A Semi-Active Robot for Steep Obstacle Ascent

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Abstract— **In this paper we propose a semi-active robot for climbing steep obstacles like steps. The key novelty of the proposed robot lies in the use of a passive mechanism for climbing steps of smaller heights and motor only while climbing steps of greater heights. Analysis of the robot's stability during its ascent phase is also investigated. Model based control is used to achieve step climbing. The other novelty of the robot, in contrast to existing active suspension step climbers, is that it does not need the knowledge of step height beforehand. Therefore, the mechanism has the advantage of height-independent climbing motion as in the case of passive mechanism along with the extra freedom of active joints for maintaining vehicle stability, when required. Efficacy of the mechanism is exhibited through simulations on steps of various heights.**

I. INTRODUCTION

The last decade has seen a surge of interest in the potential applications of robots in urban search and rescue missions [1]. The use of robots for rescue missions and surveillance would help to curtail human loss and augment rescue efforts. Given such scenarios, one would expect the robot to navigate over highly uneven surfaces autonomously with little or no help from the surroundings. Particularly, in urban scenarios, robots designed to traverse over structured obstacles (such as steps) with good terrainability [8], would have a distinct edge. This paper proposes a novel mechanism to serve this purpose.

Research into design of rough terrain vehicles has broadly led to two classes of vehicles: active suspension and passive suspension. The elegance of passive suspension vehicles [2], [7], [6] lies in their ability to surmount steep obstacles by the virtue of only wheel-ground contact forces with the help of appropriately designed linkages. This greatly simplifies the control architecture of the vehicle. But their climbing ability is limited to obstacles whose height is upto twice their wheel diameters [2]. On the other hand, active suspension mechanisms [3], [5], [9], [4] have simplified kinematic architecture but may require complicated control algorithms to maintain stability while climbing. It was shown in [5] , that the active suspension mechanism enabled the robot to climb higher obstacles than their passive suspension counterpart. For example in [9] posture control for step climbing has been implemented. However the active suspension robots require intricate control strategies and their ability to climb is limited to heights less than 1.5 times the length of an individual link in the robot

It is ideal to have a mechanism which has compliance offered by the passive systems and minimum number of actuators to enforce a control scheme for climbing higher steps.

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Such a scheme must be able to achieve height-independent climbing motion [5]. The mechanism can climb steps of lower heights using compliance and use active degrees of freedom for climbing higher steps.This motivated us to propose a mechanism which satisfies the above requirements.

In Section II, the trailer mechanism is described. The control methodology used to maintain stability while climbing is detailed in Section III. In Section IV, the simulation results are discussed and finally the conclusions are given in Section V.

II. MODEL DESCRIPTION

The proposed mechanism evolves from a 2-linked passive suspension vehicle shown in Figures 1(a)-1(c). This mechanism consists of two rigid links with wheels, connected to each other through a revolute joint. The free body diagram for this two link system is shown in the Figure II. It can be seen that once the first wheel comes in contact with the obstacle, a horizontal normal force N_1 and the resulting traction force F_1 are generated. The moments generated by these two forces are responsible for lifting link 1 off the ground and climb the obstacle. Static equilibrium equations of the system under study are shown below.

$$N_1 = F_2 + f_{2x} \tag{1}$$

$$N_2 = 2mg - F_1 + f_{2y} \tag{2}$$

$$F_1 l cos\theta_1 + N_1 l sin\theta_1 - 2m_w g l cos\theta_1 - m_l g(l/2)cos\theta_1 = 0 \tag{3}$$

Here, f_{ix} and f_{iy} represent the reaction forces at joint i in x and y directions, respectively. Similarly, F_i denotes the traction force generated by the i^{th} wheel. m denotes the total mass of link and wheel module, i.e. $m = 2m_w + m_l$, where m_w and m_l denote the masses of wheel and link respectively. The counter clockwise moments (about link joint $L1$) responsible for lifting link 1 come from N_1 and F_1, as evident from 3. Moreover, $F_1 \leq \mu N_1$, where μ is the coefficient of friction. The only clockwise moment, resisting the lift, is due to the self weight of the link. Hence, it is desirable to have lighter links and a higher N_1. Note that, in general $N_1 = \sum_{i=2}^{n} F_i$. This can be derived from equation 1 where f_2x is equal to the sum of the traction forces(F_i's) of all the wheels connected to trailing joints . The passive mechanism is able to climb steps purely based on this push force(N_1). Since it is a modular system, one can always add or subtract links depending on the push force required and coefficient of friction (μ) of the given terrain. The mechanism proposed here uses 5 links.

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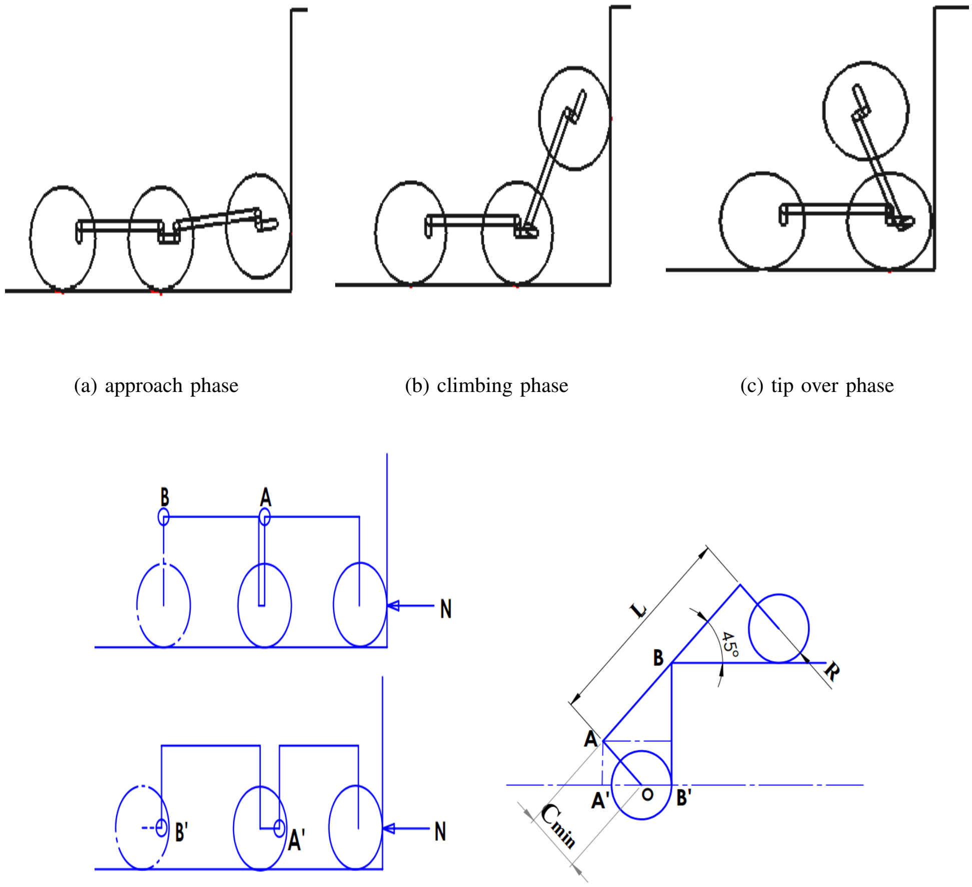

(a) approach phase (b) climbing phase (c) tip over phase

(d) (e)

Fig. 1. a)-c) A fully passive mechanism climbing a step whose height is greater than the individual link length, d) two potential joint positions, e) Configuration used for C_{min} calculation

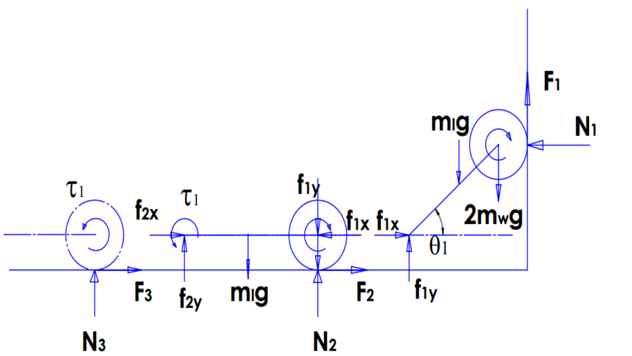

Fig. 2. free body diagram of the 2-linked system

Another important design aspect to be considered is the placement of the link joint. It is desirable to have N_1 help in lifting the first link by generating a counter clockwise moment when the wheel is pressed against the obstacle. When the link joint is placed above the point of contact of the wheel and the obstacle, N_1 will create a clockwise moment about this joint which resists the link from lifting up. A high value of $N1$ may cause link 1 to fold inwards which is undesirable. Therefore, the joint must lie on or below the line passing through wheel centres. In the proposed mechanism, the joint is on the line joining wheel centres. When the wheel collides with the obstacle, the moment due to N_1 is zero about the joint. The counter clockwise moment due to F_1 will initially help in lifting the wheel off the ground. Thereafter, the counter clockwise moment due to N_1 will gradually increase helping in the link's ascent. Figure 1(d) illustrates both these cases.

A minimum clearance, C_{min}, is required to ensure that none of the robot's links hit obstacles blunter than 90^0. C_{min} is calculated from equation 4 which is derived based on the configuration shown in Figure 1(e).

$$c_{min} = l/2 - \sqrt{2}r \tag{4}$$

This passive mechanism is successfully able to climb heights less than one link length (Figures 5(a)-5(e). However, if the height of the step is greater than the length of the link,

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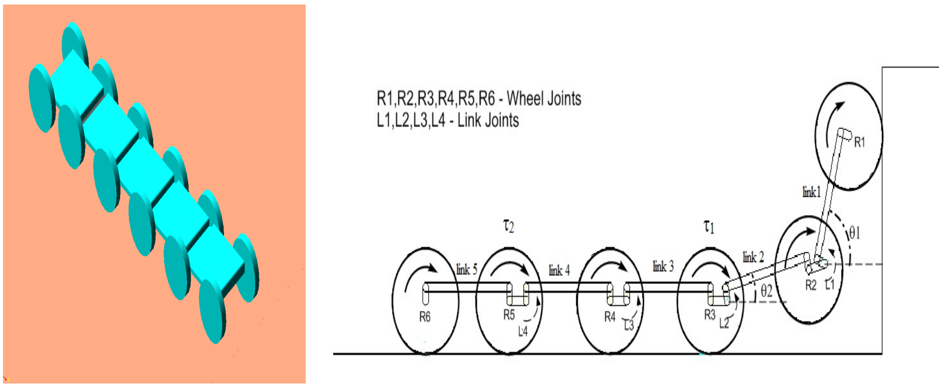

(a) (b)

Fig. 3. a) robot isometric view b) link and joint nomenclature

the first link tips over as shown in Figure 1(c). It can be inferred that if the first link crosses a certain angle, it will tip over because of the moment due to gravity. This tip over angle is $\theta_{to} = \pi/2 - tan^{-1}(\frac{y_{cm}}{x_{cm}})$ where x_{cm} and y_{cm} are the coordinates of the center of mass of the link-wheel module from the joint. Noting this drawback, use of active joints to control the relative angle between the links is proposed. By controlling the configuration of the links through active joints one can control the angle of the leading link and help it climb higher obstacles without violating the above angle condition. This forms the basis for this work. The model parameters are given below.

TABLE I
SPECIFICATIONS OF THE ROBOT

Symbols	Quantity	Values(with Units)
l	Link Length	0.18 m
b	Link Breadth	0.1 m
r	Wheel Radius	0.06 m
l_0	Wheel Joint and Link Joint Offset	0.03 m
μ	Coefficient of Friction	0.8
$\tau_l max$	Max Torque of Link Motors	15 Nm
$\tau_w max$	Max Torque of Wheel Motors	4 Nm
m_w	Mass of Each Wheel	1.0 Kg
m_l	Mass of Each Link	0.5 Kg
I_w	Moment of Inertia of the Wheel	0.000467 Kgm^2
I_l	Moment of Inertia of the Links	0.002049 Kgm^2

Figures 3(a) and 3(b) show the isometric and front views of the proposed mechanism. It consists of two passive suspension mechanisms (1(a)) connected in series. The wheel joints and link joints are denoted by $W_1 - W_6$ and $L_1 - L_4$, respectively. The detailed specifications of the robot are given in Table I.

In the next section, we discuss how one can avoid tip over during climbing using an appropriate control algorithm.

III. Control Strategies

The control algorithm is designed to maintain $\theta < \theta_{to}$ throughout the ascent. Here, θ_i is defined as the angle between the i^{th} link and the ground. The angle θ_i can also be defined in terms of relative joint angle ϕ_i (between links i and $i+1$) as,

$$\theta_i = \sum_{i}^{n} \phi_i \tag{5}$$

Noting that the mechanism shown in figure fails when $\theta \geq \theta_{to}$, it can be deduced that a control over the relative joint angles ϕ_i between the links can help in climbing greater heights before θ_1 approaches θ_{to}.

A. Control Strategy I

This strategy uses only one active joint (which is at $L2$) for maintaining vehicle stability. When only link 1 is climbing the step and link joint $L2$ is actuated, two effects are seen, 1) link 1 is lifted up and 2) θ_1 is reduced (ref. fig. 3(b)). Therefore, the robot is able to climb higher steps, which could not have been possible with passive joints. To implement this control algorithm on the vehicle, a control law is developed. It is worth noting when $\theta << \theta_{to}$, the robot can climb without any actuation at the link joints. Thus, energy is conserved by minimizing the actuation of joint $L2$ by setting up a threshold value. We define $\phi_c = \theta_{to} - 15^0$, the threshold angle, below which the robot works as a passive mechanism.For the system under study, $\theta_{to} = 75^0$ and hence $\phi_c = 60^0$. Let an error e_i be defined for the ith joint angle as

$$\begin{aligned} e_i &= \phi_i - \phi_c \\ e_1 &= \theta_1 - \phi_c \end{aligned} \tag{6}$$

With the above definition, a control system is designed block diagram of which is shown in Figure III-A.

When the error obtained from (7) is greater than zero, the actuator at $L2$ is activated. The torque actuation of the motors can be written as

$$\tau_1 = \alpha\tau_1' + \beta \tag{7}$$

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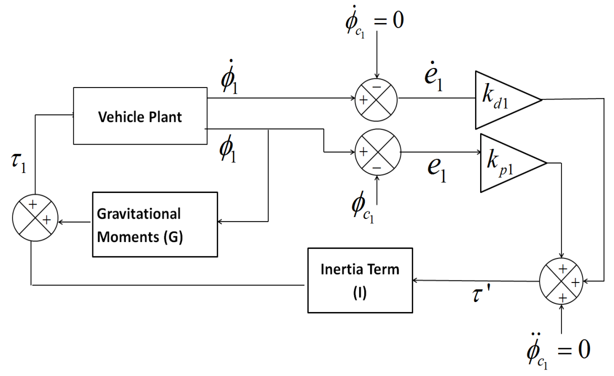


Fig. 4. Model Based Control for controlling Link 1

$$\tau_1' = \ddot{\theta_{d1}} + k_{p1}e_1 + k_{d1}\dot{e_1} \quad (8)$$

In (8), k_{p1} and k_{d1} are proportional and derivative gains of the control system. In (7), α is the inertia of links 1 and 2 about joint $L2$. β balances the moments generated due to gravity.

The robot is approximated as a 2-linked system to perform the model based control scheme (All the other links need not be controlled as they are on the ground and are only required to provide the necessary push force). Control is only needed when the leading link is climbing heights greater than its length. So one needs to calculate the torque required at the joint $L2$ to lift both links 1 and 2 when the control is activated. Hence, inertia is computed only for the 2-link system to generate the required amount of torque at joint $L2$. The more dominating moment is due to the weights of the links and wheels.

It is worth noting that when robot starts climbing, its 1^{st} and 2^{nd} link lift up in the beginning. The model base control of those two links is carried out by assuming them as a 2-link robotic system.

Other links are not controlled as they assumed to be on the ground. The simulation results are shown in Figures 6(a)-6(d). As stated earlier, motors are actuated to control joint angles between the links only when a certain threshold (ϕ_c) is crossed. Figure 6(c) depicts that as the second wheel is being lifted, the reaction moment generated at $L3$ lifts link 3 off the ground. This leads to loss of traction and instability in the robot and as a result it fails to climb the obstacle. To solve this problem a different control law is employed which utilises two active joints at L_2 and L_4 respectively.

B. Control Strategy II

As stated earlier this strategy uses two active joints at $L2$ and $L4$ for maintaining stability while climbing steps. Here, joint $L2$ is controlled using strategy illustrated in the previous subsection while joint $L4$ is controlled using PD control law. It is necessary to balance the reaction moment generated while actuating joint $L2$ as detailed in Control Strategy-I. In this strategy, an extra motor is used at link joint $L4$ for this purpose. A PD control scheme is used to counter the reactive moment acting on link 3 . This is actuated only when $\phi_3 < 0$ and joint $L2$ is active. The PD control law ensures that active joint $L2$ only lifts link 2 and keeps link 3 grounded. The control architecture for the same is shown in the Figure 8.

It is worth noting that actuation of $L4$ might lift off the fifth wheel when the reaction moment to be balanced is high. In order to overcome this disadvantage, a torsional spring is fitted at the passive joint $L3$. One cannot choose a spring of high stiffness as this makes the joint stiff. this may limit the climbing ability of the vehicle. After carefully considering the above aspects, a torsional spring of stiffness 2 Nm/rad is chosen. Figures 7(a)-7(e) show that the mechanism was successfully able to climb a step of height 330 mm using the proposed strategy.

IV. Results

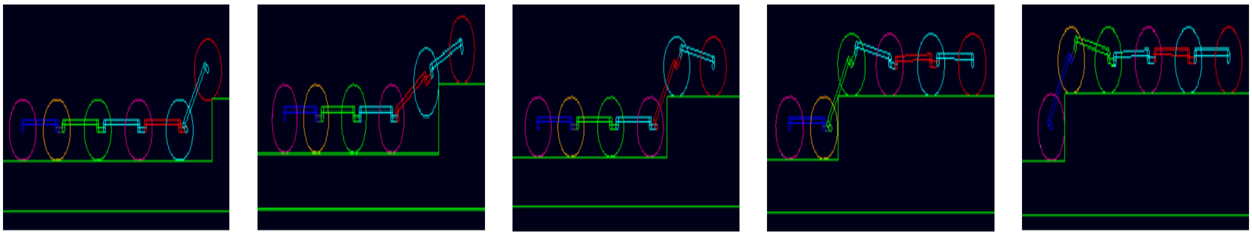
The robot was simulated on MSC ADAMS software to study its performance on steps of varying heights. The Step height was parametrized in terms of link length. The speed of the robot is 0.18 m/s. The values of k_{p1} and k_{d1} for the model based control in (8) are taken as 20 and 4 respectively. Similarly, values of k_{p2} and k_{d2} used in the PD control at link joint $L4$, are 80 and 10 respectively.

Figure (9) shows the amount of torque required at the motors during step climbing shown in figure 7(a)-7(e). It can be seen that, while ascending the first step, $L4$ applies nearly equal amount of torque(in the counter direction) as $L2$. Figure (9) shows the plot of e_1 with respect to time, calculated after the angles ϕ_1 and ϕ_3 reach threshold angle,$\phi_c = 45^0$.The threshold is lowered to study the performance of the controller at a lower threshold value. The Control Strategy succeeded in ensuring that link 1 doesn't tip over during its ascent. Thus, the robot achieves the desired climbing motion for heights upto $330mm$ which is nearly 1.8 times its link length.

Simulations were also carried out on irregular terrains, as shown in Figures 10(a)-10(g). The modularity and passivity of the robot give it a natural edge while traversing an irregular terrain. The body of the robot is able to deform itself along the shape of the obstacle and in areas where the angle of deformation is greater than ϕ_c, the active joint helps it in climbing without tipping over.

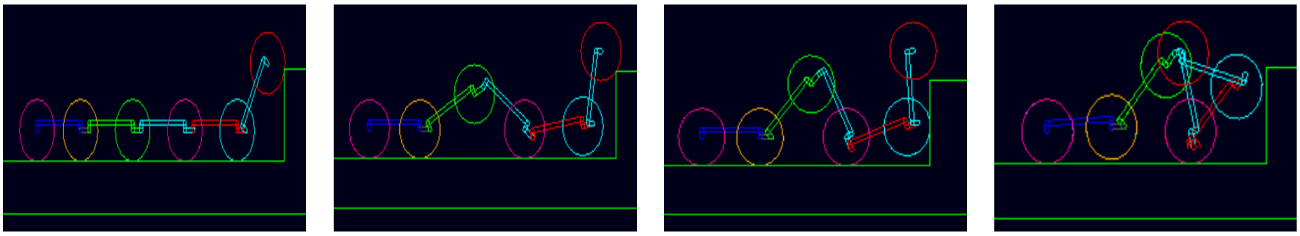
V. Conclusions and Future Work

In this work, a simple design of a modular semi-active step climbing robot has been presented. The novelty of the robot lies in the fact that it can climb heights upto 1.8 times of the link length. Two control strategies have been presented to achieve step climbing. In the first strategy only joint $L2$ was actuated when $\theta_1 \geq \theta_c$. This strategy showed some improvement over the passive mechanism but it failed to climb heights higher that 1.2 times the link length. In the second strategy joints $L2$ and $L4$ have been actuated to overcome the above disadvantage. The robot was successfully able to climb the height equal to 1.8 times the link length.



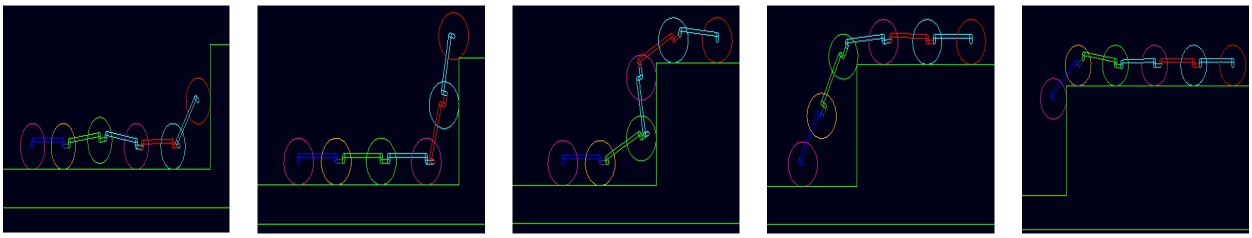
(a) (b) (c) (d) (e)

Fig. 5. Snapshots of a fully passive system climbing a step of 120 mm



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

Fig. 6. Snapshots of a system failing to climb a step of 180 mm using only Strategy I



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

Fig. 7. Snapshots of the robot climbing a Step of height 330mm using Control Strategy I and II

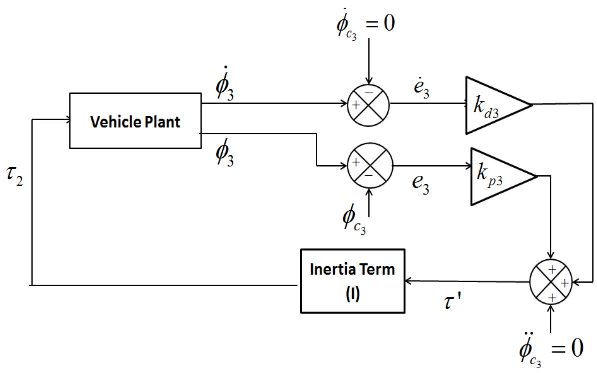


Fig. 8. PD Control for countering the reactive moment

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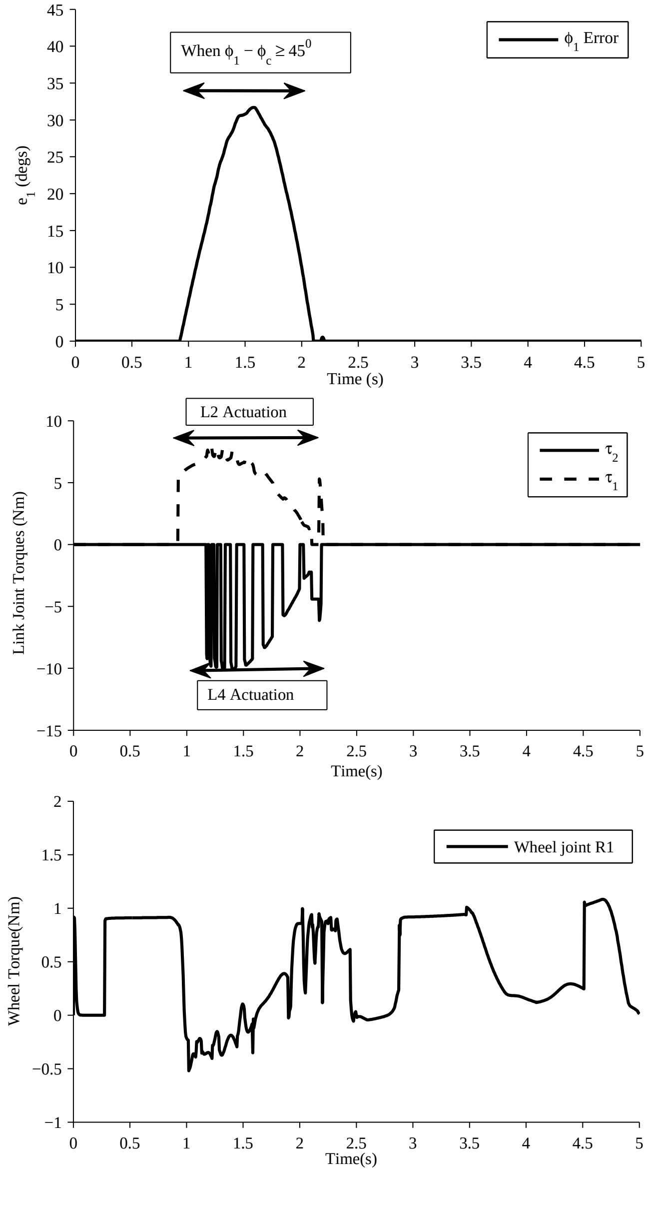

Fig. 9. Error Plot and Torques Plot

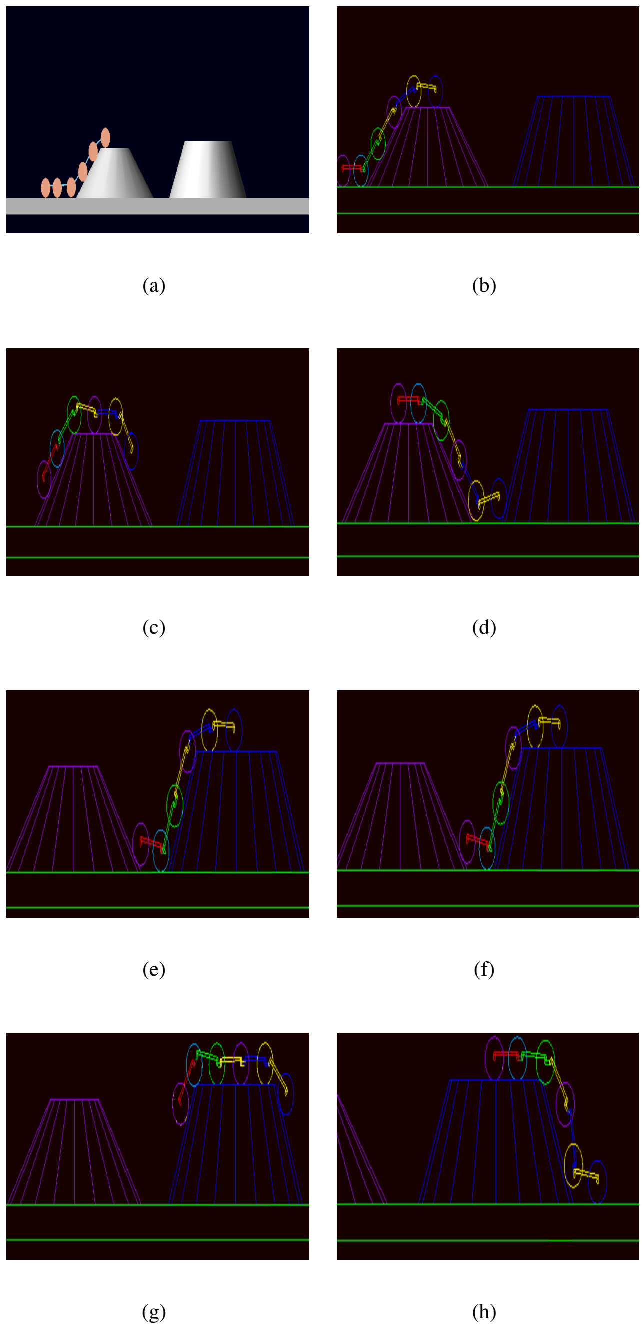

Fig. 10. Snapshots of the robot climbing steep obstacles

The proposed strategy allows the robot to move passively for smaller steps and semi-actively for bigger steps. This makes this robot very desirable for traversing on an irregular terrains and step-like obstacles in an energy efficient manner. However, the robot's climbing ability is limited to heights less than $2lsin\theta_{max}$.

Development of a working prototype of the proposed mechanism will be carried out as future work. Work also needs to be done on developing control schemes to achieve safe climbing down motion. Use of springs instead of motors to achieve similar performance can also be explored.

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