On Improving the Mobility of Vehicles in Uneven Terrain

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***Abstract*—This paper studies the problem of traversing a rough terrain by wheeled vehicles. Here rough terrain implies terrain which is geometrically not ideal. The criterion for mobility of a wheeled vehicle in any terrain is formally developed, providing insights into the mechanical structure requirements of the vehicle. A vehicle structure with an actively articulated suspension is found as a solution to improved rough terrain mobility. The contact forces of the vehicle with the surface being traversed are identified as the critical factor in determining the traversability of the surface. Hence a control strategy involving the control of the contact forces (normal and traction) is proposed. The key feature of the locomotion strategy, thus developed, is that it provides a solution involving dynamics of the main body for improving mobility in rough terrain.**

***Index Terms*—Articulated Suspension, Wheeled Robots, Rough Terrain, Mobility, Traction**

I. Introduction

Given a terrain, can we predict if a robot with a given mechanical structure can traverse the terrain? To the best of the authors' knowledge, there seems to exist no definitive answer to this question in previous work on rough terrain mobility. This paper attempts to answer the question. The answer to this question also provides the motivation for deviating from the simple rigid suspension structure to a structure that is more suitable for mobility in rough terrain. We develop this mechanical structure and introduce a strategy to improve its mobility in rough terrain.

A number of efforts towards a solution to mechanical structure problem have been made in the past [1]-[4]. Simultaneously, the development of a control strategy for the degrees of freedom of the internal configuration variables of the mechanical structure has been studied [5], [6]. This had led to the development of vehicle systems with passive articulated suspension systems such as the shrimp [1] and the JPL Rocky [2] with excellent terrain adaptability. In such systems, the only independent configuration variables are related to the wheel actuation. Another well known solution to rough terrain mobility is legged systems [7]. These systems are often inefficient in terms of power consumption, pay load capacity and speed, but are useful for surface with extreme discontinuity. The main disadvantage of the passively suspended and fixed suspension vehicles is that the robustness of these systems under varied terrain conditions is not certain. To enhance the performance of such systems, a class of robots with actively articulated suspensions called the Wheeled and Actively Articulated Vehicles (WAAVs) has been developed, the terminology first used by Srinivasan *et al.* [8]. We focus our attention to this class of vehicles as we observe they are suitable for implementation of the control strategy developed in this paper. The Hybrid Wheel-Legged Vehicles (HWLV) [9] is a class of vehicles that consists of any combination of wheeled and legged mechanisms. The Hylos [9] and WorkPartner [4] are typical examples of such vehicles.

A static analysis of the contact forces on an HWLV such as Hylos would reveal that the contact forces are functions of the body-weight, payload, posture and the contact angles [10], [11]. Hence previous work [5], [9] has aimed at controlling the posture, defined by the internal configuration parameters, with the purpose of optimizing the contact forces for maximizing traction and stability. Algorithms for traction optimization and power efficient mobility in rough terrain are presented in [10], [12]. However [10] does not speak of conditions where forward motion is not possible for a slow moving fixed suspension vehicle. Fig. 1 shows a fixed suspension vehicle on a terrain it is unable to traverse.

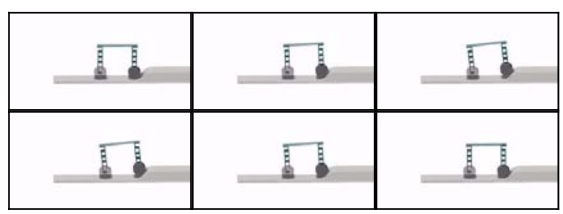

Fig. 1. Fixed suspension vehicle failing to traverse a given surface

Ch. Grand *et al.* at the Laboratoire de Robotique de Paris have developed the Hylos robot [9]. The central theme for the Hylos locomotion is to achieve a posture of the main body which maximizes stability and traction using the posture control algorithm that uses the velocity model (which maps the joint velocities to the velocity of the main body) to set velocities at the various joints based on the posture error. The interested reader is referred to [9], [13] for a detailed account of the work.

The critical assumptions made in the analysis of the Hylos [9] are: (i) sufficient contact forces exist to allow for pure rolling of the wheels, also implying that wheel-ground contact exists at all times, and (ii) the dynamic effects are neglected.

The approach in this paper can be considered inverse of the approach as stated in previous work [9] with respect to traction for mobility in rough terrain. In that, we are able to control the posture of the main body by controlling the contact forces rather than vice versa. We aim at directly controlling contact forces that result in the desired traction.

The authors believe that the method of altering the contact forces to control the posture and improve the traction performance in an actively articulated suspension would be a first attempt and hope to solve the problems prevalent due to assumptions stated in [9].

II. Mobility of a Fixed Suspension Vehicle

The mobility of a vehicle implies its ability to traverse a surface with different geometrical parameters. For a fixed suspension vehicle, the local geometry at the contact point results in the contact angle (γ_i) while the global geometry over the length scale of the wheel-base affects the pitch angle (ψ). As shown in Fig. 2, the global fixed frame is $\{XYZ\}$, where Y is parallel to the gravity force; $\{xyz\}_i$ is the contact frame at the i^{th} contact point where traction (T_i) is along x and normal contact force (N_i) along y; V_i^j is the component of the vector from the i^{th} contact point to the CG point in the j direction; and γ_i is the contact angle at the i^{th} contact point. The index i increments as we move from the rear to the front wheels.

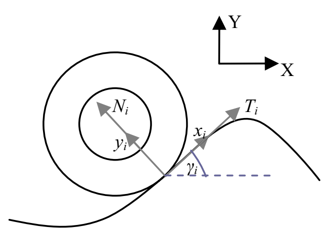

Fig. 2. Wheel terrain contact forces and parameters

The quasi-static equations that relate the normal contact and traction forces to the forces on platform for a planar two-wheeled vehicle are given by

$$A \cdot C = D \tag{1}$$

For a vehicle with two wheels in the plane, $A = A_G$.

$$A_G = \begin{bmatrix} \cos\gamma_1 & -\sin\gamma_1 & \cos\gamma_2 & -\sin\gamma_2 \\ \sin\gamma_1 & \cos\gamma_1 & \sin\gamma_2 & \cos\gamma_2 \\ V_1^y & -V_1^x & V_2^y & -V_2^x \end{bmatrix}$$

$$C = \begin{bmatrix} T_1 & N_1 & T_2 & N_2 \end{bmatrix}^T$$

$$D = \begin{bmatrix} F_X & F_Y & M_Z \end{bmatrix}^T$$

These set of equations are redundant and hence infinite solutions exist under the following constraints:

$$N_i \geq 0 \quad \forall\, i, i = \{1,2\} \tag{2}$$

$$\Gamma_i^{\min} \leq (T_i \cdot r) \leq \Gamma_i^{\max} \quad \forall\, i, i = \{1,2\} \tag{3}$$

$$T_i \leq \mu N_i \ \forall\, i, i = \{1,2\} \tag{4}$$

$\Gamma_i^{\max}, \Gamma_i^{\min}$ are the maximum and minimum torques that the motor at the i^{th} wheel can generate. For the vehicle to be able to move forward, it must at least remain in equilibrium. Therefore, we set $F_X \geq 0$, $F_Y = Wg$ and $M_Z = 0$, neglecting effects like rolling friction, inertial forces, etc. W is the mass of the vehicle in kilograms and M_Z is the moment in the plane of analysis. The above problem can be viewed as a linear programming problem, where a solution to all variables exists if the solution space is not a null set. An arbitrary objective function is chosen:

$$\min_{T_i, N_i}(S),\ S = T_1 \tag{5}$$

to evaluate the regions for γ_1, γ_2 and ψ where a solution to the above set of equality and inequality constraints (1)-(5) does not exist. As an instance, we set $\gamma_1 = 0$ and vary γ_2 from 0 to $\pi/2$ to illustrate the existence of regions with no solutions. Also the pitch angle ψ is varied from 0 to $\pi/3$.

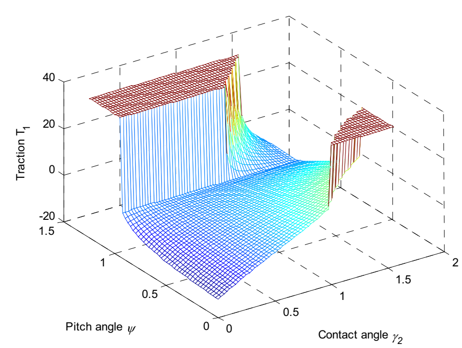

Fig. 3. Plot of min(T_1) showing regions of infeasibility (dark flat surface)

Fig. 3 shows the plot of $\min(T_1)$ as a function of the contact angle γ_2 and pitch angle ψ. The values of γ_2 and ψ corresponding to the brown (darkened and flat) region indicates the region of infeasibility where no solution for the given values of γ_2 and ψ exists. In this region, no values of traction forces at the wheels can maintain the system in equilibrium with the vehicle having a fixed suspension. Hence if the vehicle is not moving fast, it cannot overcome this state and cannot traverse the terrain.

For sufficiently uneven terrain, a large range of contact angles and pitch angles are possible. Hence to successfully traverse such a surface, a vehicle is needed for which the infeasible regions described above do not exist. The actively articulated vehicles such as the HWLV, as we shall see in later sections, are capable of achieving this.

It must be noted that since the geometry of the given surface cannot be varied to modify the feasible region, the forces T_i and N_i must be somehow modified. In further sections, we introduce the mechanical structure of the WAAV used and the control methodology, which we term as the Force Control Methodology, devised to achieve the requirement of no infeasible regions mentioned above.

III. Force Control Methodology

All previous work dealing with the control of WAAVs has focused on controlling the posture of the vehicle by utilizing the independent internal configuration parameters u with various optimization functions such as traction and stability. Here, we speak of only the parameters that are different from the parameters used for trajectory control of the vehicle. We need to find an alternate method that controls the contact forces F^c at the various contact points between the wheels and the surface such that the vehicle successfully traverses a terrain. Hence the primary motive of the vehicle is to be able to traverse a given terrain. Since our aim is to study the traction or the forward motion problem, a planar analysis will suffice as also in [10], however extensions to the 3D problem can be done.

To develop our control methodology, we use a generic platform consisting of a main body and two actuated wheels in the sagittal plane, each wheel connected to the main body through a Linear Force Actuator for development of our control methodology. We call this vehicle LFA-V (Fig. 4). It must be noted that the LFA-V has actuated prismatic joints, which we consider as a form of actively articulated suspension due to the internal degree of mobility it provides to the vehicle.

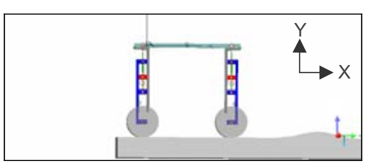

Fig. 4. The LFA-V mechanical structure

We also need a control to achieve the desired value of contact force $F^c = [T \quad N]^T$ using an articulated suspension. This issue has been addressed previously for industrial robots in a comprehensive manner [14], [15] and the work described in this paper does not focus on this issue. For all further analysis, we assume the wheels have only single point contact in the plane of analysis and that the wheels are cylindrical.

The mechanical structure for analysis consists of 2 wheels, each pinned to an outer slide link which is connected to an inner slide link through a prismatic joint. The inner slide is fixed to the main body. The prismatic joint is actuated through a linear actuator, mounted on the main body, to which a desired force F^A can be commanded. This force F^A acts between the main body and the output slide. Although the input and output slides have a finite mass, we consider this to be negligible compared to the mass of the body and therefore neglect them in our analysis.

By the kinematics of the system, we can see that the entire system when analyzed as a parallel manipulator [16] has a total of 3 degrees of freedom. These can be identified as the height h of the main body, its pitch angle ψ and the position along the horizontal direction X_v. Hence we can apply arbitrary forces F_X, F_Y and moment M_Z to main body of the vehicle. The wheel ground contacts are assumed to be no-slip contacts for the kinematic analysis.

Next we write down the quasi-static force balance equations that relate the normal contact force N_i and the traction force T_i to the forces at main body of the LFA-V. $\overline{V}_i^{\,j}$ represents the effective moment arm (scalar) of the force at the i^{th} contact point acting perpendicular to the j direction. The equations below are written by considering the force actuator force $F_i^A = N_i / \cos(\gamma_i - \psi)$. These equations are different from that for a rigidly suspended vehicle shown earlier. C, D are defined previously in (2).

$$A \cdot C = D \tag{6}$$

For the LFA-V specific mechanical structure, $A = A_L$.

$$A_L = \begin{bmatrix} c_1^3 \cdot c_3 & -\dfrac{s_3}{c_1^3} - s_1^3 \cdot c_3 & c_2^3 \cdot c_3 & -\dfrac{s_3}{c_1^3} - s_1^3 \cdot c_3 \\ c_1^3 \cdot s_3 & \dfrac{c_3}{c_1^3} - s_1^3 \cdot s_3 & c_2^3 \cdot s_3 & \dfrac{c_3}{c_2^3} - s_2^3 \cdot s_3 \\ \overline{V}_1^{\,y} & -\overline{V}_1^{\,x} & \overline{V}_2^{\,y} & -\overline{V}_2^{\,x} \end{bmatrix}$$

where c is a cosine and s is a sine function such that $c_3 \equiv \cos\psi$; $c_i^3 \equiv \cos(\gamma_i - \psi)$; and other notations follow. Also

$$\overline{V}_1^{\,y} = k_1 \sin(\theta_1)\cos(\gamma_1 - \psi) + r\cos(\gamma_1 - \psi)$$

$$\overline{V}_1^{\,x} = k_1 \cos(\theta_1)/\cos(\gamma_1 - \psi)$$

$$\overline{V}_2^{\,y} = k_2 \sin(\theta_2)\cos(\gamma_2 - \psi) + r\cos(\gamma_1 - \psi)$$

$$\overline{V}_2^{\,x} = -k_2 \cos(\theta_2)/\cos(\gamma_2 - \psi)$$

$$\theta_i = \mathrm{atan}(2l_i/w); \qquad k_i = \sqrt{\frac{w^2}{4} + l_i^2}$$

Here r is the radius of the wheel, w is the wheel base of the vehicle measured in the main body, and l_1 and l_2 are the wheel-to-frame distance along the direction of the actuator of the first and second wheel.

A reasonable choice for the objective function in the case of the LFA-V would be to maximize the force in the direction of travel i.e. F_X. Hence the objective function is:

$$\max_{T_i, N_i}(S),\ S = F_X \tag{7}$$

We observe that if we do not impose any equality constraints on F_Y, we can drop row 2 of (7) and solve the minimization problem (6) with the constraints:

$$\hat{A} \cdot C = \hat{D} \tag{8}$$

and constraints (2)-(4). Use of constraint (8) is possible for the LFA-V since it allows for dynamics at the main body in the vertical direction. We can set F_X to any arbitrary positive value to achieve a desired acceleration and control the pitch angle ψ to any desired value by defining M_Z as:

$$M_Z = \overline{k}_v \dot{e} + \overline{k}_p e \tag{9}$$

where $e = \psi_d - \psi$

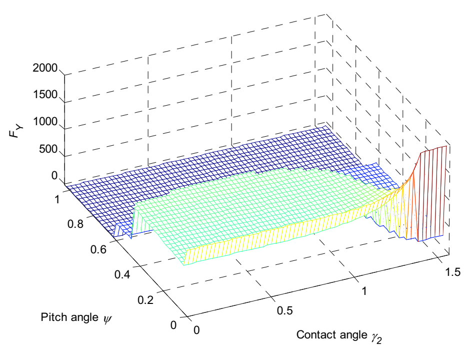

Fig. 5. Plot of F_Y showing no regions of infeasibility

Fig. 5 shows a plot of F_Y as the solution of (7) with constraints (11) and (3)-(5). It reveals that there is no infeasible set of conditions in the scanned region of $0 < \psi < 60^\circ$, $0 < \gamma_2 < 90^\circ$ for $\gamma_1 = 0$ with no limits for the linear force actuator force F^A. If actuator force limits are imposed, feasible solutions would still result. Hence theoretically it is possible to traverse all terrain by using the modified constraint equation (10).

The feasibility space modifications are due to two primary reasons: (i) the matrix A_L for the LFA-V is different from A_G due to the kinematic differences between the LFA-V and the fixed suspension vehicle, and (ii) the LFA-V allows for dynamics in the vertical direction. The important difference in the feasibility plot is that the infeasible region with low pitch angles and high contact angles present in Fig. 3 is not present. These conditions can be easily encountered in uneven terrain. Since in the LFA-V, we are allowed to specify a zero pitch angle requirement, the conditions at higher pitch angles are not of much practical usage. The plot in Fig. 5 indicates that at pitch angles of interest, a force $F_Y > Wg$ would result in a greater forward driving force F_X.

Also it is to be noted that at higher pitch angles in Fig. 5, we observe $F_Y = 0$. Hence we have two distinct regions, at sufficiently low pitch angles F_Y correspond to values greater than the weight of the main body while at higher pitch angles it is zero. The region where $F_Y = 0$ corresponds to conditions that were infeasible if instead of (8) we were to use (6). This physically means that the main body would have to move downwards under gravity for those conditions of pitch and contact angle. This is completely possible in the case of LFA-V. However the subtle point to be remembered is that we have neglected the weights of the components other than the main body here. Therefore in reality, if the weights of the suspension components and wheels were to be taken into account, the vehicle would not be able to traverse the surface under these conditions. But in case of the LFA-V, only the inertia of these components would cause the vehicle to decelerate as it moved though these conditions. Hence if the vehicle has a finite speed, it would in most cases overcome the terrain. However as mentioned earlier, these conditions of high pitch angles are not of much significance for the LFA-V.

It can be seen that by using $F_i^A = N_i/\cos(\gamma_i - \psi)$, F_i^A increases to infinity as $\cos(\gamma_i - \psi)$ decreases to 0. Hence for practical purposes with a finite force actuator, certain conditions of the pitch angle and contact angle would still yield no solution. It is for this reason that we suggest a different mechanical structure such that the force actuator can generate force normal to the contact surface i.e. $F_i^A = N_i$. In this case since an upper bound on N_i can be imposed, F_i^A remains bounded and a practical force actuator can be realized.

IV. SIMULATION RESULTS

The simulation was done using Matlab Simulink and MSC Visual Nastran. The surfaces used as terrain were higher-order continuous surfaces such as B-splines.

Fig. 6 shows the LFA-V negotiate terrain for which no solution exists if (6) is used and F_Y is fixed by the use of an equilibrium constraint of the main body in the vertical direction. Although theoretically this constitutes a feasible condition space for the LFA-V, in our analysis we neglected resistances and masses of the suspension which are present in the simulation. For the terrain shown in Fig 6, these factors are sufficient to prevent forward motion of the vehicle. From our inference in the previous section, a force $F_Y = Wg + \alpha$, where alpha is positive, increases F_X and hence overcomes resistances. Hence in the simulation in Fig. 6 dynamics is introduced into the main body using $\alpha = 0.5$ and the vehicle successfully traverses the surface. Fig. 7 shows the time history of α as the vehicle moves over the terrain.

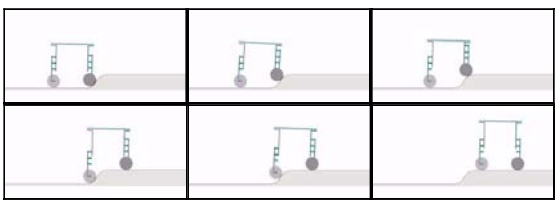

Fig 6. The LFA-V overcoming a steep slope

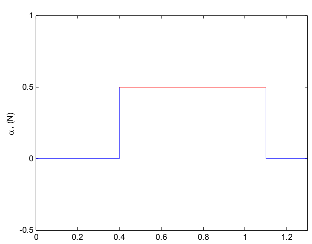

Fig. 7. Time History of α

It is also possible to control the posture and motion of the vehicle by defining F_Y, M_Z and F_X based on set point values of parameters height h and pitch angle ψ.

$$F_Y = k_v \dot{e} + k_p e + Wg \tag{10}$$

where $e = h_d - h$, and

$$M_Z = \bar{k}_v \dot{e} + \bar{k}_p e \tag{11}$$

where $e = \psi_d - \psi$

and F_X set to any desired positive value.

Further $\{T_1, N_1, T_2, N_2\}$ can be solved by using (6) in conjunction with an equal traction constraint, $T_1 = T_2$. The equal traction constraint, often also used in automobiles makes matrix A invertible. This makes the control computationally inexpensive. Fig. 8 describes one such simulation. However the satisfaction of the inequality constraints mentioned previously is not guaranteed by this method. Therefore as in [9] it is applicable only in feasible contact conditions described earlier.

Hence the force control methodology using the normal contact force and traction forces work satisfactorily to maintain posture and ensure the vehicle traverses the terrain. Thus an alternate solution to control the posture of a WAAV such as the LFA-V is provided, based on the contact forces at the contact points, which can also be utilized in terrain conditions difficult to traverse.

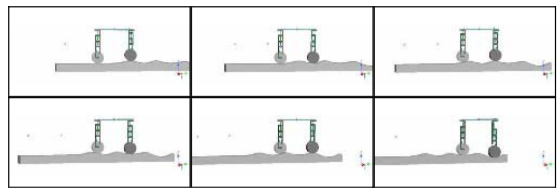

Fig. 8. Illustration of the simulation with ψ_d=0, h=h_d

V. CONCLUSIONS AND FUTURE WORK

It is formally understood that rigid or fixed suspension vehicles are unsuited for successful operation under certain terrain conditions. This brings out the primary motivation for using WAAVs to maximize traversability of the terrain. Therefore a method based on controlling the contact forces responsible for causing the motion of a WAAV like the LFA-V is developed. This provides a strategy for successfully traversing a terrain and also controlling the posture of the vehicle.

As future work, we plan to build a physical implementation of a system utilizing the force control methodology. The force actuator element to generate the required contact forces for the physical implementation has been identified as a 2-dof leg with a wheel (leg-wheel) as the end effecter. Control for this leg-wheel has been formulated to generate required normal contact forces, which has been studied in past research. Also extension to deformable surfaces of contact, particularly for outdoor field environments is needed.

REFERENCES

[1] T. Estier, Y. Crausaz, B. Merminod, M. Lauria, R. Piguet, and R. Siegwart, "An innovative space rover with extended climbing abilities," in *Proc. Int. Conf. Robotics in Challenging Environments*, Albuquerque, USA, 2000.

[2] R. Volpe, J. Balaram, T. Ohm and R. Ivlev, "Rocky 7: A next generation mars rover prototype," *J. Advanced Robotics*, vol. 11, no. 4, pp. 341–358, Dec. 1997.

[3] F. Michaud and *et al.*, "Azimut, a leg-track-wheel robot," in *Proc. IEEE/RSJ Int. Conf. Intelligent Robots and Systems (IROS)*, Las Vegas, Nevada, 2003, pp. 2553–2558.

[4] A. Halme, I. Leppänen, S. Salmi and S. Ylönen, "Hybrid locomotion of a wheel-legged machine," in *Proc. Int. Conf. Climbing and Walking Robots (CLAWAR)*, Madrid, Spain, 2000.

[5] K. Iagnemma, A. Rzepniewski, S. Dubowsky and P. Schenker, “Control of robotic vehicles with actively articulated suspensions in rough terrain,” *Autonomous Robots*, vol. 14, no. 1, pp. 5–16, 2003.
[6] S. V. Sreenivasan and B. H. Wilcox, “Stability and traction control of an actively actuated micro-rover,” *J. Robotic Systems*, vol. 11, no. 6, pp. 487–502, 1994.
[7] U. Saranli, M. Buehler and D. E. Koditschek, “Rhex: a simple and highly mobile hexapod robot,” *Int. J. Robotics Research*, vol. 20, no. 7, pp. 616–631, 2001.S. V. Sreenivasan and K. J. Waldron, “Displacement analysis of an actively articulated wheeled vehicule configuration with extensions to motion planning on uneven terrain,” *ASME J. Mechanical Design*, vol. 118, no. 6, pp. 312–317, 1996.
[8] S. V. Sreenivasan and K. J. Waldron, “Displacement analysis of an actively articulated wheeled vehicule configuration with extensions to motion planning on uneven terrain,” *ASME J. Mechanical Design*, vol. 118, no. 6, pp. 312–317, 1996.
[9] Ch. Grand, F. BenAmar, F. Plumet and Ph. Bidaud, “Stability and traction optimization of a reconfigurable wheel-legged robot,” *Int. J. Robotics Research*, Oct. 2004.
[10] K. Iagnemma and S. Dubowsky, “Traction control of wheeled robotic vehicles in rough terrain with application to planetary rovers,” *Int. J. Robotics Research*, vol. 23, no. 10-11, pp. 1029-1040, Oct.-Nov. 2004.
[11] M. H. Hung, D. E. Orin and K. J. Waldron, “Force distribution equations for general tree-structured robotic mechanisms with a mobile base,” in *Proc. IEEE Int. Conf. Robotics and Automation*, Detroit, MI, USA, 1999, vol. 4, pp. 2711-2716.
[12] P. Lamon, A. Krebs, M. Lauria, R. Siegwart and S. Shooter, “Wheel torque control in rough terrain – modeling and simulation,” in *Proc. IEEE Int. Conf. Robotics and Automation*, 2005, pp. 867- 871.
[13] Ch. Grand, F. BenAmar, F. Plumet and Ph. Bidaud, “Decoupled control of posture and trajectory of the hybrid wheel-legged robot hylos,” in *Proc. IEEE Int. Conf. Robotics and Automation*, New Orleans, LA, 2004, vol. 5, pp. 5111-5116.
[14] J. T. Wen and S. Murphy, “Stability analysis of position and force control for robot arms,” *IEEE Trans. Automatic Control*, vol. 36, no. 3, pp. 365-371, 1991.
[15] L. L. Whitcomb, S. Arimoto, T. Naniwa and F. Ozaki, “Adaptive model-based hybrid control of geometrically constrained robot arms,” *IEEE Trans. Robotics and Automation*, vol. 13, no. 1, pp. 105-116, Feb. 1997.
[16] N. Chakraborty and A. Ghosal, “Dynamic modeling and simulation of a wheeled mobile robot for traversing uneven terrain without slip,” *ASME J. Mechanical Design*, vol. 127, no. 5, pp. 901-909, Sept. 2005.