PERFORMANCE EVALUATION OF TWIN RIGID-FRAMES HEXAPOD PLANETARY ROVERS

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ABSTRACT
The present paper describes a mathematical model able to predict the performances of twin rigid-frames hexapod walking machines, like the demonstrator for an hexapod walking planetary microrover built by the Mechatronics Lab of the Politecnico di Torino, in cooperation with Alenia Spazio. As its performances were found to satisfy the design requirements, a research activity aimed to investigate the applicability of such machines to a range of space missions was undertaken. In particular, while it was clear that the chosen configuration is particularly convenient in the case of small, slow, low powered machines, its limits of applicability were still to be determined. The model here described has been validated using the results of the experimental tests performed on the demonstrator.

INTRODUCTION
Rovers and microrovers for scientific planetary and asteroid exploration are considered a critical enabling technology for many future space missions. The advantages of walking machines as robotic planetary rovers are well known. They include a great mobility on rough terrain and in very low gravity environments, good isolation from ground irregularities, low environmental damage, and good theoretical energy efficiency [1]. Their drawbacks are also clear: a greater complexity of both the mechanical and control subsytems, a far less settled technology and in many case a poor energetic efficiency due to the actual implementation of the concept.

A proposal of a layout allowing to build a very simple hexapod walking machine was forwarded by the authors [2]. The proposed microver was initially designated as ALGEN and then a prototype, named WALKIE 6, was built (Figure 1 a). Although being

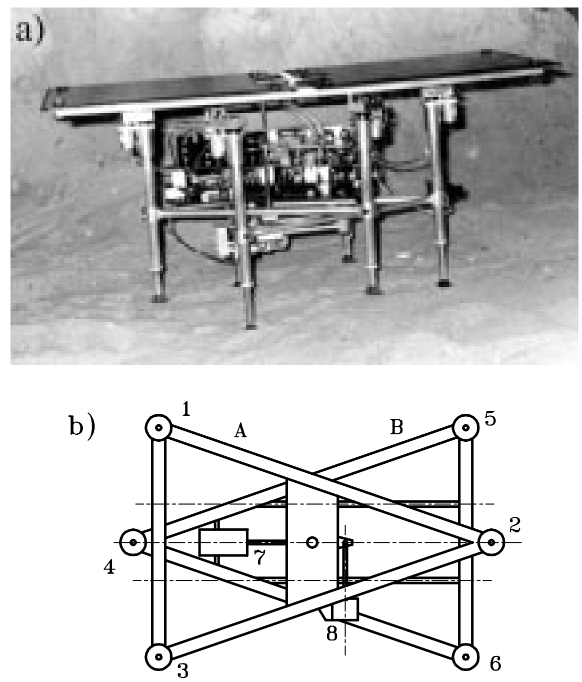

FIGURE 1: a) WALKIE 6; b) top view of the frames.

a demonstrator, built using off-the-shelf components, WALKIE 6 was designed to comply with ESA specifications for Micro-Robots for Scientific Applications (Micro-RoSA), with particular regard to a Mars exploration mission - RoSA/M [3].

The chosen architecture is based on two rigid frames, each one carrying a set of three legs, able to move in longitudinal direction and rotate with respect to each other. Twin frame walking machines are described in the literature (e.g. [4]) with reference to octopod robots, using an alternate tetrapod gait. WALKIE 6 is on the contrary an hexapod and uses an alternate tripod gait.

The rover has exceeded the stated specifications, particularly for what the speed (about 20 m/h), the power consumption (less than 2.5 W at top speed on the surface of the Earth, but about 0.8 W at reduced speed) and the ability to walk autonomously on rough ground and avoiding obstacles.

The chosen configuration assures a complete mechanical uncoupling between the horizontal and vertical displacements of the feet and the generation of exact feet trajectories in all walking conditions; a feature which reduces the required power and the stressing of the mechanical components when walking on rough terrain. As the actuators are all nonreversible, no energy is consumed during the stance phase.

The main disadvantage, i.e. the frequent acceleration and deceleration of the vehicle body, is important only at high speed: this architecture is suitable only for slow vehicles. However a quick order-of-magnitute check shows that in the case of WALKIE 6 the energy needed to accelerate the electric motors is far greater than that needed to accelerate the reciprocating parts: an accurate choice of the mechanical components can allow to increase the overall efficiency of the machine. The possibility of recovering some of the kinetic energy is also an important issue.

The aim of the present paper is to study in detail the energetic aspects of twin-frames walking machines to assess the possibility of increasing their speed performances while reducing the power consumption.

ENERGETIC REQUIREMENTS

Consider the walking machine sketched in Figure 1b. Frames A and B are supplied with three screw actuators each (actuators 1-6), a longitudinal actuator (7) and another screw actuator (8) for the rotation of the frames. The upper frame B carries all power and control subsystems and the payload. The robot has a total of just eight degrees of freedom.

All actuators are composed by an electric motor (moment of inertia J_m, efficiency η_m, nominal speed ω_m), a transmission (moment of inertia J_t, which includes also that of the screw, efficiency η_t, gear ratio τ) and a screw (pitch p, efficiency η_s). The masses of the two frames, including the mass of the legs, are m_A and m_B, while the mass of the moving part each leg is m_l.

The rover can move either in horizontal direction of one complete step, or in vertical direction. No simultaneous motion in the two direction is considered. Also rotational motion to change the direction is considered uncoupled.

Vertical motion

The speed and the power needed for vertical motion under the action of the three actuators of one of the frames are

$$V_v = \omega_{m_1} \frac{\tau_1 p_1}{2\pi} , \tag{1}$$

$$\overline{P}_v = \frac{1}{\eta_{m1}\eta_{t1}} \left[\frac{m_{ev} V_z^3}{h_v} + \frac{(m_A + m_B - 3m_l) g V_z}{\eta_s} \right] , \tag{2}$$

where h_v is the vertical travel and the equivalent mass m_{ev} is

$$m_{ev} = 12\pi^2 \left(\frac{J_{m1}\eta_{t1}}{(\tau_1 p_1)^2} + \frac{J_{t1}}{p_1^2} \right) + \frac{m_A + m_B - 3m_l}{\eta_{s1}} .$$

Subscript 1 refers to the actuator of the first leg (all legs are assumed to be equal). The inclusion of the efficiency of the transmission and of the screw in the equivalent mass is consistent with a common practice in motor vehicle dynamics [5] but compels to change the definition of the equivalent mass when the power flow is reversed, as in the case of energy recovering.

Horizontal motion

A step can be divided into six phases: rising legs 1 to 3, moving frame A, lowering legs 1 to 3, rising legs 4 to 6, moving frame B, lowering legs 4 to 6. The average speed computed on a step, whose length is equal to the total travel of the frames d, is

$$\overline{V} = \frac{d V_z V_b}{4 h_z V_b + 2 d V_z} = \frac{V_b}{2(1+\alpha)} , \tag{3}$$

where V_z is the speed at which the foot is raised and lowered (equal to V_v (equation 1), if the leg motor runs at the same speed in vertical and horizontal motion), V_b is the relative speed of the frames (expressed by equation (1), with subscript 7 instead of 1), h_z is the height at which the foot is raised and nondimentional parameter α is

$$\alpha = 2 \frac{h_z}{d} \frac{V_b}{V_z} . \tag{4}$$

The average power for walking on a level surface is then

$$\overline{P}_h = \frac{4 m_{eav} \overline{V}^3 (1+\alpha)^2}{\eta_{m7}\eta_{t7} d} (1 + \beta + \gamma + \delta) , \tag{5}$$

where the average equivalent mass m_{eav} is equal to

$$m_{e7} = 4\pi^2 \left(\frac{J_{m7}\eta_{t7}}{(\tau_7 p_7)^2} + \frac{J_{t7}}{p_7^2} \right) + \frac{m_A + m_B}{2\eta_{s7}}$$

and

$$\beta = 6\frac{\eta_{m7}\eta_{t7}}{\eta_{m1}\eta_{t1}}\frac{m_{e1}}{m_{eav}}\left(\frac{V_z}{V_b}\right)^2 ,$$

$$\gamma = 6\frac{\eta_{m7}\eta_{t7}}{\eta_{m1}\eta_{t1}}\frac{m_l g h_z}{m_{eav}V_b^2}2\left(\frac{1}{\eta_{s1}}-1\right) \text{ for } \eta_{s1} \leq 0.5$$

$$\gamma = 6\frac{\eta_{m7}\eta_{t7}}{\eta_{m1}\eta_{t1}}\frac{m_l g h_z}{m_{eav}V_b^2}\left(\frac{1}{\eta_{s1}}\right) \text{ for } \eta_{s1} > 0.5$$

$$\delta = g(f_b + i)d\frac{m_A + m_B}{\eta_{s7}m_{eav}V_b^2} ,$$

f_b is the friction coeffcient in the relative motion of the frames and i is the inclination of the guide, which can be nonzero owing to the dead-band of the horizontality control. The equivalent mass m_{e1} is equal to m_{e7} with subcript 1 instead of 7 and m_l instead of $(m_A+m_B)/2$.

Parameters α, β, γ and δ have an immediate meaning: the first one is linked with the time taken by the raising and lowering of the legs, the second with the inertia of the leg actuators, the third one with the energy dissipations in the leg and the last one with the energy dissipations in the motion of the frames. The two different values of γ take into account the possibility of using reversible actuators with brakes. In the ideal case (no friction and negligible traslational inertia) their values are $\gamma \simeq 0$, $\delta = 0$ and $\beta \approx 6$ and the following expression for the average power holds

$$\overline{P_h} = \frac{28 J_m \overline{V}^3 (1+\alpha)^2}{d}\left(\frac{2\pi}{\tau p}\right)^2 . \qquad (6)$$

WALKIE 6 ENERGY TRADEOFF

The main reference data for the WALKIE 6 rover walking on the Earth surface are:

J_m	$=1 \times 10^{-7}$ kg m^2	η_m	$= 0.495$
ω_m	$= 16{,}275$ rpm	τ	$= 1/12.667$
J_t	$=3.5 \times 10^{-8}$ kg m^2	η_t	$= 0.8$
p	$= 0.7$ mm	m_l	$= 0.015$ kg
η_s	$= 0.17$	m_A	$= 0.72$ kg
m_B	$= 3.125$ kg	f_b	$= 0.27$
d	$= 80$ mm	i	$= 0$

All actuators are equal. As $V_z = V_b = 15$ mm/s, assuming that the feet are raised of 10 mm, $\alpha = 0.25$ and the average walking speed is $\overline{V} = 6$ mm/s $= 21.6$ m/h. The power needed to walk on level ground in ideal conditions (equation 6) is $\overline{P} = 0.152$ W. Taking into account the inertia of all the parts of the machine (equation 5), the value of the average power is only slightly higher: $\overline{P} = 0.153$ W.

Taking into account the efficiencies of the various components and the friction, $\beta = 5.937$, $\gamma = 0.366$ and $\delta = 20.325$ and the average power increases to $\overline{P} = 1.232$ W: more than 3/4 of the power required for motion is due to the losses and that there is not a large advantage in recovering the kinetic energy of the motors, which can be accomplished at the expense of added control complexities: even if more than 50% of the kinetic energy of the motors could be recovered, an energy saving lower than about 15% would result.

Another obvious consideration is the low importance of the losses in the leg actuators (low γ) while most of the inefficencies are to be ascribed to the frame screw and guide (high δ).

Note that the overall energy efficiency of the vehicle is very low: although its meaning is at best dubious in this context, the value of parameter P/mgV is 5.44 (0.67 if no losses are accounted for). This value is very high for a slow vehicle, comparable to that of a supersonic fighter plane (about 1.5). A natural walker, as a horse, has a value of about 0.015 at 10 km/h [5].

The average power needed for vertical motion can be easily computed. By assuming a total vertical travel $h_v = 100$ mm, the value $\overline{P}_v = 8.57$ W is obtained. Note that the power needed to raise the load at the required speed is, neglecting inertial effects, of 0.56 W neglecting power losses and 8.3 W taking them into account.

SECOND APPROXIMATION MODEL

The model described in the previous sections has the advantage of not being restricted to any particular type of actuator, being so applicable to a wide variety of actual design choices. However, the lack of a detailed description of the actual configuration prevents from attaining good quantitative predictions. In particular, the energy losses of the electric motors are badly modeled by introducing a constant efficiency and the lack of a torque-speed chatacteristic doesn't allow to compute the actual motor speed. Without entering the complexities of modelling accurately friction, it is possible to introduce the model for the DC electric motors described in [6] and reported in Figure 2.

The model, which although neglecting the voltage drop in the brushes is considered as a quite realistic one, yields linear torque-speed and current-speed characteristics:

$$M = M_1 - K_m\omega \qquad ; \qquad I = I_1 - \frac{(I_1 - I_0)}{\omega_0}\omega , \quad (7)$$

where $M_1 = V(I_1 - I_0)/\omega_0$ and I_1 are the starting torque and current, $K_m = M_1/\omega_0$ is the mechanical constant and I_0 and ω_0 are the no-load current and speed. The motors are controlled by a simple

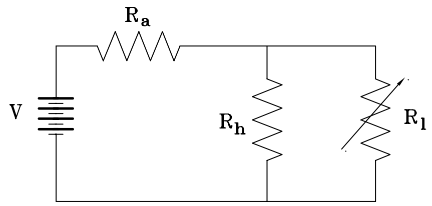

FIGURE 2: Electric circuit used to model a DC electric motor. R_a: resistance modelling Joule losses; R_h: resistance modelling mechanical and windage losses; R_l: variable resistance modelling the back electromotive force.

on-off controller and the applied voltage V can be considered constant.

The speed-time curve in each powered phase can be easily computed

$$\omega = \frac{M_1 - M_r}{K_m}\left(1 - e^{-\frac{K_m}{J_e}t}\right) , \qquad (8)$$

where M_r and J_e are the resisting torque (due to friction and the work performed by the motor) and the equivalent moment of inertia.

The steady state speed reached under a constant load M_r is $\omega_r = (M_1 - M_r)/K_m$ and the time t_1 needed for the actuator to elongate of the distance d can be easily computed from the equation

$$d\frac{2\pi}{\tau p} = \omega_r\left[t_1 - \frac{J_e}{K_m}\left(1 - e^{-\frac{K_m}{J_e}t_1}\right)\right] , \qquad (9)$$

which can be easily solved numerically, i.e. using the Newton-Raphson procedure. It has been obtained assuming that the motor stops istantaneously.

The energy the motor uses to move the actuator through distance d is then

$$E = V\left(I_1 t_1 - d\frac{2\pi}{\tau p}\,\frac{I_1 - I_0}{\omega_0}\right) . \qquad (10)$$

A mathematical model based on the above mentioned relationships has been built. Assuming that $\omega_0 = 21,600$ rpm, $I_1 = 0.560$ A, $I_0 = 0.061$ A $V = 6$ V, the speed for horizontal walking on the Earth and the power consumption are respectively $\overline{V} = 5.4$ mm/s $= 19.6$ m/h. (21.6 m/h for the previous model) and $\overline{P} = 1.752$ W (1.232 W). As expected, the simplified model evaluates accurately the speed, while understimating the power.

By assuming a vertical travel $h_v = 100$ mm, the average speed and power in vertical motion are $\overline{V}_v = 9.57$ mm/s and $\overline{P}_v = 5.85$ W.

To compute the performances of the rover on uneven ground it is possible to state various values of the height h_z the feet are raised. Similarily walking on a slope can be considered as the combination of

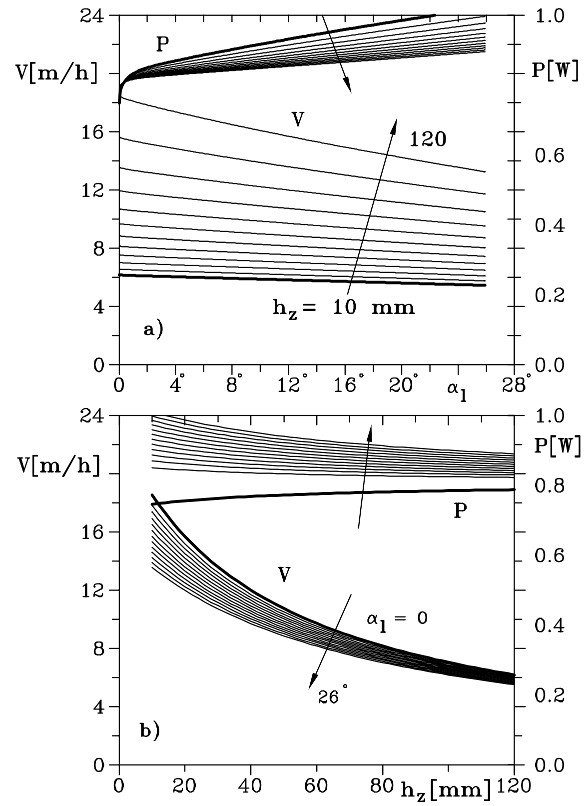

FIGURE 3: Speed and power required for walking on a grade and on uneven road. (a) Speed and power as a function of the longitudinal slope α_l. (b) Speed and power as a function of h_z.

horizontal and vertical motions. The performance of Walkie 6 on a grade and on uneven ground is reported in Figure 3.

The horizontal component of the walking speed and the power required for motion are reported as functions of the longitudinal slope in Figure 3a. The curves are related to values of h_z between 10 mm and 120 mm. The speed and power are also reported as a function of h_z in Figure 3b, for $0 < \alpha_l < 26°$.

The speed reduces both with the slope and the uneveness of the ground, while the power increases with increasing slope but decreases with the ground irregularities when walking on a grade (on level ground it increases with h_z as it could be expected): the power is an average of the power needed to perform a complete step and the increase of the step time is greater than that of the energy needed for walking. Different results would have been obtained if the comparison had been made keeping the speed constant.

Note also that the control system of Walkie 6 is unable to control the speed, as the motor are controlled just by on-off switches. To slow down the rover stopping phases can be inserted in each step.

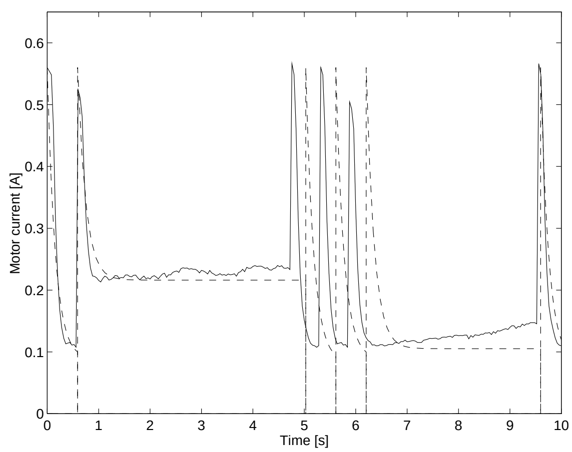

FIGURE 4: Motor currents as functions of time during a step. Measured (full lines) and computed (dashed lines) values.

VALIDATION OF THE MODEL

The currents in the motors used in straight walking were recorded as functions of time with the machine walking on level ground (Figure 4, full lines). The characteristics of the electric motors were then measured accurately, taking into account also the no-load drag torque due to the bearings on the screw and the gear wheels, and the motion was simulated using the mathematical model reported above (results reported in Figure 4, dashed lines). The overall results are the following

	Speed[m/h]	Power[W]	Step time[s]
Exper.	17.8	2.12	10.1
Numer.	17.7	2.01	10.1

From the figure it is possible to state that the overall pattern of the numerical results is very similar to that obtained during the tests, the main differences being a more irregular behaviour during phases 2 and 5 and a not exact timing of the various phases. The first feature is due to the irregular friction in the sliders linking the frames; the increase of current in phase 5 can be due to misalignement of the giudes. The second one is linked to the very control logic used: the motors are stopped when the currents in the motors raise above a threshold, as a symptom that the legs have touched the ground or the frames have reached the end of the travel. The uncertainities of both these mechanisms are intrinsic and cannot be avoided, if not with radical changes of the mechanical architecture or the control logic.

The mathematical model is therefore adequate to model the actual system, even if in a somewhat idealized form.

UPGRADING WALKIE 6

The aim of WALKIE 6 was to perform a proof of principle and no attempt to optimize its performances has been made. The areas in which improvements can be easily performed are mainly two: the inertial characteristics of the electric motors and the effciency of the components, mainly of the screws, but also of the guides and the motors. Just using coreless motors allows to reduce the energy spent for accelerating all moving parts. Even larger improvements can be expected by using ball screws and ball linear bearings in the guides. A reduction of f_b and an increase of η_s will result, keeping however in mind that very high efficiencies cannot be reached if non-reversible actuators are used. It is clear that a better efficiency can be reached using reversible actuators, but this compels to use brakes or self-braking motors, which increase the complexity of the system and contraddicts the design phylosophy on which Walkie 6 is based.

The original design was based on eight equal actuators, designed keeping in mind the most demanding requirement, i.e. vertical motion. The walking speed can thus be increased simply by increasing the pitch of the horizontal screw, or changing the transmission ratio between the motor and the screw. The power needed for walking on level road and for vertical motion as a function of the walking speed is reported in Figure 5a and b, curves 1. The power for vertical motion remains constant, as it is unaffected by the pitch of the screw of actuator 7, while that need for walking on level road increases almost linearily and then more rapidly when the motor of the actuator is required to supply too much power. While small improvements can be obtained in this way, to increase substantially the speed deeper changes are needed.

In curves 2 the efficiency of the screws is raised from 0.17 to 0.45, while the friction of the guides is reduced from 0.27 to 0.1. The power is substantially reduced and the walking speed can be substantially increased.

Curves 3 have been obtained by increasing the pitch of all screw actuators, while keeping the same values of the efficiency as in the case of curves 2. The maximum achievable speed, but the power needed for vertical movements becomes unacceptable. This way of increasing the performances can however be acceptable in case of low gravity environments: curves 4 are referred to a gravitational acceleration equal to 50% of the one on the Earth (about the same as on Mars surface) while curves 5 to a gravitational acceleration equal to 15% of the one on the Earth (about the same as on the Moon). Curves 6 have been computed neglecting the gravitational acceleration, as it is the case of an asteroid or a comet nucleus. In this

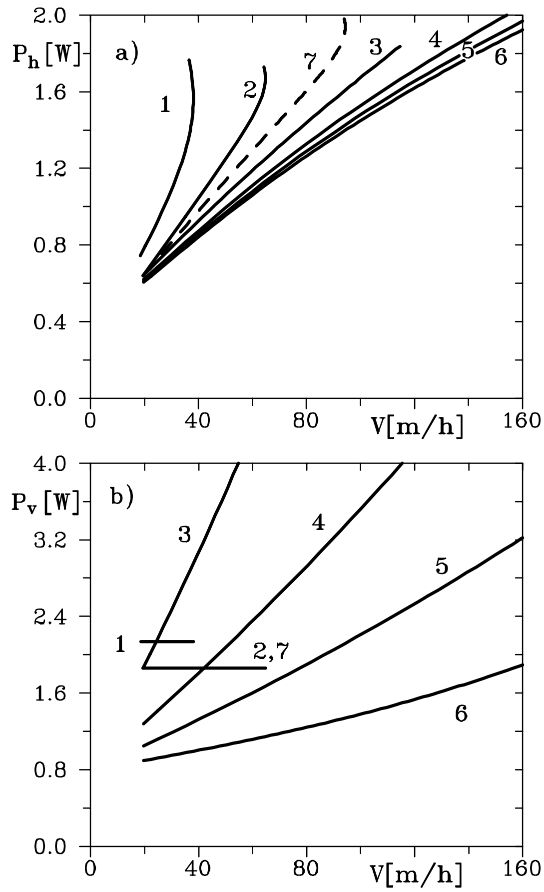

FIGURE 5: Power needed for walking on level road (a) and for vertical motion (b) as a function of the walking speed.

case the power needed for vertical motion is due to the need of accelerating vertically the mass of the vehicle.

One of the limitations of the layout here considered is the need for the leg actuators to be able to move the vehicle vertically while having to raise the feet in horizontal walking: these two radically differents modes actually require different transmission ratio and/or different motors. The two frames can be different from each other: one of them carries three legs with a shorter transmission ratio (or screw pitch), used to perform the vertical motion, while the other has three legs with the same transmission ratio of the body actuator. This strategy has been used to plot the dotted curve in Figure 5a (curve 7). The horizontal performaces are better than those of curve 2, while the vertical ones are the same (curves 2 and 7 are superimposed in Figure 5b). The disadvantage is a lower flexibility, as only one of the two frames can be used for raising the body.

More radical changes are needed to further improve WALKIE 6 performances, as increasing its length (the power needed for level walking decreases while increasing the travel d, even if less that the dependance on $1/d$ as equation 6 seems to suggest), using more efficient motors and actuators or more elaborate motor control laws.

CONCLUSIONS

The models here described for robots based on two rigid frames with three legs each has proven to be able to predict their performances. The simpler one allows to perform qualitative evaluations of the influence of the variour design paramters, while the second allows to obtain quantitative evaluations regarding the power needed for horizontal and vertical motion at different speeds. It can be easily modified to include different types of electric motors and more elaborate motor control strategies.

The simulations performed allow to predict the possibility of increasing the performance of WALKIE 6 to a field of velocities higher than those initially assumed for this type of planetary rovers.

It must be however kept in mind that the main advantage of twin rigid frames rovers is their very simple mechanical and control layouts and that design changes aimed to increase their performances should not compromise too much on this issue.

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