Evolution of a Four Wheeled Active Suspension Rover with Minimal Actuation for Rough Terrain Mobility

Arun Kumar Singh, Vijay Prakash Eathakota. K.Madhava Krishna., and Arun.H.Patil.

***Abstract*—In this paper we deduce the evolution of a four wheeled active suspension rover from a five wheeled passive suspension rover. The aim of this paper is to design a suspension mechanism which utilizes the advantages of both passive suspension and active suspension rover. Both the design considered here are simpler than the existing suspension mechanisms in the sense that the number of links as wells as the number of joints have been significantly reduced without compromising the climbing capability of the rover. We first analyze the kinematics of the five wheeled rover and its motion pattern while climbing an obstacle and try to deduce the same motion pattern and capability in the four wheeled rover. Both the suspension mechanism consists of two planar closed kinematic chains on each side of the rover. We also deduce the control strategy for the active suspension rover wherein only two actuators are used to control the internal configuration of the rover. To the best of author's knowledge this is the minimum number of actuators required to control the internal configuration of a active suspension while operating on a fully 3D rough terrain. Extensive uneven terrain simulations are performed for both 5-wheeled and 4-wheeled rover and a comparative analysis has been done on maximum coefficient of friction and torque requirements.**

I. INTRODUCTION

To design an effective suspension mechanism with minimum design and control complexity is the focus of the research here. Past research on wheeled all terrain vehicles has led to the development of two types of suspension mechanisms: active and passive. Passive suspension rovers adapt passively to the underlying by the virtue of contact forces and hence do not require any actuators for controlling the internal configuration of the vehicle thus significantly reducing the control architecture. Rocky7[1] is one such vehicle which utilizes one of the most simplest suspension mechanisms called rocker bogie. But the climbing ability and specially the lateral stability is limited as compared to shrimp[2] which utilizes a more sophisticated design derived from the four bar mechanism to enhance climbing ability. But as sophistication increases the number of joints and links also increases significantly increasing the overall complexity and weight of the system. . In general joints are heavy parts and can easily lead to trouble in space environments[3].Passive suspension rovers are usually multi wheel drive system[MWD] e.g some rovers such as Lunokhod[4] and Marshakhod[5] have 6 or more wheels. Though the system has higher degree of mobility the system is intended to be heavier and hence not ideally applicable to medium to small scale rovers. Moreover the closed kinematic structures of passive suspension rovers pose additional constraint on the kinematic analysis and motion planning robot. Active suspension rovers on the other hand are based mainly on open kinematic joints which are simple but require actuators to maintain static stability of the system. One such system named Hylos [6] requires 8 actuators to control its internal configuration of four 2*dof* leg. But simplicity in the kinematic structure has to be compensated by increasing the complexity at the control architecture level.

In our work we aim to find a mechanism where the elements of passive as well as active suspension mechanism are utilized. We first analyze a five wheeled passive suspension rover and try to replicate the same motion with a similar 4-wheeled active suspension design. The control strategy proposed for the deduced four wheeled rover is simple and require the knowledge of only the angular velocity of the back leg of the rover. The complexity of the design is greatly reduced in terms of the number of joints and links comprising the system without compromising with the traversibilty of the rover. The novelties of the work includes two new suspension mechanisms and a simplified control methodology for the 4-wheeled active suspension mechanism

II KINEMATIC MODEL OF THE FIVE WHEELD ROVER

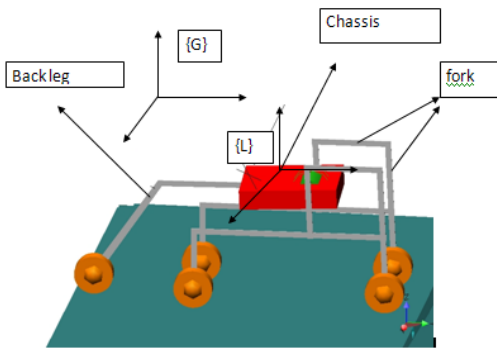

Fig1 kinematic model of the rover

The kinematic model of the rover is shown in figure1. It consists of two planar mechanisms on two sides of the

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chassis. The front wheel on both sides is connected to the end of the fork which is derived from the four bar mechanism. The back leg is made common while joining the two planar suspensions to form the complete rover. The common back leg is attached to the chassis through some compliance in the form of rotational joint passively controlled by torsion spring of high spring constant. This is one of the novelties of the design because unlike other designs such as [2] where back leg is directly connected by rigid joint, we introduce some compliance between the back leg and the wheel. This modification allows the rover to have some level of adaptivity on uneven terrains even while moving backward and requirement of the coefficient of friction for the back wheel to climb over the obstacle decreases. The other important novelty of the proposed design is the reduction in number of joints and links. Planar view of the robot with its joints is shown in figure2.

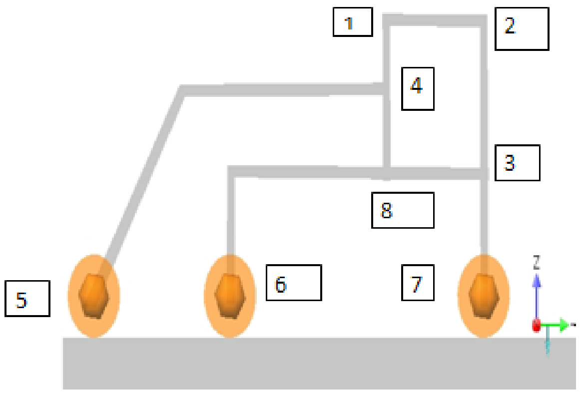


Fig2 front view of the rover

All designated joints are revolute with 5, 6, 7 being the actuated joint for driving the wheels and joint 4 being controlled passively by a torsion spring joint. The number of joints are 14 in total with 7 being on each side and number of bodies (excluding ground) is 16 with 8 being on each side. A similar functioning design found in [2] employs 18 bodies and 22 joints. Joints are generally heavier and critical part because they have maximum tendency of failing and hence corresponding decrease of the number of joints in the proposed design not only reduces the overall weight of the system but also increases the reliability of the system.

The degree of freedom of this planar suspension can be calculated by grubler's criterion $dof = 6(N - J - 1) + \sum_{i=1}^{J} F_i$ where N is the total number for bodies J is the total number of joints and F_i is the degree of freedom for each joint. Here N = 9(three wheels, five links, and ground).J = 11(3 wheel ground contact points, and 8 revolute joints shown in figure2). F_i = 11(1 degree of freedom for each revolute joint and wheel ground contact point can be modeled as one *dof* joint for the planar case[8]). So the total *dof* of the mechanism comes out to be 2.Out of this one *dof* has to be controlled to maintain the static stability of the system. Here we passively control the joint by incorporating torsion spring in the joint as stated before and the other *dof* corresponds to the rotation of the wheel i.e the mechanism can be set into motion by actuating any one wheel but rough terrain rovers are usually redundantly actuated at the wheels to have better terrain adaptability [7].

III MOTION SEQUENCE OF THE FIVE WHEELED ROVER

The analysis of the five-wheeled rover forms an important point because we aim at deducing the 4-wheeled rover and its control strategy in such a manner that it simulates the motion of the five wheel without the back wheel. Figure3 shows the climbing sequence.

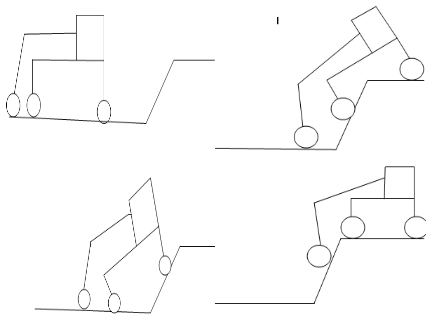


Figure4 climbing sequence of five wheeled rover

When the front wheel comes in contact the wheel the four bar mechanism fork rises due to the traction and normal forces. The back wheel which is directly connected to the fork stabilizes the movement of the fork and prevents the front wheel from slipping back. The middle wheel is coupled directly to the fork through a revolute joint (3 in figure2), so the reconfiguration of the fork directly allows for the redistribution of the normal force towards the middle and back wheel. This redistribution results in enhanced traction in the middle and back wheel which propels the vehicle forward. When the second wheel climbs the obstacle the fork tries to get to the original configuration which produces an assisting moment at the middle leg. Moreover the redistribution of the normal force is towards the front and the back wheel. The back wheel at this instant also helps in preventing the middle wheel from falling back. During climbing of the back wheel weight distribution is towards the front and the back wheel. As discussed above the climbing ability of the rover is critically dependent on the back wheel because it provides stabilizes the motion of the fork when the front wheel is climbing and prevents back wheel from slipping back when the second wheel is climbing the obstacle. Since we deduce the 4-wheeled rover by removing the back wheel from this design we need to find an adequate yet computationally simple control strategy to maintain the same climbing pattern of the remaining portion of the suspension. The reduction of the design to 4-wheel further reduces the number of links and joints in the system

IV 4- WHEEL MODIFICATION

As discussed above the 4wheeled rover is deduced from the five wheel by removing the back wheel. Removing the back leg and the wheel does not effect the overall *dof* of the system which remains 2 (N = 7,J=8,Fi = 8). So we need to control any one of the joints comprising the fork shown in figure3. Passively control of the joints as in the case of 5wheeled will not yield satisfactory result here because use of a torsion spring of low stiffness will result in unstable oscillations of the fork and a torsion spring of high stiffness will hamper the climbing motion of the fork. So we actuate the joint 1 shown in figure3 to control the motion of the fork. Moreover actuation will ensure proper control over the internal configuration. The modified kinematic model and its planar view is shown in figure5 and figure6.

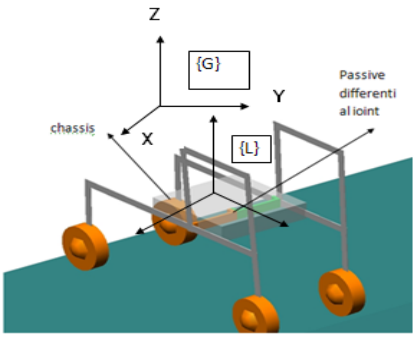


Fig5 isometric view of the rover

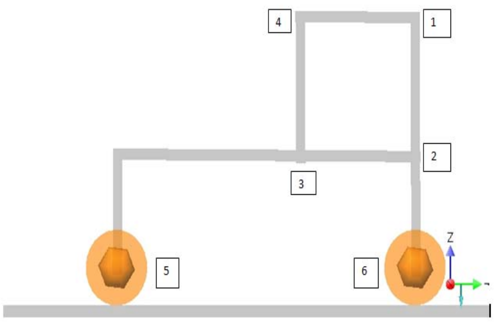


Fig 6 Front view of the 4-wheeled suspension mechanism

The 4-wheeled mechanism shown in figure6 consists of two planar mechanism on the two sides of the rover. The differential rotary joint connecting the two halves ensures all wheels are in contact with the ground when both halves are operating on different slopes. This joint is similar to the differential joint found in rocker bogie suspensions. One possible way of implementing such joint has been proposed in [8] and is shown in figure7. Part A can be joined to one half B to the other and C can be joined to the main platform.

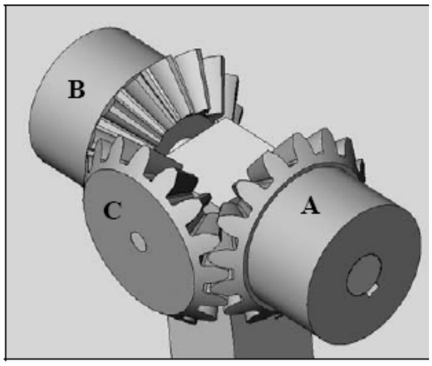


Fig7 differential joint between two part of the suspensions

The front view of the suspension mechanism with the respective joints is shown in figure6. Joints 1, 2, 3 are the passive rotary joints while joints 4, 5, 6 are the active rotary joints. Joints 5 and 6 active joints to drive the wheels while joint 4 determine the configuration of the front leg joints 1,2,3,4 form the part of the four bar mechanism form which the front fork is derived. Figure6 describes the synthesis of the suspension mechanism where the front fork of the shrimp is combined with a regular bogie with the omission of a wheel to get the required design.

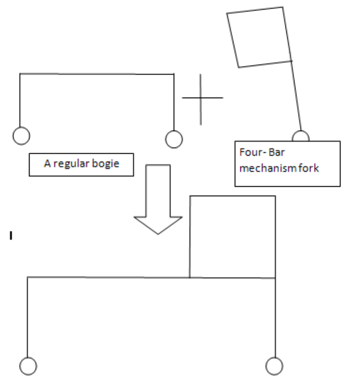


Fig8 Describing the synthesis of the mechanism

V CLIMBING SEQUENCE OF 4-WHEELED ROVER

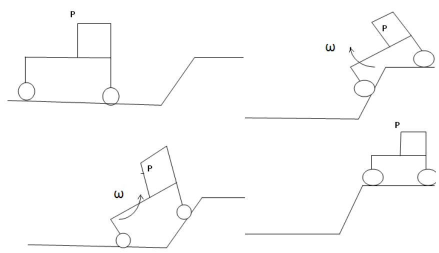


Fig 9 climbing sequence of 4-wheeled rover

As shown above the climbing sequence of the four wheeled rover can also be split into 4different parts. When the front wheel encounters the obstacle, the active joint P rotates clockwise and pulls the front wheel upwards along the surface of the terrain. This leads to the reconfiguration similar to 5-wheeled rover and redistribution of the normal forces towards the back wheel. When the second wheel encounters the obstacle the active joint rotates anticlockwise. This produces an assisting moment on the back wheel which helps it to climb over the obstacle. Moreover at this instant the redistribution of the normal forces is towards the front wheel similar to what happens in 5-wheeld rover.

VI CONTROL METHODOLOGY AND GOVERNING EQUATION

As discussed above the climbing sequence depends upon the direction of the velocity of the active joint P. It is clockwise when the front wheel is climbing the obstacle and negative when the back wheel is climbing over the obstacle. It is to be noted that the pitch line angular velocity also follows the same pattern. Hence we propose a velocity based control strategy for the active joint P where the angular velocity of the joint is determined by the pitch angular velocity of the back leg. Let ψ_f , α_f and β_f and ψ_b , α_b , β_b be the pitch, roll and yaw angles respectively of the back leg of the front and back part of the suspension mechanism corresponding to *Z-Y-X* Euler angle parameterization, then the angular velocity of the two active joints are given by

$$\omega_{pf} = \dot{\beta}_f \cos(\alpha_f)\cos(\psi_f) - \dot{\alpha}_f \sin(\psi_f) \quad (1)$$

$$\omega_{pb} = \dot{\beta}_b \cos(\alpha_b)\cos(\psi_b) - \dot{\alpha}_b \sin(\psi_b) \quad (2)$$

As clear from above discussion rover requires only two actuators (one on each side) to control the internal configuration. This is the minimum number of actuators that an active suspension rover can employ to control its internal configuration according to the underlying terrain.

VII KINEMATICS OF FORK

As discussed earlier the front part of the suspension mechanism has been derived from the four-bar mechanism. The dimension of the fork can be optimized for a given terrain conditions. Hence the trajectory of the fork gives an important information about the kind of terrains which is best suited for a given fork geometry and conditions. Figure10 gives the geometrical and link parameters of the fork.

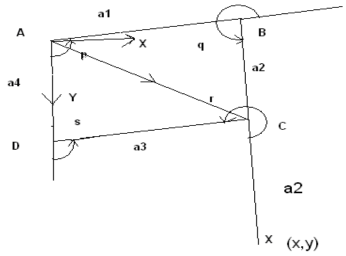


Figure10 geometrical parameters of fork

X denotes the point of attachment of the wheel to the forkTo generate the trajectory of point X considering joint A to be the input angle we derive the two loop closure equations for the four bar mechanism ABCD following the work of [9] and is briefly reviewed here. Consider the four bar mechanism to be broken at point C which will result in two planar 2R and 1R serial kinematic chain. This is shown in figure 10. Since the mechanism has been broken at point C passive variable r will not appear in the loop closure constraint equation. From Figure 10 we have :

$$y = a_1\cos(p) + 2a_2\cos(p+q) \quad (3)$$

$$x = a_1\sin(p) + 2a_2\sin(p+q) \quad (4)$$

$$y = a_3\cos(s) + a_4 + a_2\cos(p+q) \quad (5)$$

$$x = a_3\sin(s) + a_2\sin(p+q) \quad (6)$$

$$y = a_1\cos(p) + 2a_2\cos(p+q) = a_4 + a_3\cos(s) + a_2\cos(p+q) \quad (7)$$

$$x = a_1\sin(p) + 2a_2\sin(p+q) = a_3\sin(s) + a_2\sin(p+q) \quad (8)$$

From equations (7) and (8) we can eliminate the passive variables q, s and get x and y as a function of active joint variable p. Hence the trajectory of point X for various values of p is shown in Figure11

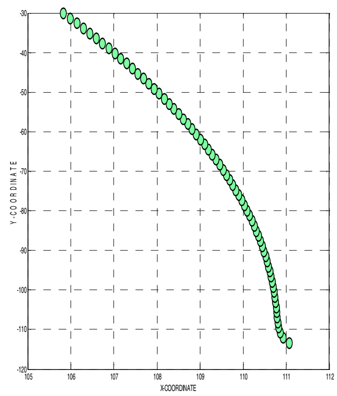


Figure11 trajectory of fork

From the trajectory of the fork we can see that for y co-ordinate varying from -110 to -90 there is very minimal variation in the x co-ordinate i.e the slope during that part of the trajectory is almost 90^0. This signifies that for step like obstacles upto the height of 20cm the fork will show a smooth climbing sequence with minimal loss of contact with the vertical surface of the step. For obstacles of height greater than 20cm the fork will show smoother climbing for lesser slope angles which will decrease with corresponding increase with obstacle diameter. Moreover the actual climbing ability of the fork will depend greatly on the overall dimension of the fork as well as of the whole rover.

VII SIMULATIONS AND RESULT

Simulations are performed using MATLAB and MSC Visual Nastran. Extensive simulations on uneven terrain for both 5-wheeled and 4-wheeled rover were done. Maximum coefficient of friction and maximum torque requirement were selected as the major parameters for comparison between the mechanisms. Dimensions of 5-wheeled and 4-wheeled rover are made comparable to ensure a proper comparison between the two. We set the maximum permissible torque of the motor at 6N-m.The coefficient of friction between the wheel and terrain was varied and minimum co-efficient of friction required to overcome the given terrain was noted for both suspension mechanisms. Figure12 shows 5-wheeled climbing a terrain with 70^0 degree discontinuity about two times the wheel diameter. Figure13 shows 4-wheeled rover traversing on the same terrain with similar climbing sequence. The plot of the wheel motor torques for this terrain is shown in figure14 and figure15 for the 5-wheeled and 4-wheeled design respectively.

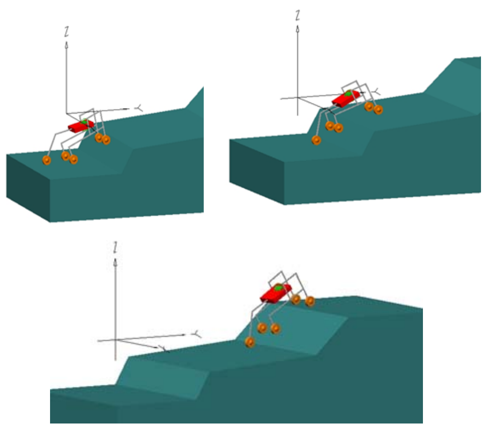


Figure12 5-wheeled rover climbing over series of obstacles

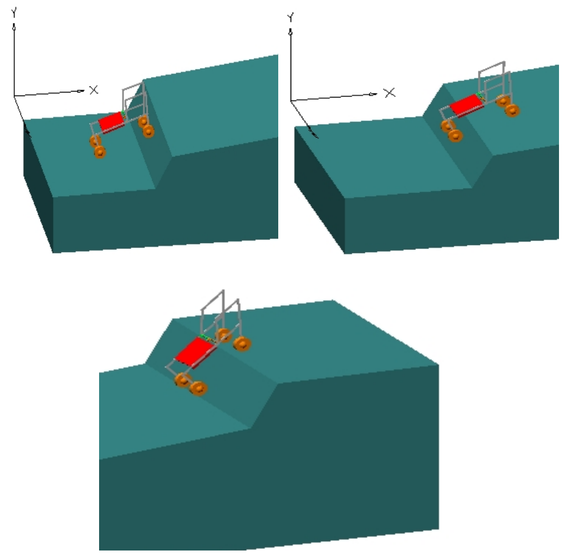


Figure13 4-wheeled rover climbing over series of obstacles

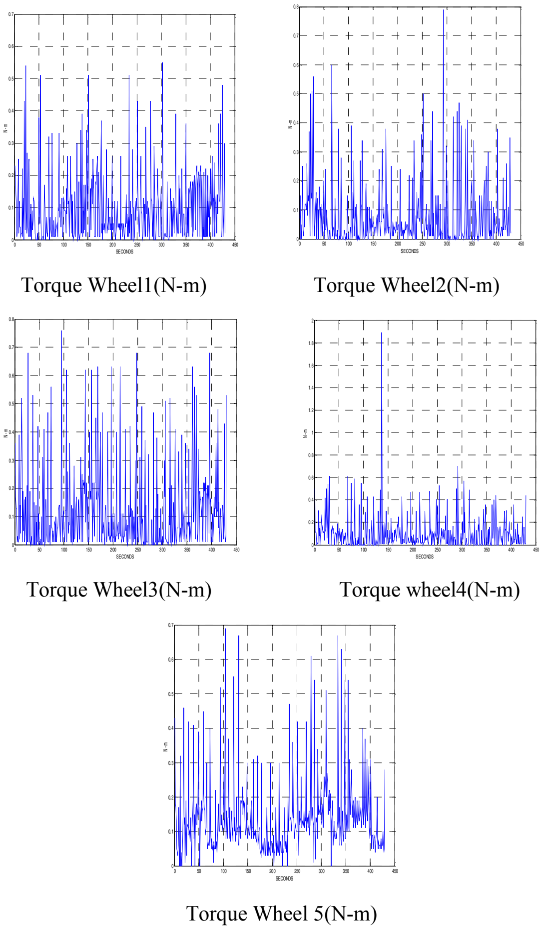
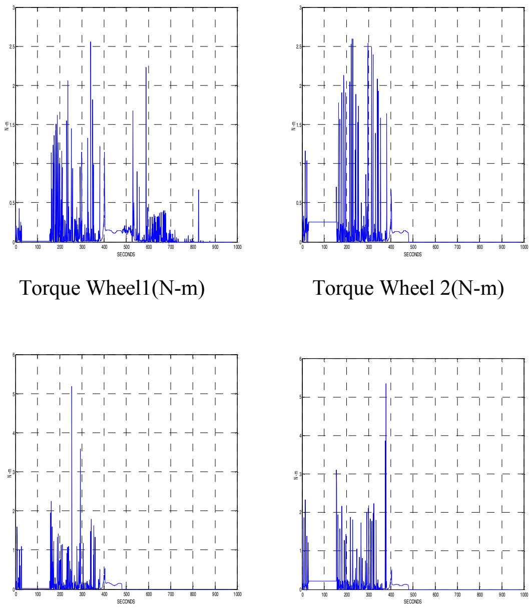


Figure14 plot of wheel motor torques for 5-wheeled rover

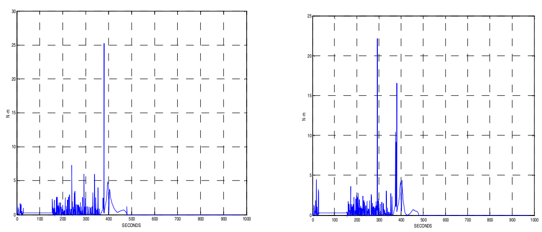


Torque Wheel1(N-m) Torque Wheel 2(N-m)

Torque Wheel3 (N-m) Torque Wheel4 (N-m)

Fig15 plot of wheel torques for 4-wheeled rover

From the plot of wheel torques it can be seen that the maximum wheel torque rating for the 4-wheeled rover is around 5.5 N-m whereas for the 5-wheeled rover it is around 1.9N-m. The increment in the torque requirement was expected because the weight distribution is now on 4-wheels as compared to 5 in the previous case. The corresponding increase in the torque requirement is compensated by the decrease in the requirement of friction. The 5wheeled rover required a minimum coefficient of friction of 0.7 to climb over the obstacle whereas for the 4-wheeled rover this requirement went down to 0.5. This arises due to the fact that the motion of the 5wheeled rover while climbing over an obstacle is primarily dependent on frictional force between the terrain and the wheel but for the 4wheeled rover the motion of the front and back portion over the obstacle is assisted by the moment generated by the active joint. The plot of the torques generated by the active joints is shown in figure16.



Torque Active joint1(N-m) Torque Active Joint2(N-m)

Figure16 plot of the torques of the active joints

VIII CONCLUSIONS AND FUTURE WORK

In this paper we have presented two novel suspension mechanism designs, one passive and one active for rough terrain navigation. The passive suspension mechanism has 5 wheels and the evolution of the 4-wheel active suspension has been deduced from the analyzing the climbing sequence of the 5-wheel rover. The control methodology proposed for controlling the active joints of the 4-wheel ensures that the climbing sequence of the 4-wheel rover closely follows that of 5-wheeled one. The trajectory of the fork has been shown and its relation with climbing ability of the fork has been shown. The future work is related to the development of the prototype of the vehicles and developing path tracking algorithms for both the vehicles

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