system which is modeled with C and R elements in bond graph as shown in Fig. 5.4.

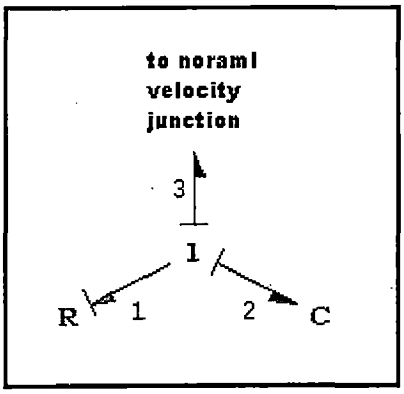



**Fig. 5.4.** Bond graph model of ground

## 5.6 The Forces:

The tangential force (T) and normal force (N) come from the motor and the ground respectively. The external forces ($F_x$, $F_y$ and M) are modeled with 'SE' elements in bond graph.

## 5.7 The Complete model:

After integrating the all above models and incorporating the forces, the combined bond graph model for the system is shown in Fig. 5.5.

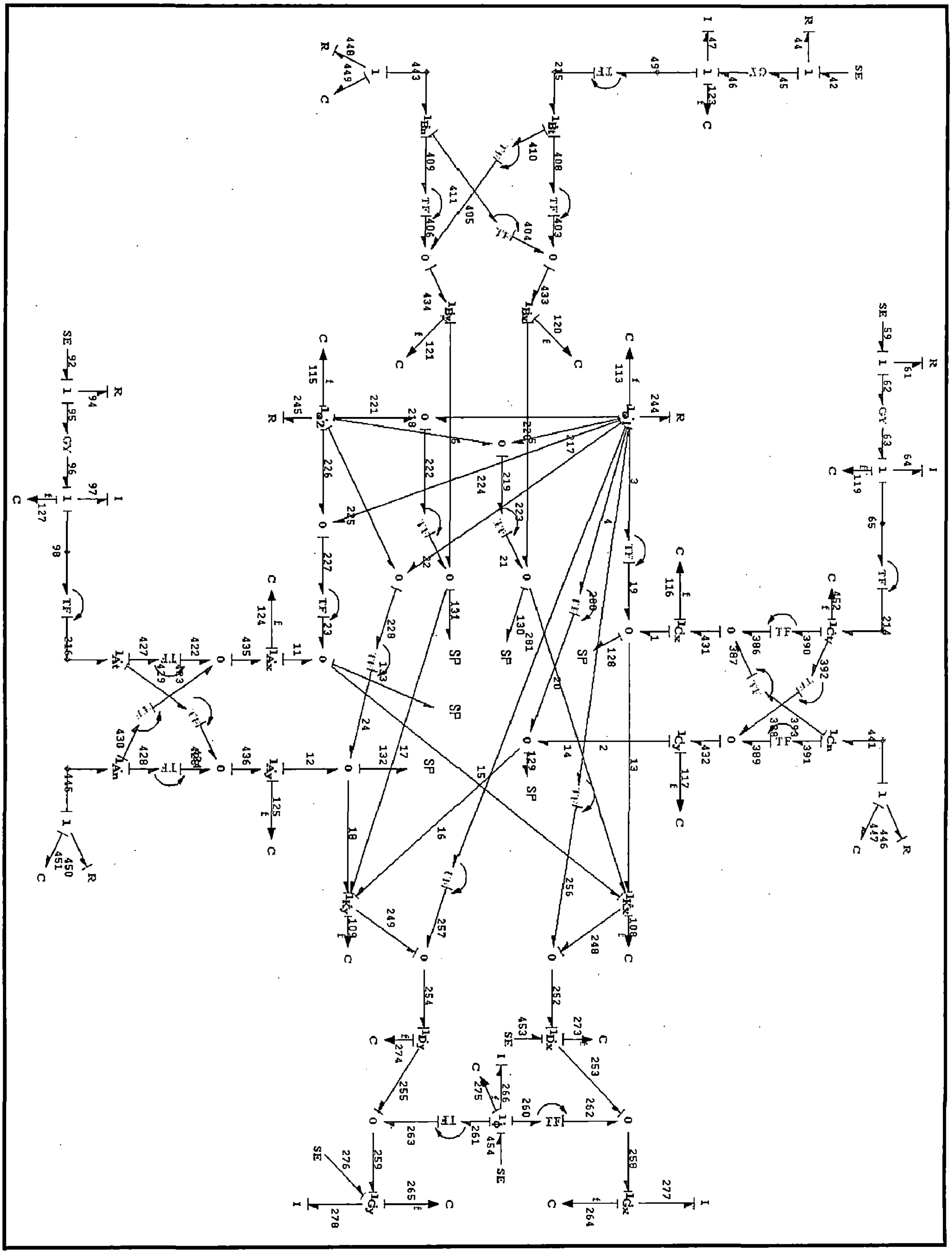


**Fig. 5.5.** Integrated bond graph model

# Chapter 6
# SIMULATION AND RESULTS

## 6.1 Parameters:

The parameters for the model are depicted in Fig. 6.1 and Table 1 lists the respective values for the mars exploration rover (MER). Note that the exact dimensions of the MER are not available in literature; therefore the dimensions may slightly differ.

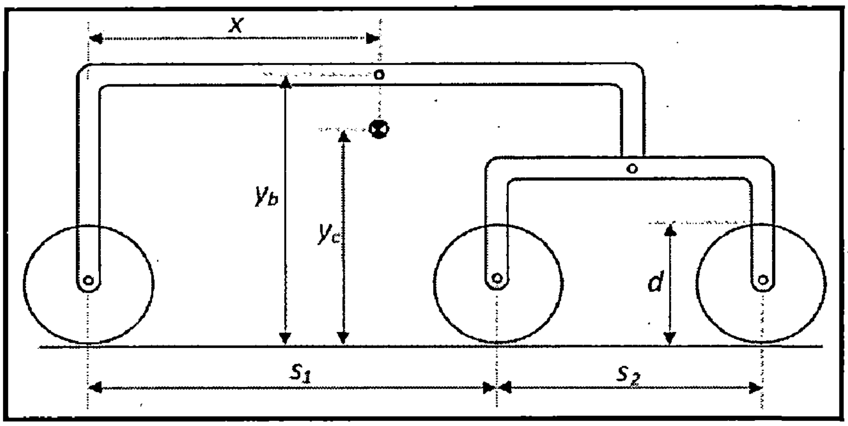



**Fig. 6.1.** Rover parameters

**Table No. 6.1.** Parameters used in simulation study

| S.N. | Parameter | Value |
|---|---|---|
| 1. | Main body mass | 17.5 kg |
| 2. | Main body position ($x$)<br>($y_b$) | 0.344 m<br>0.229 m |
| 3. | Body's CoM position ($x$)<br>($y_c$) | 0.344 m<br>0.22 m |
| 4. | Wheel diameter ($d$) | 0.2 m |
| 5. | Wheel distance ($s_1$)<br>($s_2$) | 0.389 m<br>0.259 m |

## 6.2 Rover on flat ground:

The system is verified in Symbol Shakti software. In Fig. 6.2, the trajectory of the wheels and body CoM is shown. The rover moves on the flat ground when motor is actuated.

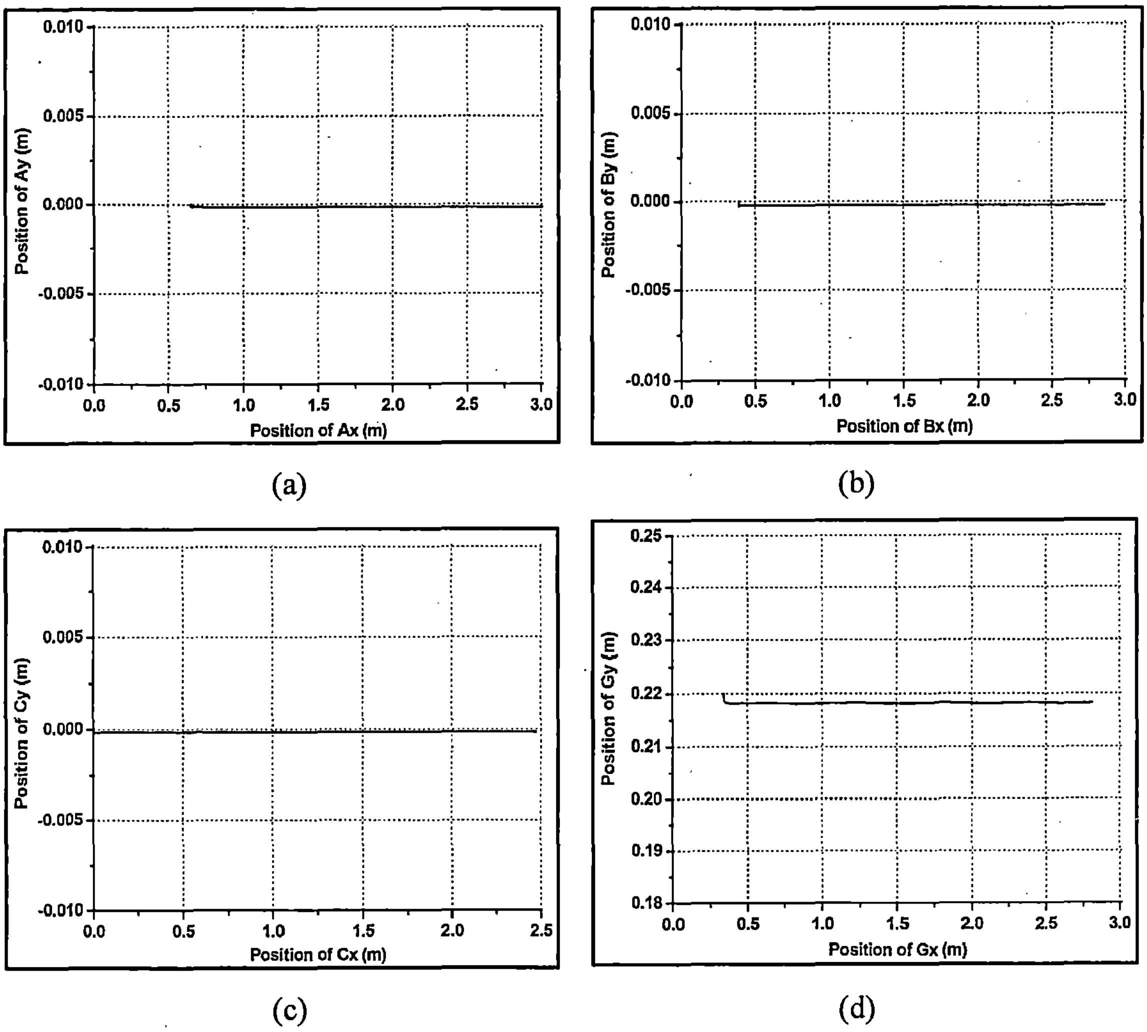



**Fig. 6.2.** Rover's trajectory on flat ground. (a) Front wheel trajectory (b) Middle wheel trajectory (c) Rear wheel trajectory (d) Body CoM trajectory

In Fig. 6.3, the velocity of rover is plotted with respect to time. When motors are actuated, the rover moves with a constant speed of 16 cm/s. The animation frame is shown in Fig. 6.4.

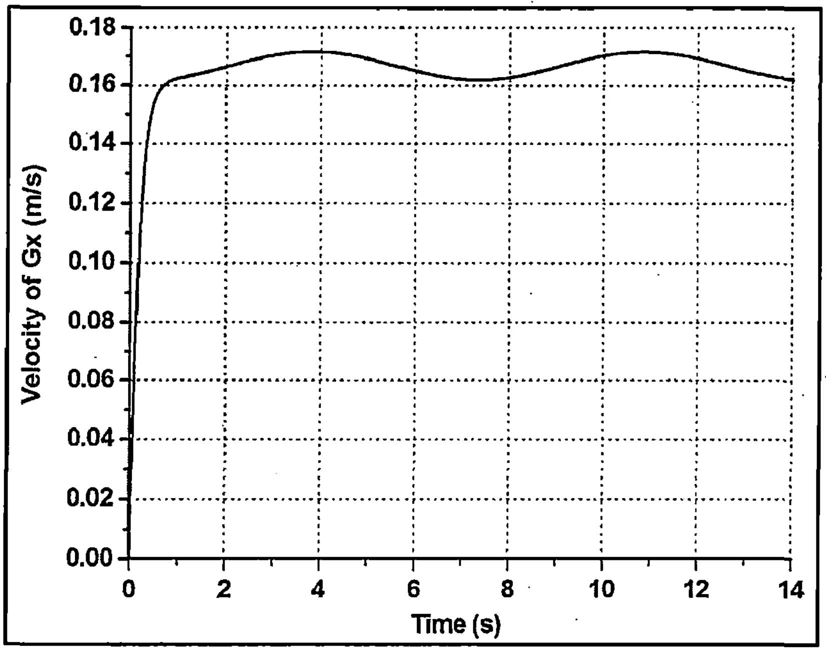



**Fig. 6.3.** Velocity of rover on flat ground.

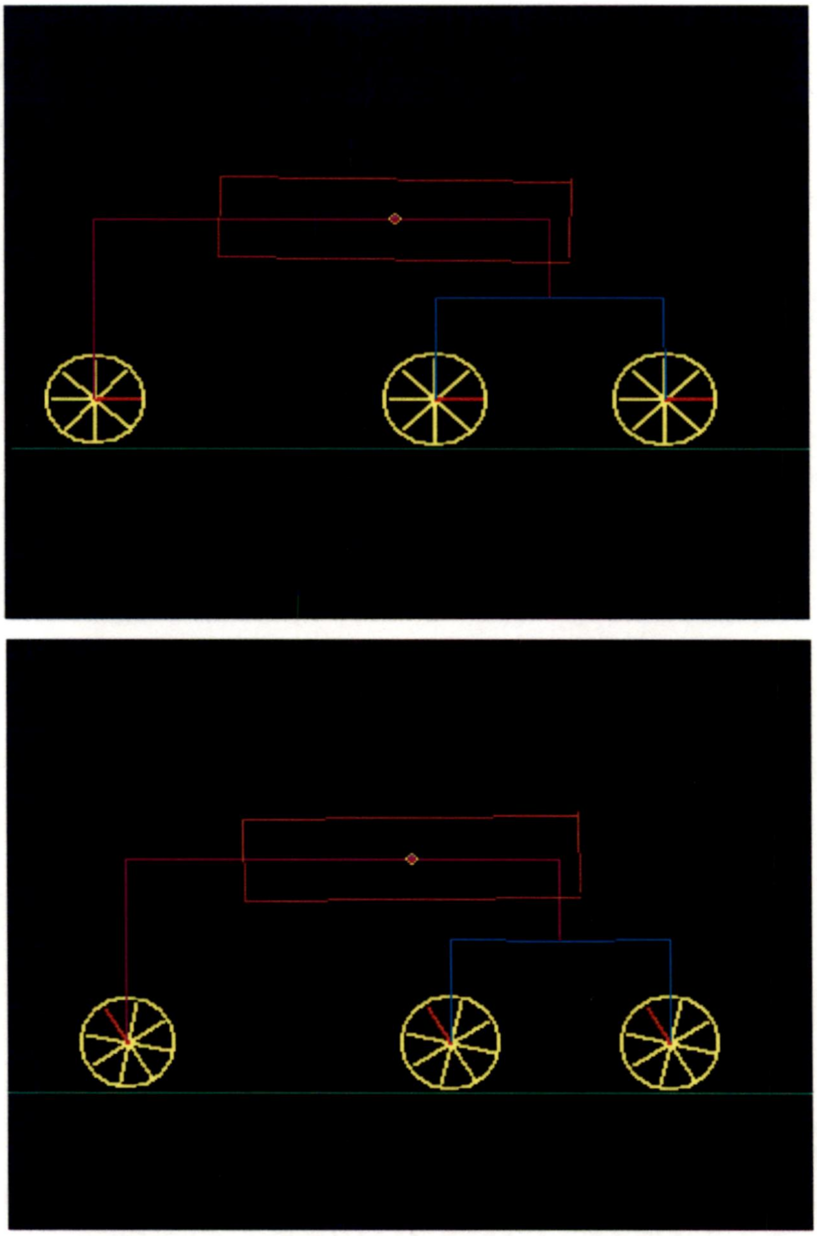
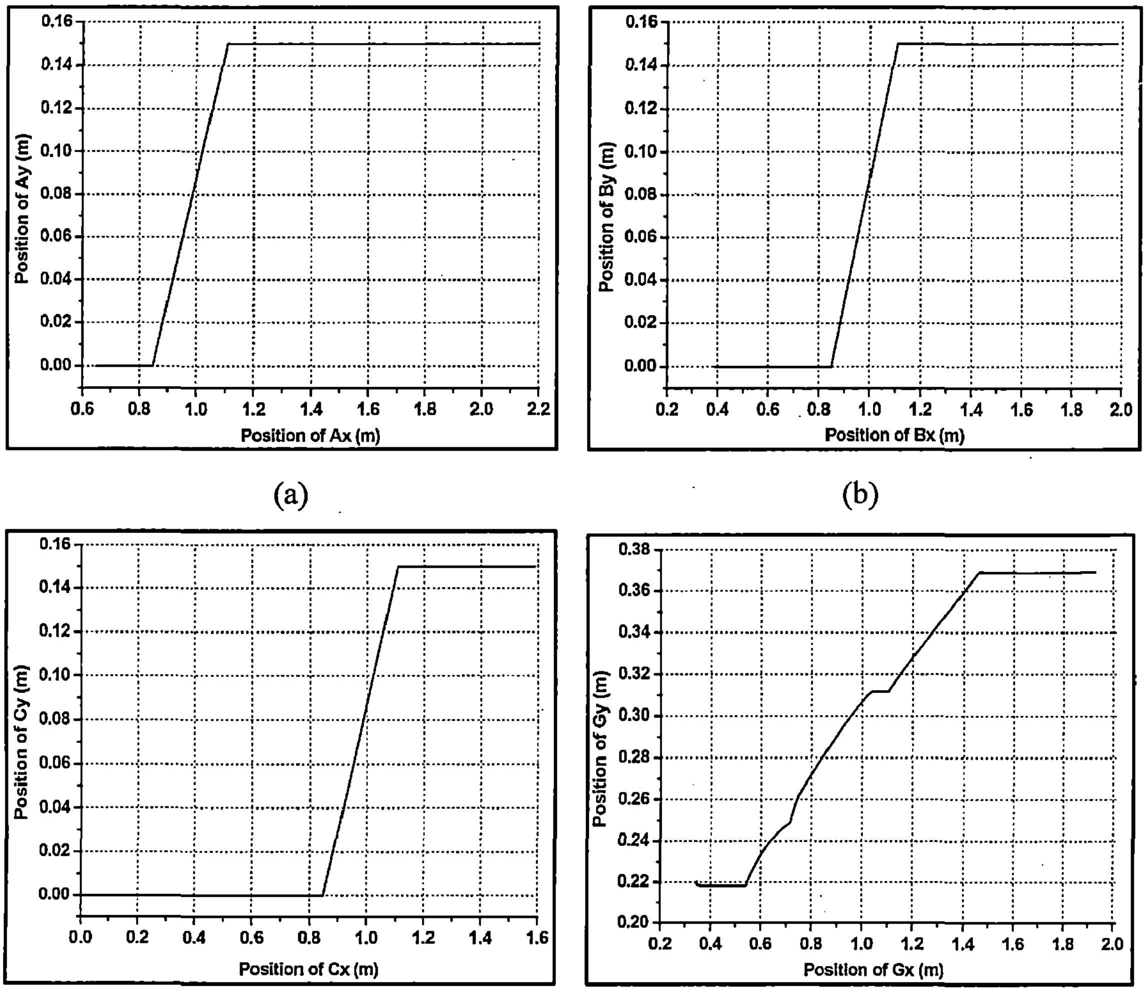


**Fig. 6.4.** Animation of rover on flat ground.

## 6.3 Rover climbing up a slope:

In Fig. 6.5, the rover is moving over a 30-degree slope. The trajectory of the wheels and body CoM is shown in the figure.




(a) (b)

(c) (d)

**Fig. 6.5.** Rover's trajectory on 30-degree slope. (a) Front wheel trajectory (b) Middle wheel trajectory (c) Rear wheel trajectory (d) Body CoM trajectory

Refer Fig. 6.6, the rover moves at speed 16 cm/s, then at time 1.36 sec the front wheel touches the slope and begins to climb up, the rover velocity reduces to 8 cm/s. Then at time 3.24 sec the middle wheel touches the slope and the rover velocity reduces to 3 cm/s. Then middle wheel climbs up and the velocity of the rover starts to increase and goes to 16 cm/s until rear wheel touches the slope. When rear wheel touches the slope at time 8.74 sec the velocity again decreases to 10 cm/s and the rover continues to climb. When all the wheels have covered the slope the velocity of the rover again increases to constant value 16 cm/s. The animation frame of the rover is shown in Fig. 6.7.

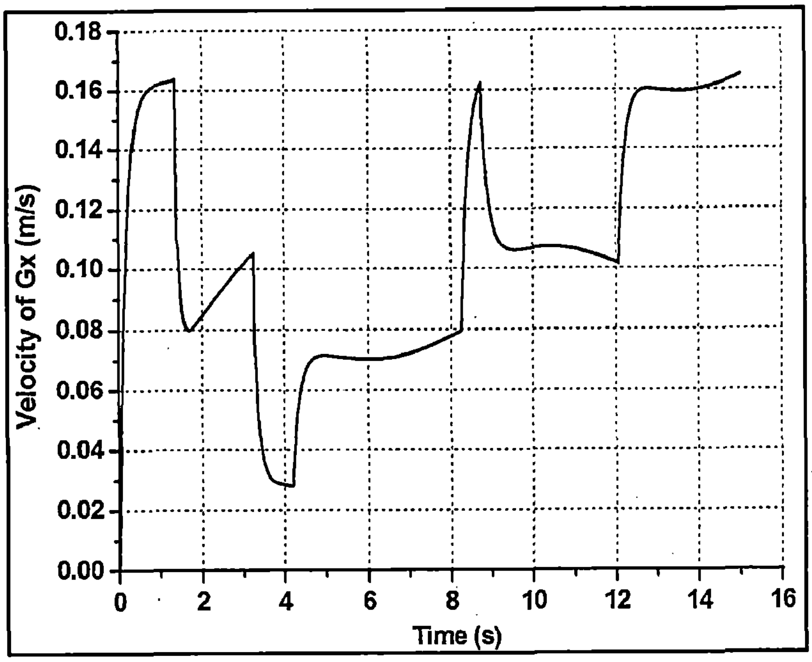



**Fig. 6.6.** Velocity of rover on 30-degree slope.

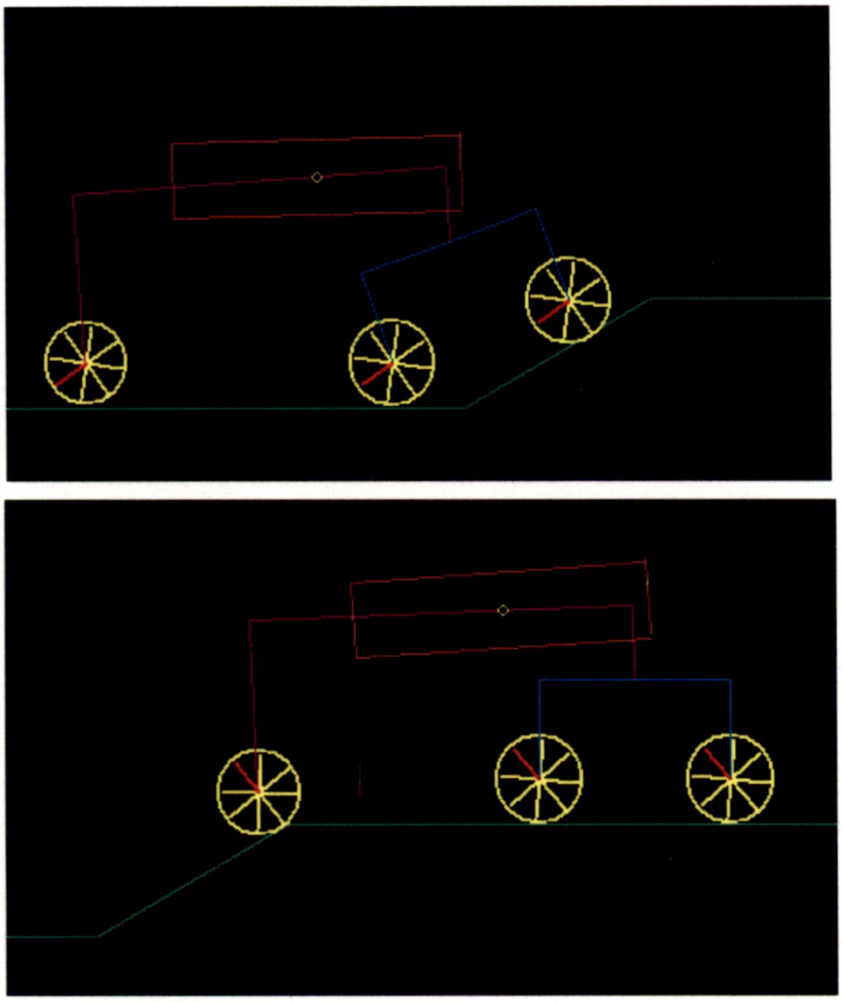
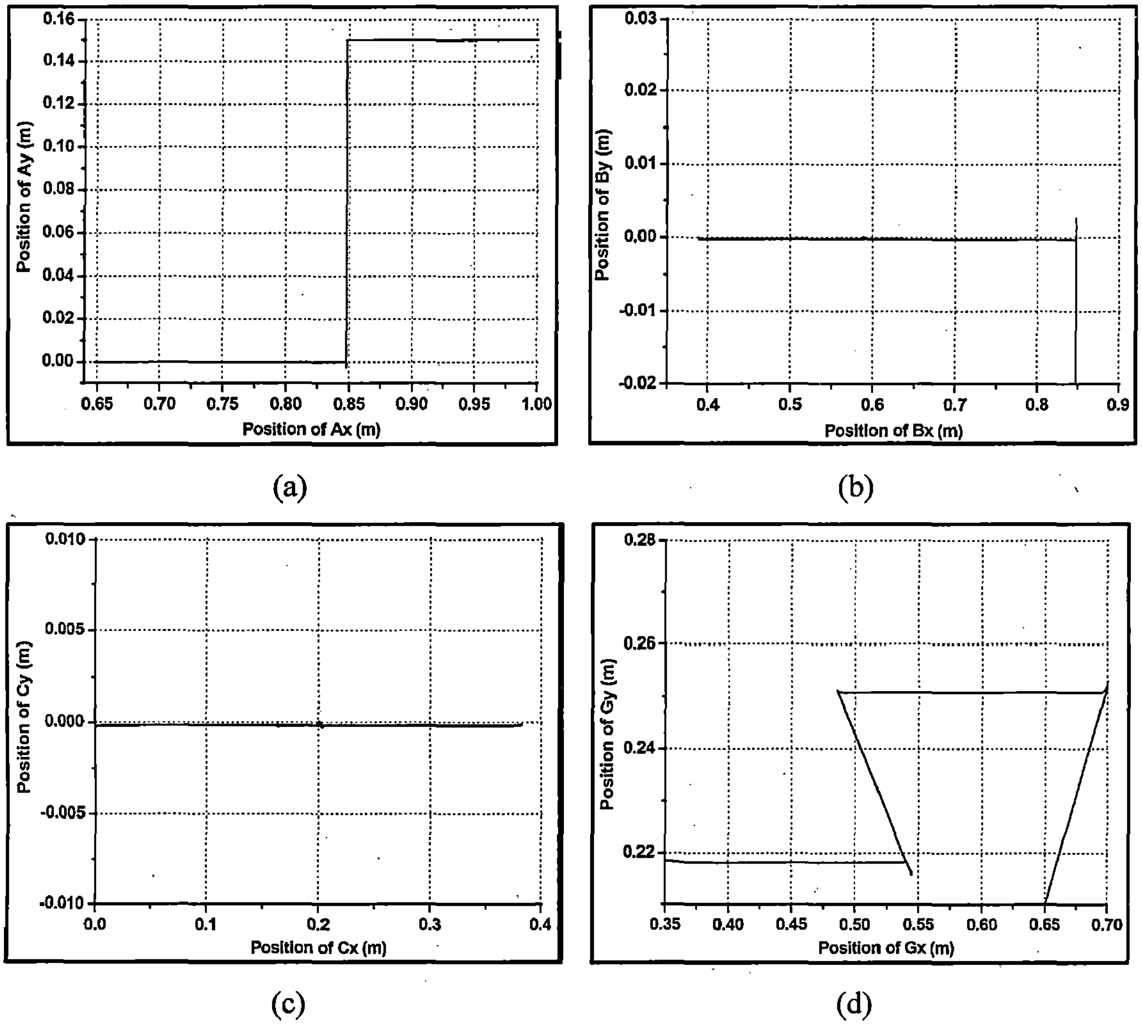


**Fig. 6.7.** Animation of rover climbing 30-degree slope.

## 6.4 Rover climbing up a step:

In Fig. 6.8, the rover is moving over a step like obstacle. The trajectory of the wheels and body CoM is shown in the figure.




(a) (b) (c) (d)

**Fig. 6.8.** Rover's trajectory on a step. (a) Front wheel trajectory (b) Middle wheel trajectory (c) Rear wheel trajectory (d) Body CoM trajectory

In Fig. 6.9, the rover velocity is plotted against time, the rover moves at a speed of 16 cm/s. The front wheel hit the step at time 1.36 sec and begins to climb up, the velocity decreases and reaches to zero. When front wheel is over the step, velocity again starts to increase and becomes 16 cm/s. Then at time 4.18 sec the middle wheel hit the step and velocity of the rover decrease to zero; now the middle wheel is not able to climb up the step. In Fig. 6.10, the animation frame of the rover climbing up a step is shown.

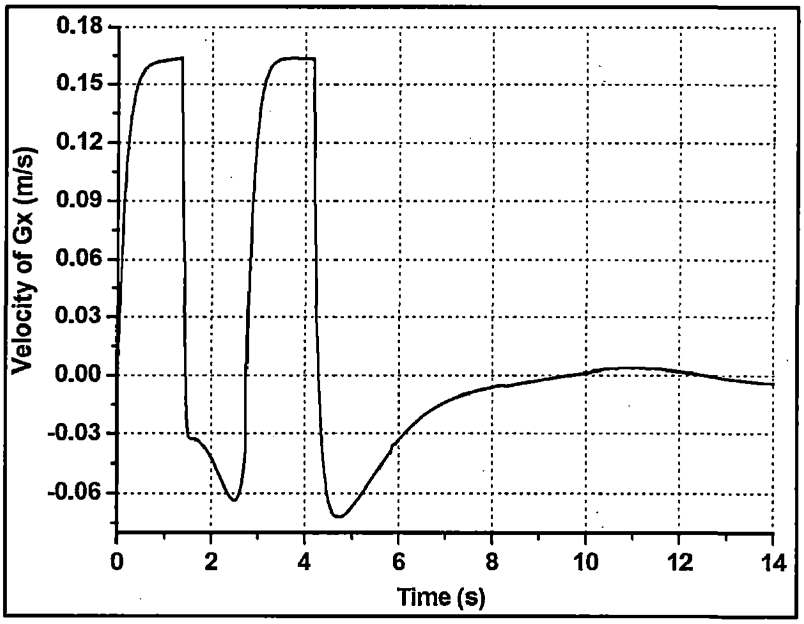



**Fig. 6.9.** Velocity of rover on a step.

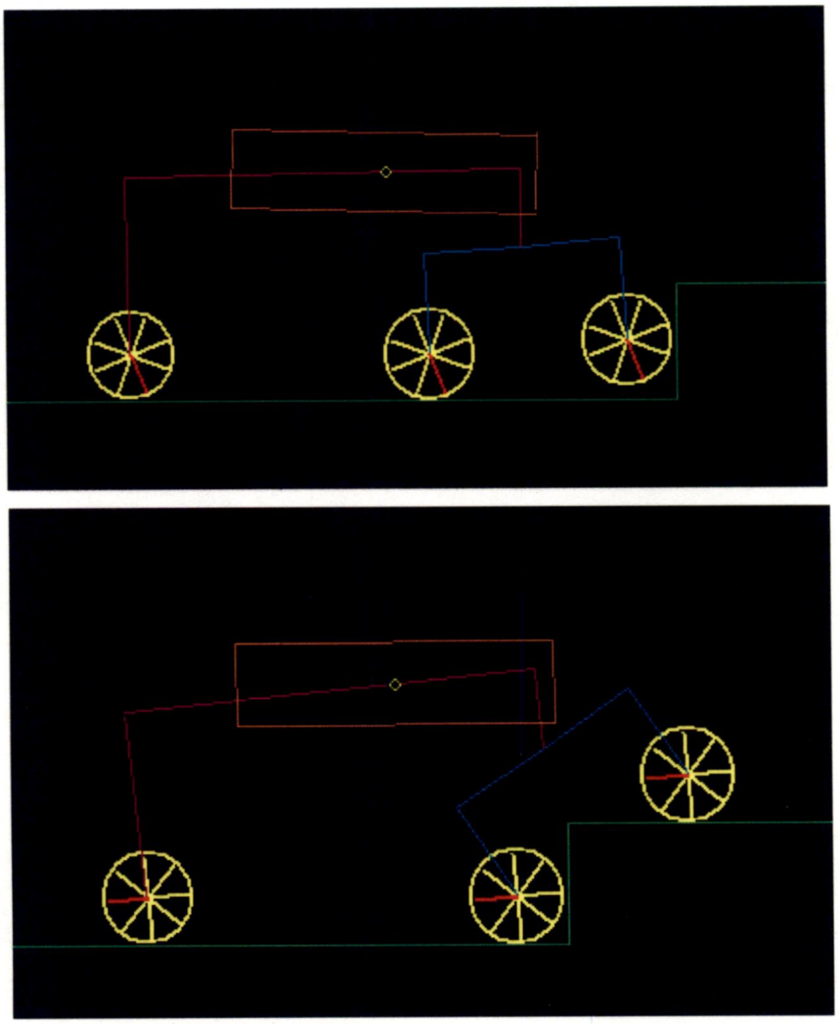


**Fig. 6.10.** Animation of rover climbing up a step.

## 6.5 Rover encountering a ditch:

Here rover is moving to a ditch. The trajectory of the wheels and body CoM is shown in the Fig. 6.11.

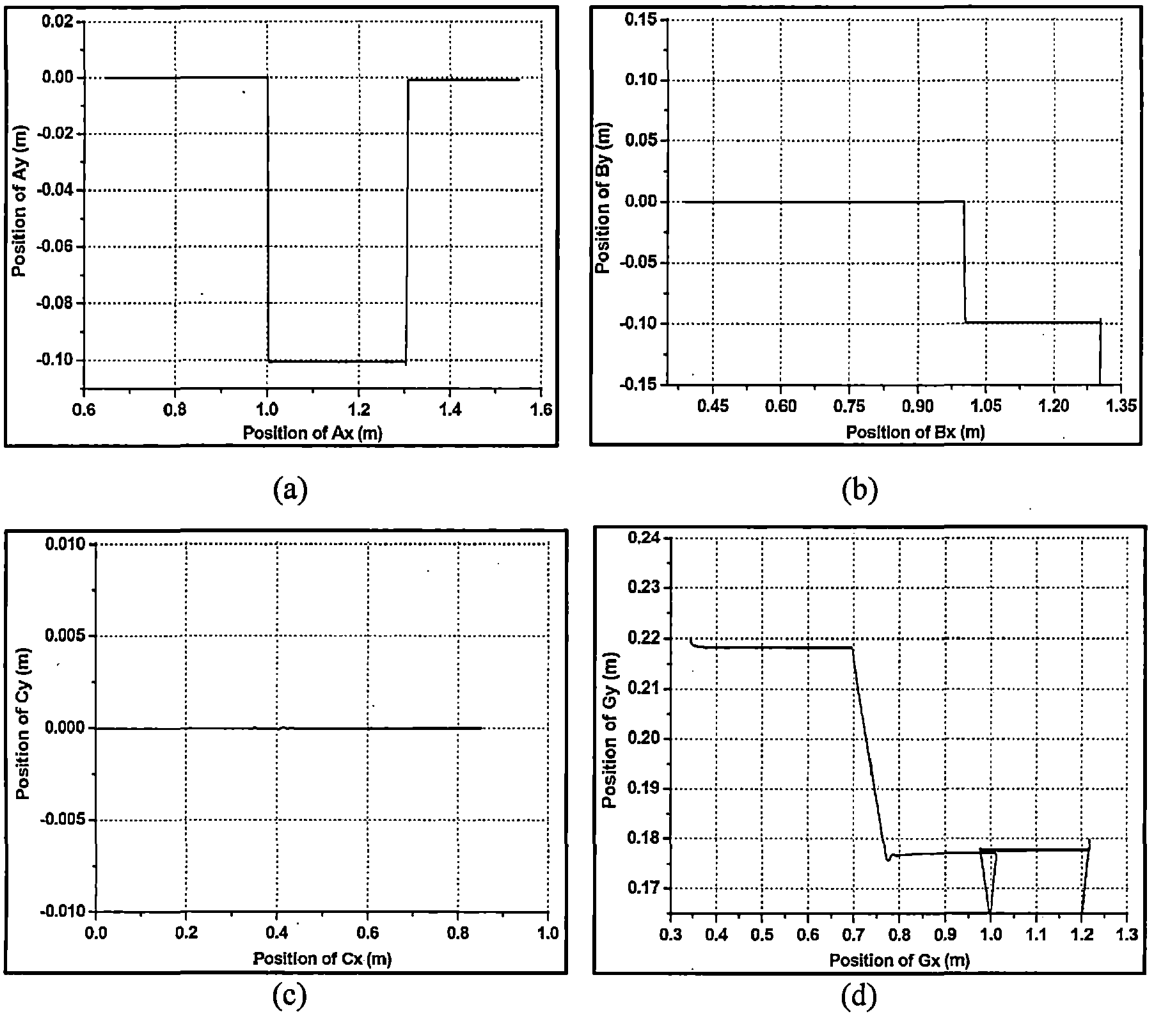



**Fig. 6.11.** Rover's trajectory on a ditch. (a) Front wheel trajectory (b) Middle wheel trajectory (c) Rear wheel trajectory (d) Body CoM trajectory

Refer Fig. 6.12, the rover moves at speed 16 cm/s, then at time 2.28 sec the front wheel touches the ditch and velocity increases to 40 cm/s. The middle wheel touches the ditch at time 3.76 sec and velocity decreases to zero even goes in negative direction, when middle wheel comes down, velocity again increases to 14 cm/s. Then at time 4.52 sec front wheel hit the up of ditch and begins to climb up, the velocity decreases and reaches to zero. When front wheel is over the step, velocity again starts to increase and becomes 16 cm/s. Then at time 7.65 sec the middle wheel hit the up of ditch and velocity of the rover decrease to zero; now the middle wheel is not able to climb up the step. In Fig. 6.13, the animation frame of the rover on the ditch is shown.

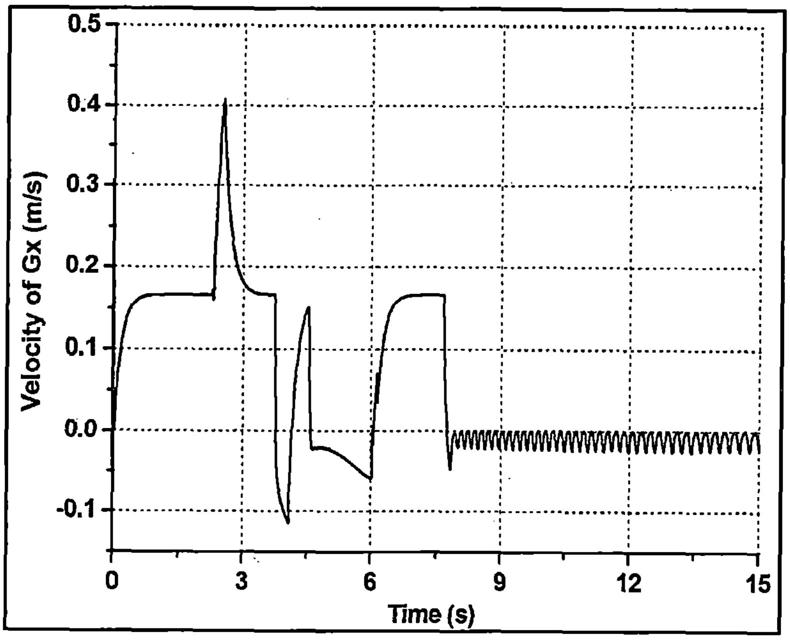



**Fig. 6.12.** Velocity of rover on a ditch.

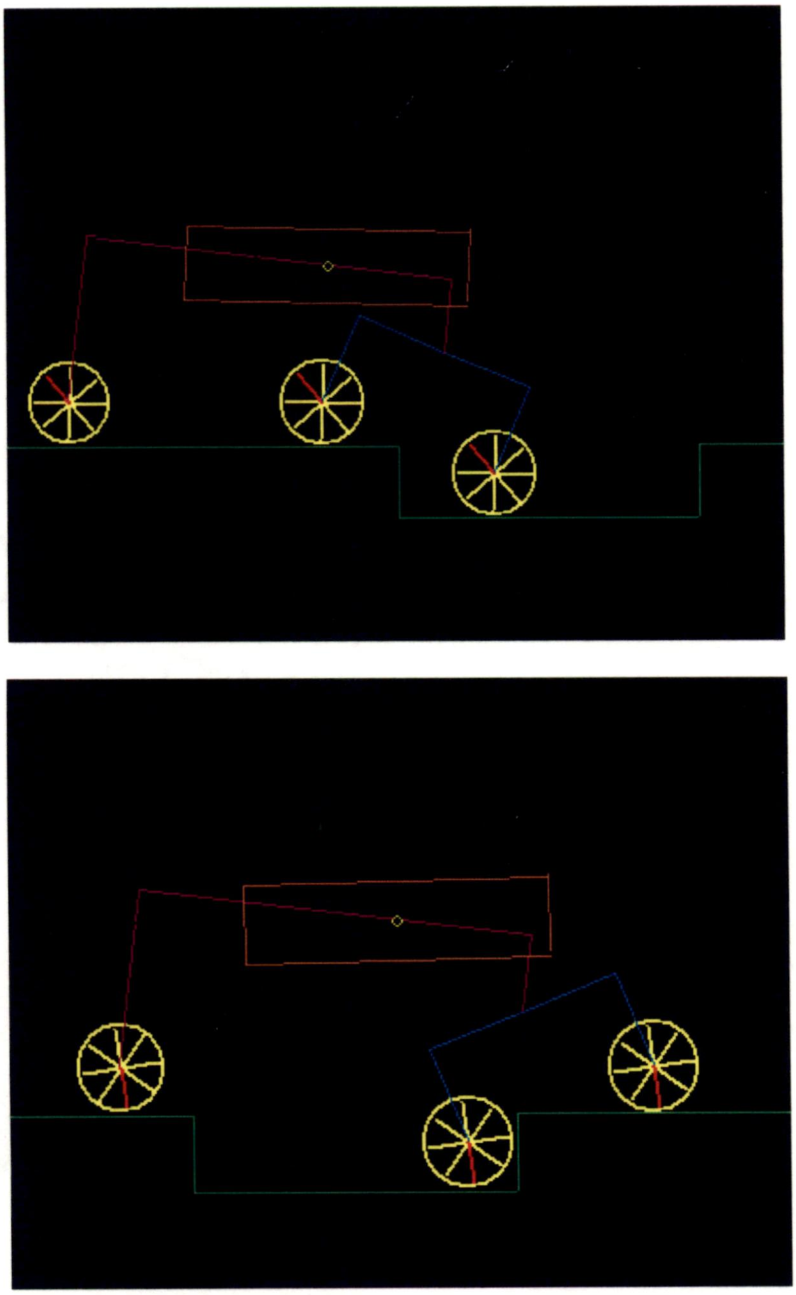


**Fig. 6.13.** Animation of rover on a ditch.

# Chapter 7
# CONCLUSION & FUTURE SCOPE

In this thesis work we have analyzed the six wheeled rocker-bogie rover. The Kinematics of the rover is presented in detail and quasi-static force analysis is also done for the rover for planar case. The bond graph model for the rover is developed which represents the dynamics of the system and motor dynamics is also added to the system. The rover is simulated over various uneven terrains and the performance of the rover is analyzed over flat, slope, step and ditch profile of surface. The results of simulation show that rover crosses flat and slope profiles. In case of step profile only front wheel crosses the step, when middle wheel hit the step the velocity becomes zero and it is not able to climb. In case of ditch profile also only front wheel crosses the ditch, when middle wheel hit the up of ditch the velocity goes to zero and it is not able to climb.

In the future work, some control strategies will be added to the system so that it can cross step and ditch profiles of ground without being stuck. The three dimensional bond graph modeling can be the future work.

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