Non Zoomorphic Rigid Frame Walking Micro-Rover for Uneven Ground: from a Demonstrator to an Engineering Prototype

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Keywords: Walking machines, microrover, planetary exploration

Abstract WALKIE 6 is a demonstrator of an hexapod walking microrover for exploration , based on the twin rigid-frames layout. WALKIE 6 proved to be one of the few walking machines able to move on uneven ground without the need of frequent repairs and maintenance, while not requiring an umbilical cord neither for power nor for control. The advantages of this type of machines when used as microrovers, particularly in the case of planets with a gravity lower than that of the Earth end even in very low gravity conditions have been described in several papers.

The configuration of WALKIE 6 allows to both scale up or down the machine to adapt it to different types of missions and to different payloads. Different versions have been designed, built and thoroughly tested in the last 4 years. The present paper describes the improvements of the mechanics and electronics introduced in order to build an engineering model.

1. Introduction

The number of configurations which have been proposed in the past for rovers and microrovers, to perform multiple tasks on uneven grounds, is large and include wheeled and tracked vehicles, walking machines of different types, hopping devices and many moving object of unconventional (and in some cases quite strange) configuration [1 - 11]. Each one of them has peculiar advantages and disadvantages, which must be carefully balanced when choosing the configuration of a particular machine for any given mission. The result of this trade-off has been in the past quite unequivocal: except very few cases, wheeled vehicles have always been chosen.

The choice of wheeled rovers, in spite of the advantages of other solutions mainly for what the ability of moving on uneven ground and managing obstacles is concerned, is justified by a number of reasons. Perhaps the main one is the fact that wheeled vehicles have a tradition that cannot be matched by other configurations and this means that the designer can base his choices on a well consolidated technology, without the need of resorting to simulations, experimental tests and other studies which slow the design process and increase the cost. Even if proposed in the past [19], tracked vehicles are often ruled out by energetic consideration and other reasons which are beyond the scope of the present paper. But wheeled vehicles are chosen not only for a consolidated design practice: legged vehicles are usually highly stressed, have reciprocating parts which undergo to a high number of fatigue cycles, require complex control systems and in some case have a higher energy consumption in actual working, in spite of a greater theoretical efficiency. Other unconventional layouts suffer from the same problems in an even higher degree.

However the difficulties encountered in achieving high speeds is usually of no concern in many applications as in planetary exploration, underwater and archaeological survey and humanitarian deminig The velocity is strongly limited by other considerations, mainly strict limitations to the available power and the impossibility of having a human in the control loop. More simplified layouts, as the twin-rigid frames solution here presented, can be adopted in such applications. In the present paper a slaw small-size demonstrator of a walking rover for planetary exploration, and the improvements of the mechanics and electronics introduced to build an engineering model, are described. The configuration allows to both scale up or down the machine to adapt it to different types of missions and to different payloads.

2. Twin rigid-frames walking machines

Most multi-legged, walking machines are based on zoomorphic configurations, which try to match the very high performances of living beings. However this approach has never proven to be really successful and may well be a losing strategy when dealing with planetary rovers. One of the reasons is without any doubt the lack of materials with performances matching those of biological materials: it is enough to think to the way in which the structure of bones optimises the material geometry and properties and to the properties of muscles, which have no matching mechanical actuators supplying high forces with low strokes without the need of bulky and costly ancillary equipment.

The control of zoomorphic walking machines is much demanding. Generally speaking, the minimum number of degrees of freedom is 3 times the number of legs (18 degrees of freedom for a hexapod machine and 12 for a quadruped) to achieve a correct kinematic working, but legged animals have a much larger number of degrees of freedom. The actuators must be coordinated and the control system must insure that the legs follow well determined trajectories with a good precision. Even if the precision required is lower than that typical of industrial robots, the larger number of degrees of freedom and the higher speed (it would be useless to adopt a zoomorphic configuration and then walk at a speed achievable also by simpler layouts) makes the control task much more complicated than what is typical in robotics. Also from this viewpoint, even the simplest animal brain can perform tasks which go well beyond those we can entrust to artificial control systems.

But it is not just a matter of materials and control: natural walking machines have a reliability which is unacceptably low for artificial machinery and particularly machines which must operate without the possibility of repair and maintenance. All organisms shaped by evolution are expendable, since what matters is the species and not the individual, and hence reliability is a secondary factor. To this the possibility of self-repair of biological materials must be added: bones and muscles remodel and repair themselves in a way which is impossible for the materials used in machines. These considerations explain why the very high stressing encountered in walking machines may be acceptable in animals and unacceptable in artificial walkers.

It is true that rovers used in low gravity environments may circumvent structural and actuator problems thanks to the low loads induced by gravity, but at present it is difficult to exploit this advantage: it may well be possible to build a zoomorphic walking machine suitable to work on Mars or, even better, on an asteroid, but it would be very difficult to test it before it reaches its destination: all means we can think to compensate for gravity will do so only partially and will introduce difficulties in performing significant tests.

The above mentioned reasons suggest to use non-zoomorphic, highly simplified layouts for multi-legged walking machines. Twin rigid-frames machines proved to be simpler and solved some problems related to mechanical reliability, control system complexity and autonomous working, at the cost of reducing the performances mainly for what the maximum speed is concerned. Their layout is based on two frames (A and B in figure 1) which can move with respect to each other following a translation in a single direction (taken as longitudinal direction of the machine, x-axis in figure 1a) and rotate about a common axis located in vertical direction.

Each frame may have any number of supports (legs); since the two frames need not to have the same number of legs the machine may have an odd number of legs. To achieve static stability in all phases of walking, each frame must have at least 3 legs. Each support has a single degree of freedom, namely vertical translation. In this way, if the frames are kept horizontal, the motion of the feet with respect to the body are always kinematically correct and horizontal and vertical motions are completely uncoupled.

Each step (forward or backward) is performed in 6 phases:

1. rising the feet of the legs of frame B;
2. moving forward frame B, with the legs of frame A supporting the vehicle (figure 1b);
3. lowering the feet of legs of frame B until each one touches the ground;
4. rising the feet of legs of frame A;
5. moving forward frame A with the legs of frame B supporting the vehicle (figure 1c);
6. lowering the feet of legs of frame A.

To steer the machine performs a step in which the frames rotate with respect to each other instead of moving in longitudinal direction during the phases 2 and 5.

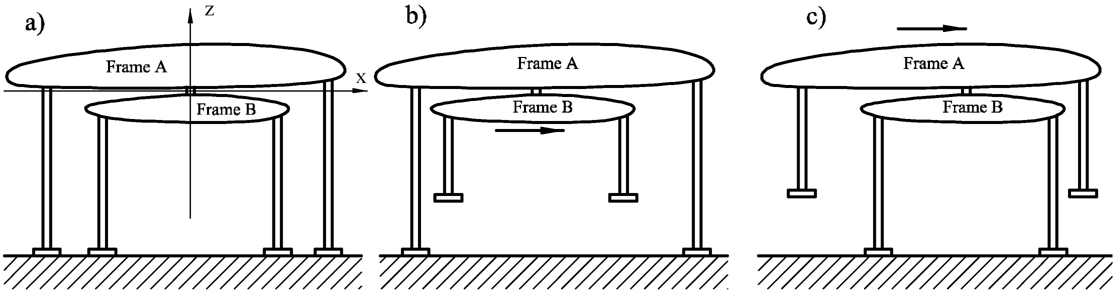

Fig. 1. a): Scheme of a twin rigid-frames walking machine; b): Phase 2 of a step – motion of frame B; c): Phase 5 of a step – motion of frame A.

To follow the above mentioned sequence each actuator need not to be controlled in velocity or to be accurately synchronised: a simple on-off controller is adequate. Each leg actuator needs only a touch sensor, to check when the corresponding foot touches the ground and possibly a position sensor, in such a way the controller knows at any instant the configuration of the machine. The actuators which move the body (longitudinal translation and rotation about the vertical axis) need just a touch sensor and possibly a position sensor. In this way the machine realises when it touches and obstacle. In case electric actuators are used, monitoring the actuation currents has proven to be an effective way for detecting when the feet or the body touch against an obstacle, at least in Earth's gravity. In very low gravity this may be not sufficient, and other types of touch sensors are more suitable.

The operational mode described above has the disadvantage of requiring a start-stop cycle for each frame at each step. This is of little inconvenience in slow walking, but is a limiting factor in higher speeds are required.

The total number of degrees of freedom of a machine of this type is $2+n_A+n_B$, where n_A and n_B are the number of legs respectively of frames A and B: the minimum number of degrees of freedom is then equal to 8, for a machine with 6 legs. Some proposals to reduce the number of degrees of freedom to 4, by operating all the legs of each frame using a single actuator, have been forwarded [6]. This solution may be used only in case of walking on perfectly flat and smooth terrain, and hence is of no use in practical applications (there is no interest in walking machines for operation on very smooth terrain, where wheels are at their best). Such a solution doesn't even allow to keep the body horizontal while walking on a slope.

The first examples of successful rigid-frames walking machines are the RECUS (remote controlled underwater surveyor) built by Komatsu [4] and the Walking Beam built by NASA [5]. The first machine is a very heavy and slow octopod, which has been used for underwater civil engineering works. The second one is an eptapod, designed by Martin Marietta for Mars exploration. The project has been developed to build a prototype and then abandoned. More recently, the authors built several versions of a demonstrator of a microrover for planetary exploration based of the twin-frames hexapod configuration, initially designated as Algen [1] and then WALKIE 6 [2]. The results obtained by the above mentioned models point out that rigid-frames layouts can operate with high pressure condition or in low gravity environment. Small (Walkie 6), medium (Walking Beam) or very large configurations (ReCuS) have shown to have a good functionality if no high velocity is required. Performances, and mainly the walking speed, depend on the size more than zoomophic ore wheeled solutions.

2.1 Walkie 6 microrover

The experience accumulated in the design of several versions of WALKIE 6 and their operation for prolonged periods of time did show that this approach can lead to overcome the reliability problems, while at the same time reducing the control complexity and not penalising too much performances. Actually WALKIE 6.2 is one of the few walking machines able to perform autonomously (the power and the control systems are completely on board and needs no umbilical cord) for very long times without maintenance. Its low power requirements (less than 3 W at 52 m/h) remain unmatched.

At present a new version, WALKIE 6.3, is being developed. Its size is still in the microrover range, but several improvements will allow to reach a speed of about 120 m/h. Larger twin-frames machines can walk faster than that and, while this configuration will always be limited to low speeds, it is uncertain what is the maximum achievable walking speed. Only experiments with larger rovers will allow to answer this question.

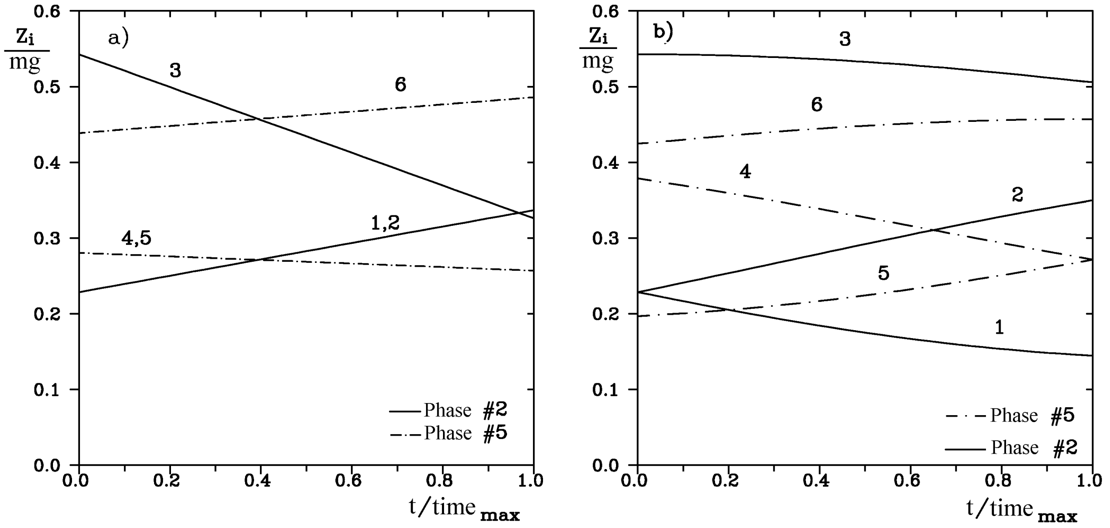

Fig. 2. WALKIE 6.1: ratio between the forces on the ground Z_i and the weight *mg* during a longitudinal step and a rotation (legs 1, 2, 3 belong to frame A, legs 4, 5, 6 belong to frame B).

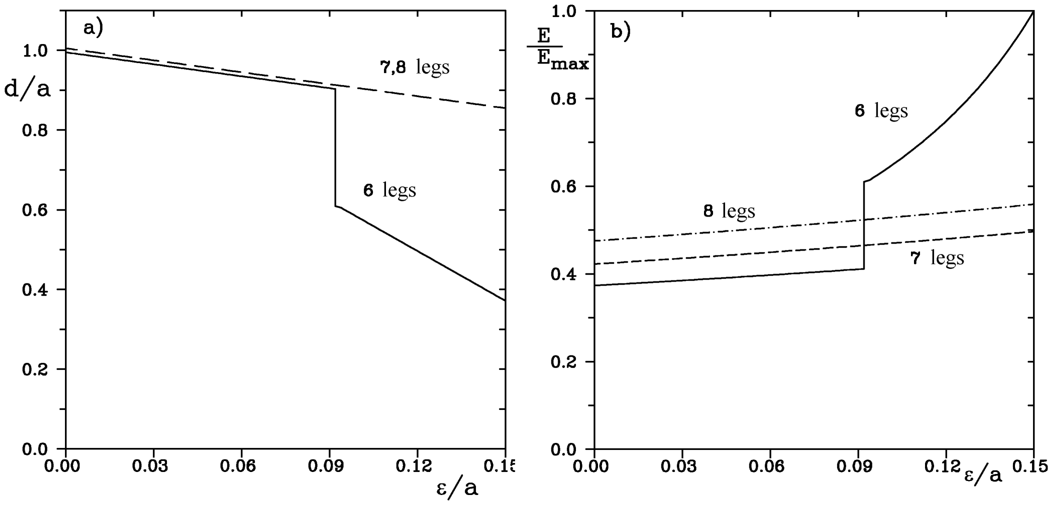

Fig. 3. WALKIE 6.1: Ratio between the maximum travel *d* and the "legbase" of the machine *a* (a) and ratio between the energy required for walking and power needed for motion in actual conditions and the value achievable using a travel equal to *a* (b) as functions of the uncertainty of the position of the centre of mass.

An important issue for all walking machines is the safety against overturning, particularly when overcoming high obstacles or climbing steep slopes. Rigid frames machines have a definite advantage also from this viewpoint over other types of walking machines, due to the fact that the body can be maintained in a horizontal position. Safety against overturning is assured, provided that the load is suitably distributed on the various legs. In the case of hexapod machines, the limit condition is reached when the vertical load on a leg reduces to zero; if more legs are used, the load distribution is normally statically indeterminate and it is possible to allow that in certain conditions some legs do not support any load. A plot of the forces on the ground during a forward step and a rotation for the WALKIE 6.1 machine are reported in figure 2 [14]. During forward motion, the minimum load on the legs is never less than 22% of the weight of the machine, showing a very good stability. This is also due to the low forward travel of WALKIE 6.1, which has the drawback of limiting its speed.

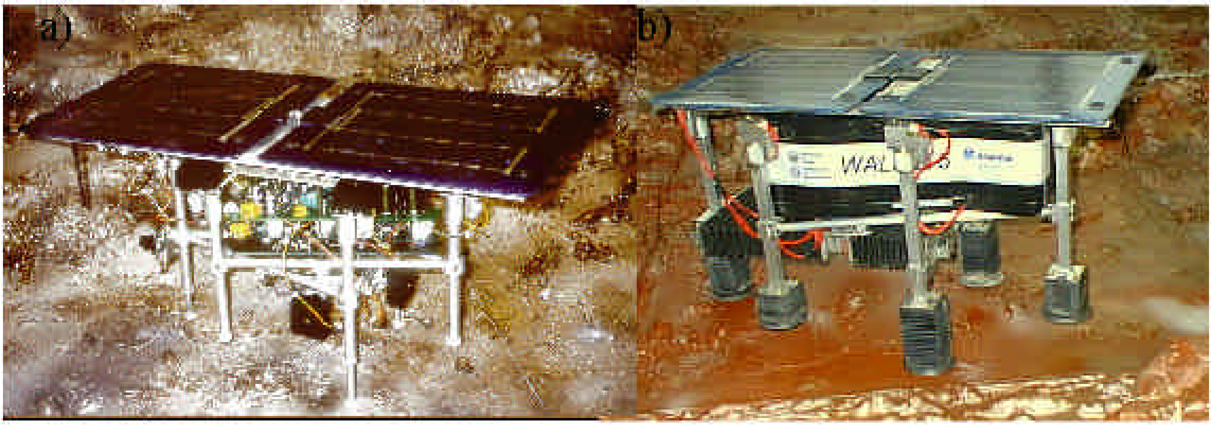

Fig. 4. Pictures of Walkie 6.0 (a) and Walkie 6.1 (b) while walking on a test surface.

By increasing the travel, the speed can be increased and the energy consumption lowered, but this increases the danger of overturning: it is possible to design a strategy in which the whole travel is used only on smooth ground, when the vehicle rides more close to the ground, while on rough terrain, when the danger of overturning increases, is reduced.

In this respect it may be convenient to increase the number of legs and, particularly in the case in which the two frames have different mass, it can be expedient to use a different number of legs (the lighter frame having more). Note that in the case of the Walking Beam it was the frame with the payload (the heavier) which had 4 legs, a solution which doesn't help stability. The ratio between the maximum travel *d* and the "legbase" of the machine *a* is reported as a function of the ratio between the uncertainty of the position of the centre of mass *e* and *a* in figure 3a [14], obtained using the data of WALKIE 6.1. It is clear that if the uncertainties on the position of the centre of mass are large, the use of 7 or 8 legs allows to increase the travel, and hence increase the speed and reduce the energy consumption (figure 3b). The main characteristics and the performances of the three prototypes built and extensively tested are reported in Table 1. The difference between 6.0 and 6.1 version is the use on the latter of a ball screw and ball linear guides instead of a regular screw and teflon bushes for the longitudinal motion of the frames. The higher efficiency and the longer pitch of the screw (1 mm instead of 0.7 mm) allows to increase the speed while reducing the power consumption. Version 6.2 is larger than the previous ones, and in particular has a far longer travel of one frame with respect to the other. In this way it was possible to increase the speed, while reducing the power consumption. Also the drive used for the rotation of the frames was completely changed. All linear actuators are protected by bellows which prevent dust from entering into the delicate parts of the machine. Pictures of the WALKIE 6.0 and WALKIE 6.2 versions are shown in figure 4a and b.

The basic information the robot receives from the environment are tactile ones. Monitoring motor currents has proven to be a satisfactory means to detect both foot contact on the ground and body contact against obstacles. Contact detection by measuring motor currents is complemented by measuring the position of the feet with respect to the frames and of the frames with respect to each other, by means of optical encoders on the actuator screws. Four quicksilver switches provide on-off information on the horizontality of the vehicle body. This solution, dictated mainly by the need of reducing costs, proved to be weakest point of the whole sensors-controller subsystem, as the reaction to attitude changes is not very prompt and the precision with which the horizontality of the body is ensured is not very good.

Version	6.0	6.1	6.2	6.3
Size (LxWxH) [mm]	300×200×200		430×300×260	500×400×300
Max. horizontal speed [m/h]	17.8	29.5	52.9	(124.7)
Walking power [W]	2.01	1.19	1.15	(3.2)
Vert. Obstacle clearance [mm]	120		164	(260)
Max. longitudinal slope	16° at 6.5 m/h 19° at 2.2 m/h	16° at 7.4 m/h 19° at 2.3 m/h	14° at 8.3 m/h 19° at 1.8 m/h	(14° at 64 m/h) (19° at 49 m/h)
Max. lateral	29°		27°	36°
Step length [mm]	80		180	250
Rotation speed at 0 m/	360°/min		2,520°/min	
Max. crevice length [mm]	70		160	(230)
Mass + max. payload [kg]	3+6		4+8	4.5+10
Volume for payload [mm]	250×160×100 (trian.)		300×230×130	400×300×200
Motor type	Standard DC			Brushless
Vert. Screws pitch [mm]	0.7	0,7	1	1.5
Hor. Screw pitch [mm]	0.7	1	2	2
Power (solar panels) [W]	5			
Solar panels [dm^2]	12.5 on top			
Telecommand [Kb/s]	0.1			
Telemetry [Kb/s]	0.5			
Camera	512×512 B/W			512×512 Colour
Camera frame rate	50 frames/s			
Images transfer rate [Mb/s]	30			
Obstacle avoidance strategy	Yes			
Inclinometers	On-Off Hg switches			Accelerometers
Incl. Accuracy at standstill	±10°			±2°
Main processor	68HC11 8Mhz			8051/8055
FPGA	2 x MAX7128 (ALTERA)			1 x FLEX 10 k
Memory [Kb]	64 NVRAM			128 NVRAM
Memory mass storage [Kb]	10			128
Sensors	8 optical incr. Encoders + 8 motor current meters +			
	2 Hg switches			2 accelerometers sensors on feet

Table 1: Main characteristics of the three versions of WALKIE 6 already built and of the one under construction. The figures in brackets for WALKIE 6.3 have been obtained through numerical simulation.

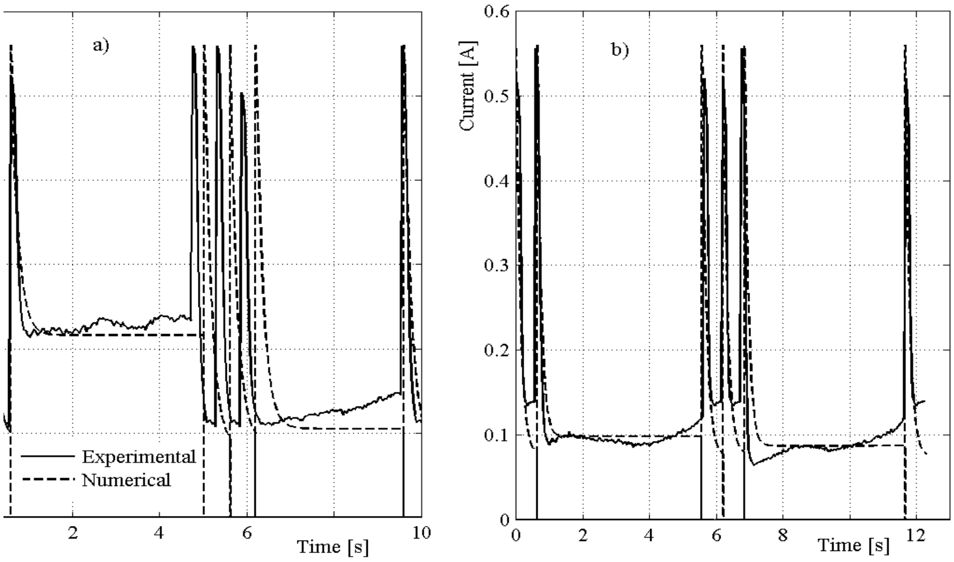

Fig. 5: Time history of the motor currents during a step performed in six phases. (a) Version 6.0; (b) Version 6.2.

Fig. 6: Test bench used to perform tests in vacuum; a) vacuum pump, b) Walkie 6.2 in the vacuum camera.

The rover is provided with two radio links and a black and white microcamera. The first unidirectional, high bandwidth radio link is used to transmit video images at full rate; the second one, bidirectional, with lower bandwidth, to exchange telemetry and telecommands between the rover and the ground station. The human operator on the ground may use the visual information from the camera to supply navigation and payload commands to the rover. The study of the control system has initially been focused on the simpler level and coordination functions, namely leg positioning and body movements but it then proved very successful also for obstacle avoidance. Therefore WALKIE 6 can autonomously walk on any type of terrain, passing over obstacles and managing slopes within the rover limits. On the other hand, obstacles higher than the intrinsic limit of the rover, canyons and too steep grades are automatically avoided, causing the rover to change direction when needed.

WALKIE 6 was tested on a very rough simulated planetary surface, which includes obstacles of different size and patches covered with a deep layer of ash (to simulate fine dust). The tests showed that the control algorithm used is successful in giving the rover the required autonomy. The rover is actually able to detect the contact of the feet with the ground and to maintain the body in horizontal position even when crossing the worst obstacles which are within its capabilities. When obstacles, which cannot be overcome are encountered, the rover retreats and changes its walking direction, going around the obstacle.

The experimental and numerical (obtained though a numerical simulator purposely built during the design stage) [13] time histories of the currents in the motors (figure 6) show that a good deal of power is used to accelerate the motors (the current peaks at the beginning of each phase) while the current then drops in steady-state working. The figure shows the large improvements obtained in version 6.2, in particular in reducing the energy consumption during the forward motion of the heaviest frame.

Experimental tests have been performed in Earth environment (pressure=1 bar, T=15 °C) and in vacuum at a pressure of $1.9*10^{-3}$ bar and atmosphere saturated with CO_2. This is a typical environment on Mars and figure 6 shows the vacuum camera used to perform the tests. The experimental results, reported in table 2, point out that the performances of the machine are not affected when it works in very different environment. The presence of carbon dioxide at low pressure ensures a good functionality of brush motors even if their life and reliability decrease drastically.

Test	Velocity [m/h]	Energy [J/m]	Power [W]	Time per step [s]
Numerical	30.7	152	1.29	21.12
Earth environment	30.54	156.7	1.33	21.22
In vacuum with CO_2	30.22	162.5	1.36	21.44

Table 2:Numerical and experimental results of Walkie 6.2 walking on flat surface in typical Earth and Mars environment. The rising and lowering of the legs h_z is 50 mm, the longitudinal travel d of the frames is 180 mm.

4 Walkie 6.3, characteristics of the engineering prototype

At present a new version, named 6.3, is under design and construction. The basic improvements are in new solutions of mechanical parts, in the use of brushless motors instead of standard DC motors and high efficiency non-reversible leg screws instead of normal screws, in a new electronics based on space qualifiable and programmable components, in the use of accelerometers instead of on-off Hg switches for detecting the attitude of the body.

While retaining the touch sensing based on the measuring of the currents in the motors, the new version has also touch sensors in the feet, based on a number of redundant switches able to detect when a foot starts carrying the load. The availability of this dual touch feeling systems allows also a certain redundancy and fault tolerance. The use of brushless motors, with their built in position sensors, allows also to dispense with separate encoders to detect the position of one part of the rover with respect of the other ones.

The standard screws used in the legs of the previous versions have been substituted by precision, teflon coated, screws which allows to increase the efficiency (η_{screw}=0.45) although maintaining non-reversible transmission and, thanks to a reduction of misalignments and play, to increase the travel, so improving the obstacle crossing performances. A set of legs has already been built and the computed reduction of the energy needed for moving the feet has been confirmed by the measurements. An increase of the size of the body, and a subsequent increase of the forward travel of the frames, allows to increase the walking speed to more than 100 m/h with a limited increase of the power required for walking, which remains at any rate at about 3 W. The rotating block was completely redesigned using a non-reversible vite senza fine and ruota elicoidale system which has shown to be more reliable than the previous solution based on a reversible transmission train to transfer the motion from the electric motor to the rotating shaft (the rotating and the motor shaft were both vertical).

The control system is based on a set of finite state automata, designed to control individual leg movements, coordination, gait, obstacle avoidance, and recovery from anomalies. Each state has a set of parameters that can be optimized by neural or fuzzy algorithms running on the on-board CPU while the finite state machine are implemented on hardware using programmable logic devices (FPGA). The prototype of this board is shown in figure 7 [16, 17]. Actually the fitness function implemented on the CPU can manage different goals like power consumption optimization, speed optimization or stability of the platform on rough terrain in order to guarantee the best condition for the payload.

The new version of the control platform (see figure 8) will support dynamical re-configuration of the FPGA device: the basic idea is to create a flexible architecture based on components such as DSP and FPGA. In this way is possible to "virtualize" both HW and SW resources allowing the control algorithms to store different configurations on non-volatile memories and use them only when really needed by the system [18].

Another result of this architecture is an increased fault tolerance of the entire control system: in fact is quite easy to repair a data error (caused for example by radiation or heavy ions) with the re-configuration of the "damaged" component.

The DSP chosen for the new architecture is a Texas TMS320C2407: this component is very interesting for this kind of application because it has several peripherals implemented directly on chip such as A/D converters, PWM drivers, etc. The two programmable logic devices present on the board (PLD SYS and PLD USR in figure 7) are two commercial ALTERA devices. The first one (PLD SYS) will take care of all the support functions of the system and will be a kind of co-processor of the DSP (address decoder, host interface, etc): this component is a EEPROM device (MAX7000 family).

The second FPGA (PLD USR) will be the hardware reconfigurable part of the control system. On this device will be downloaded all the different version of the control system and all the other hardware functionality needed by the system while the software optimization and all the “system supervisor” functions are performed by the DSP. The PLD USR is a RAM device (FLEX10K family). All the different configurations are stored in the FLASH memory and downloaded on the PLD USR through the PLD SYS.

Low-power strategies and components are also considered. All the system is designed to optimize power consumption using different solutions (clock optimization, stand-by of unused components, stand-by of the whole system under critical conditions, etc.).

Furthermore “design for testability” is an important concept: in fact most of the control systems designed for space applications are implemented using certified components. This means that the available components are 10-15 years old (technologically speaking). With this project we propose to use state-of-the-art components and to adopt a design for testability approach to easily test the whole equipment.

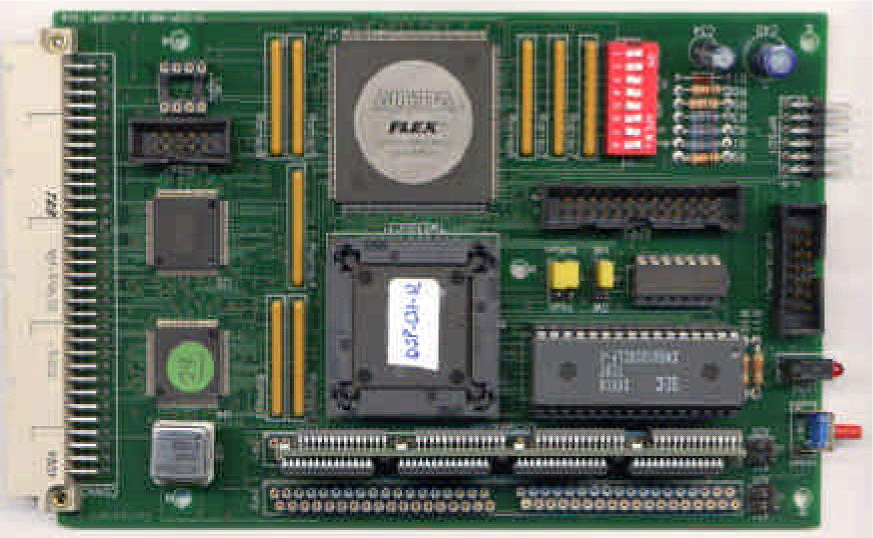

Fig.7 : the prototype board of the Walkie 6.3 control system.

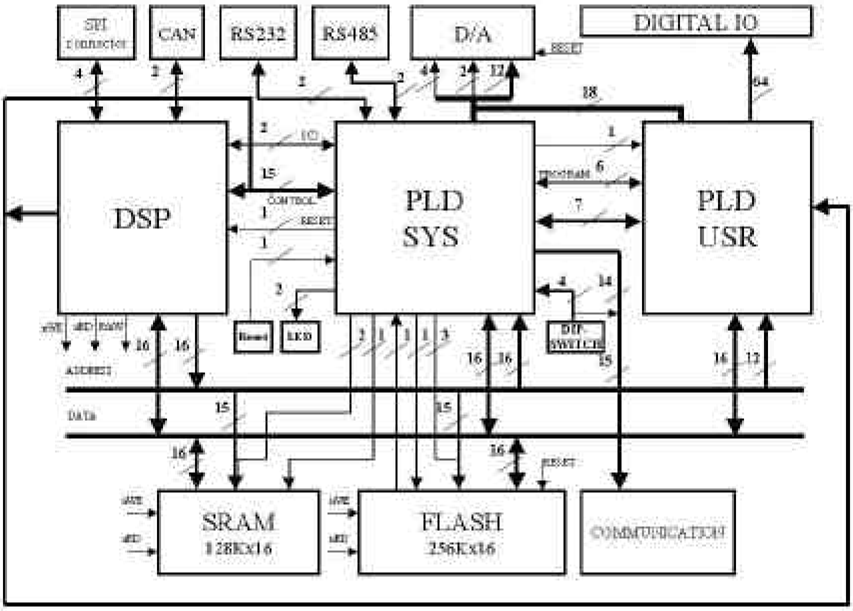

Fig. 8: DSP-FPGA based architecture for the reconfigurable control system

5 Conclusions

WALKIE 6, with its architecture based on two rigid frames with three legs each, proved to be very promising as rover to perform tasks on uneven grounds. Its advantages are mainly linked with the very low speed requirements, which make inertia forces negligible, but the capability of rovers of this type to achieve higher speed, needs further investigation. At any rate the walking speed obtained in the tests is higher than that of small wheeled and tracked rovers. The very simple layout and the absence of fast moving parts allow the use of a rover of this type also in very low gravity environments, as those encountered on asteroids and comets, where the danger of tipping over or even accidental lifting off due to inertia forces is great and in conditions with very high pressure, as those encountered during underwater operations. The simple strategies used to implement obstacle management and/or avoidance and semi-autonomous navigation proved to be very effective and the machine proved able to move on rough surfaces, simulating those which can be encountered in Moon or planetary exploration, with ease.

The new 6.3 version will use components (motors, electronics, mechanical components) suited to be used in space. Its performances, in terms of walking speed, low energy consumption and ability to manage very rough terrain have been improved, while retaining the basic characteristics of simple mechanical and control layout and high reliability.

Preliminary experimental results performed on the new legs confirm the expected improvements of the leg actuators.

1. References

[1] L.Bussolino, D. Del Corso, G. Genta, M.A. Perino, R.Somma, 1997, ALGEN - A Walking Robotic Rover for Planetary Exploration, Int. Conf. on Mobile Planetary Robots & Rover Roundup, Santa Monica.

[2] Amati N., Chiaberge M., Genta G., Miranda E., Reyneri L.M., 1999, Twin Rigid-Frames Walking Microrovers: a Perspective for Miniaturization, Journal of the British Interplanetary Society, Vol. 52, n. 7/8, pp. 301-304.

[3] Genta G., 2000, The Saha Crater Radioastronomic And Seti Observatory, 6th Conference on Chemical Evolution, Trieste.

[4] D.J. Todd, 1985, Walking Machines: an Introduction to Legged Robots, Kogan Page Ltd., London.

[5] M. E. Roseheim , 1994, Robot Evolution: the Development of Anthrorobotic, Wiley, New York.

[6] J. Peabody, H. B. Gurocak, 1998, Design of a Robot that Walks in Any Direction, Journal of Robotic System, pp. 75-83.

[7] P. Alexandre, Y. Ngounou, I. Doroftei, A. Preumont, 1996, A Conceptual Walking Vehicle for Planetary exploration, ESA WPP-122, 4th ESA Workshop on Advanced Space Technologies for Robot Applications - ASTRA 96, ESTEC, Noordwijk.

[8] Micro-Robots for Scientific Applications - Micro-RoSA, 1995, ESA Invitation to Tender AO/1-3094/96/NL/JG.

[9] S. M. Song, K. J. Waldron, 1989, Machines that Walk : the Adaptive Suspension Vehicle, Cambridge-MIT.

[10] A.Martin Alvarez, W.de Peuter, P.Gonzalez de Santos, M.A.Armada, 1994, A Survey of Locomotion Concepts for Planetary Exploration Rovers, ESA WPP-075, presented at the "3rd ESA Workshop on Advanced Space Technologies for Robot Applications - ASTRA 94", ESTEC, Noordwijk.

[11] Schilling, C. Jungius, 1995, Mobile Robots for Planetary Exploration, in A.Halme / K.Koskinen (eds.), Intelligent Autonomous Vehicles, pp.110-120.

[12] Amati N., Chiaberge M., Genta G., Miranda E., Reyneri L.M., 2000, WALKIE 6 – A Walking Demonstrator for Planetary Exploration, Space Forum, Vol. 5, n.4, pp. 259-277.

[13] Genta G., Amati N., 1998, Performance Evaluation of Twin Rigid-Frames Hexapod Planetary Rovers, Fourth Int. Conf. on Motion and Vibration Control, Zurigo.

[14] Genta G., Amati N., 1998, Prestazioni su terreno accidentato di veicoli esapodi a telai rigidi, XXVII Conv. Naz. AIAS, Perugia.

[15] D. Bassani, M. Chiaberge, D. Del Corso, G. Genta, F. Zanetti, 1995, Simulation of a Hexapod Walking Machine Controlled by Neural Networks, ISMCR '93, Torino.

[16] L.M. Reyneri, M. Chiaberge, 1995, CINTIA: A Neuro-Fuzzy Real Time Controller for Low Power Embedded Systems, in IEEE MICRO, pp. 40-47.

[17] M. Chiaberge, E. Miranda Sologuren, L.M. Reyneri, A Pulse Stream System for Low Power Neuro-Fuzzy Computation, IEEE Transactions on Circuits and Systems, vol. 42 no. 11, pp. 946-954.

[18] M. Chiaberge, W. Santero, D. Amerio, 2001, Digital Solutions for reProgrammability, SCI'2001, The Fifth Multi-Conference on Systemics, Cybernetics and Informatics, Orlando, Florida.

[19] R. Bertrand, M. V. Winnendael and R. Rieder, 1999, Nanokohod microrover for scientific mission to Mars, 50th International Astronautical Congress, pp. 1-6.