Twin rigid-frames walking microrovers: a perspective for miniaturization

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Abstract

Twin rigid frames walking machines are a promising layout for walking exploration microrovers.

Introduction

The term 'microrover' is currently used to designate small automatic devices (often with a mass significantly below 10 kg) used in planetary exploration. The prefix micro in this case however does not have any reference with a micro-metric scale, but is just stating that the rover is smaller than the large machines used in the high cost missions of the recent past.

Robotic devices of this kind are not limited to automatic exploration, as they can be very useful in performing a variety of tasks in scientific or application missions. Many operations related to the construction of a lunar base, for example, or to the commercial exploitation of space resources need the use of automatic or semiautomatic devices able to move objects around and to perform different operations.

How small can be a microrover? This question as little meaning unless the mission has been defined in its goals, characteristics and cost allowance. If it is true that a small size is beneficial in cutting costs, on the other hand it reduces the mobility, the speed and the capacity of carrying useful payloads and sophysticated control systems. Some of these limitations are mainly linked with the mass, while other ones, notably its mobility and speed, are more related to the size of the machine. Mass and size limits, although interconnected, can thus play a different role, both for what advantages and limitations are concerned. Launch costs are for example more affected by the mass of the device than by its size, at least if it remains below an allowable envelope.

As a first general statement, miniaturization in the payload, instrumentation, control and power system subsystems is obviously always welcome, as it allows to improve the performances of the machine at a given cost and complexity level. The same can be said for a lighweight construction of the mechanical part.

Another general consideration is that a rover is usually a part of the payload of a probe and the reduction of the size of the former is worthwhile only if it is not already much smaller than that of the second, with the possible exception of swarms of cooperating microrovers, which will not be dealt here.

The present paper deals only with a specific type of rovers, the twin-rigid frames hexapod walking machines. While some conclusion could be generalized, other ones are strictly related to the layout considered.

Twin rigid frames layout

Many alternatives to wheels are possible for land locomotion and have been throughly studied, like the use of tracks, leg systems and many other unconventional devices [1], [2] [3], wallking machines being an interesting choice for their better mobility, a higher isolation from terrain irregularities, a lower environmental impact and an improved theoretical energetic efficiency on very rough ground [4], [5], [6].

However they always suffered from the disadvantages of greater mechanical and control complexity, which can reduce the operating reliability, and of a lower speed with respect of their wheeled counterparts. While the last disadvantage is of little importance in many robotic exploration missions, where velocity is limited more drastically by the very low available power and by the difficulty of teleoperating the rover from the Earth, the former one requires a deep rethinking of the overall design.

A layout allowing to build a very simple hexapod walking machine was forwarded by the authors [7] and a demonstrator, named WALKIE 6, was built using off-the-shelf components (Figure 1). It is based on the twin rigid-frames concept, which is not new in general, having been already used for octopode machines [6], but is here adapted to a hexapod configuration. The resulting device, whose main chracteristics are a mass lower than 3 kg, a stowed volume entering into an envelope of $0.2 \times 0.3 \times 0.3$ m, the possibility of overcoming maximum slopes of up to 15°, obstacles of maximum height of 120 mm and holes of maximum width 80 mm and a speed in excess 15 m/h with an electric power consumption of about 2 W, with peaks not greater than 5 W, is in a sense the simple possible hexapod machine, having just eight internal degrees of freedom. It is easily implemented using simple electric actuators which are controlled just in an on-off mode, without the need to of controlling them in velocity or torque or even to exactly synchronizing their operation. The complexity of the control system is lower than that of a wheeled vehicle with independent motors on the wheels.

A pictures of the mechanical subassembly is shown in Figure 2. As the vertical and horizontal motions of the feet are wholly uncoupled, the load can be carried by unpowered actuators, either by the use of non-reversible devices of by locking them using brakes, an effective measure to reducing power consumption. The trajectories of the feet are intrinsically correct both in straight walking and on curved paths, which avoids high stressing of the legs and high power consumption on uneven ground. A further advantage is that the payload is maintained in a horizontal position during motion, even when walking on a slope or over obstacles.

The reduced number of internal degrees of freedom and the simplicity of the control prevents from exploiting the very high mobility of walking machines, making it impossible for example to cross obstacles higher than the vehicle body, a feature which however would require a very advanced mechanical and control layout even using a different general configuration. The ability of twin frames walking machines to negotiate obstacles and to walk of a sloping surface depends strictly on its geometrical characteristics, namely on the travel of the leg actuators and on the distance between the front and the rear legs in the maximum elongation position. This is a first strict limitation to miniaturization.

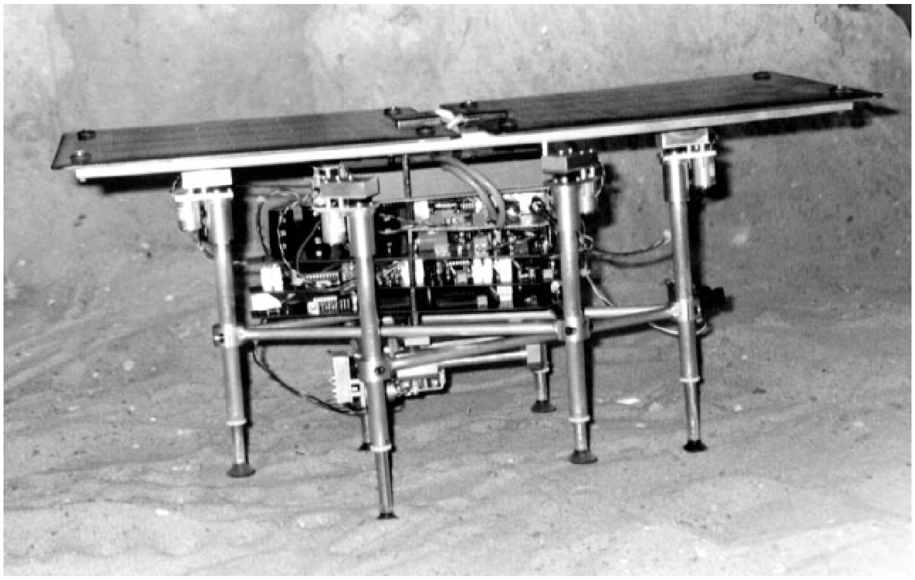

Figure 1: Picture of WALKIE 6 microrover, while walking on a test surface (b).

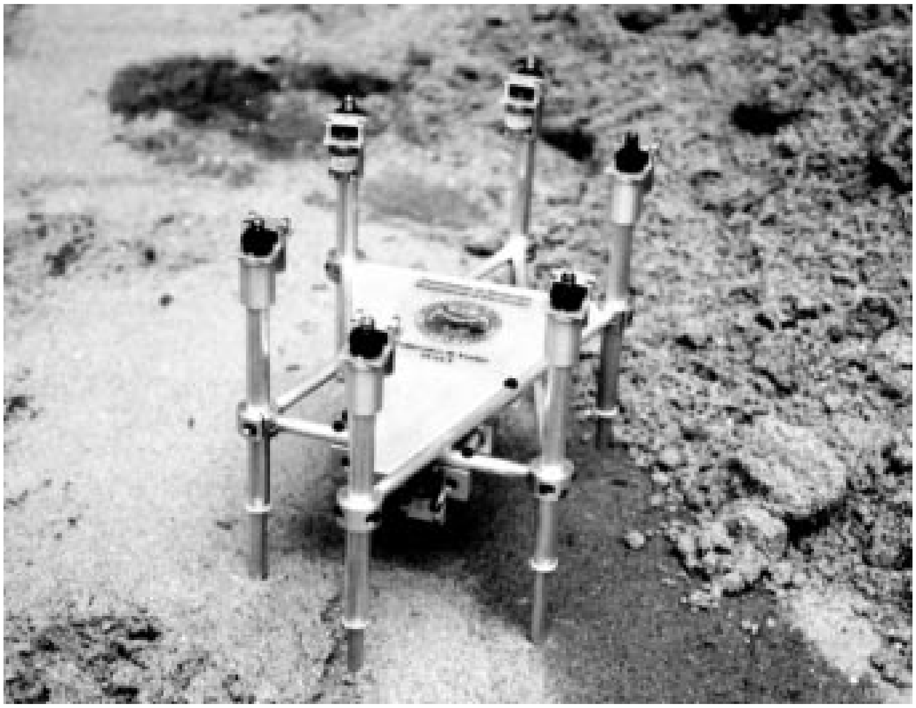

Figure 2: Picture of the mechanical subassembly of WALKIE 6.

Another limitation of the chosen configuration is that each one of the frames has a stop and start cycle at each step and each leg has two cycles. This limits the maximum speed which can be attained by machines of this kind, as inertia forces due to these cycles increase very rapidly with the vehicle speed. However this consideration must not be overstated at the design speed typical of microrovers: inertia forces due to translational motion start to become the limiting factors at speeds well in excess (perhaps one order of magnitude or more) than those typical of microrovers. If the actuators are based on electric motors, on the contrary, their rotational inertia can be an important factor in determining the power consumption in level walking. This feature has conflicting effects on miniaturization: masses and hence inertia forces reduce drastically, but on the other side the frequency at which each cycle has to be gone through increases, if the speed has to be maintained.

A final consideration: the proposed layout is based on prysmatic joints between the various parts. The two frames slide with respect to each other and the legs perform translational motions with respect to the body. In very small machines rotational joints are usually preferred, particularly if elastic hinges are used. Prysmatic joint are likely to produce comparatively higher friction, to have high wear and to require higher precision and hence to lead to higher manufacturing costs.

Walkie 6 is based on screw actuators using plain standard screws and on prysmatic guides in which aluminium bars move inside teflon bushes. At present a version which can be qualified for space use is being studied and in this device ball or better roller screws and rolling elements guides, which have already been qualified for space use, will be used. These components have limitations for what the miniaturization is concerned.

Control system

The basic information the robot receives from the environment are tactile ones. Monitoring motor currents has proven to be a satisfactory mean to detect both foot contact on the ground and body contact against obstacles. As an alternative, proximity switches on the feet can also be used. Contact detection 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.

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 from rover to the ground station; 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. Studies aimed to use visual information for autonomous navigation are planned in the near future.

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.

Therefore the rover behaves as a semiautonomous vehicle, which moves the payload

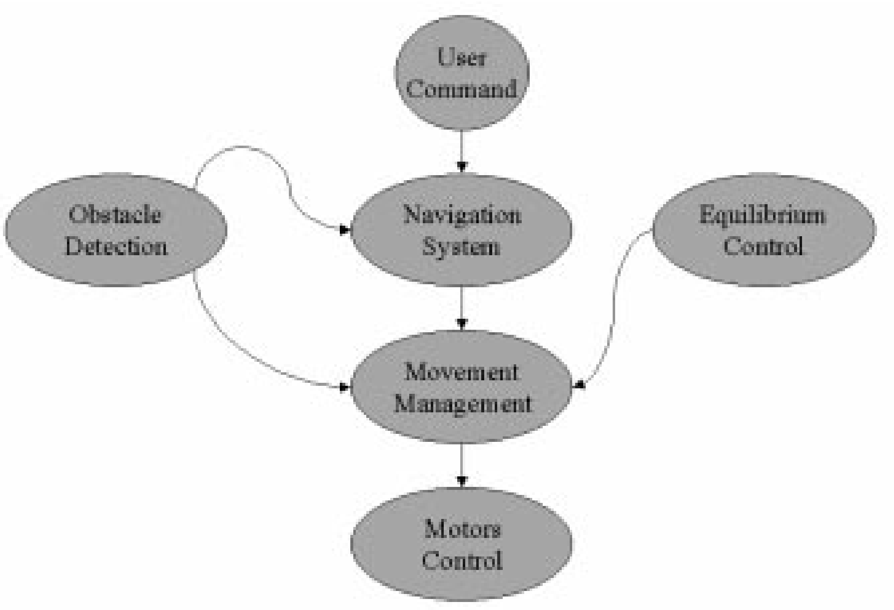

Figure 3: Schematic diagram of the WALKIE6 control system.

around according to the mission goals. The navigation system has so to provide only high-level guidance information, pointing when and in which direction the rover has to move. As an alternative, navigation functions may be left to remote human guidance.

The control system of Walkie 6 is based on a set of interacting finite state automata, designed to control individual leg movements, coordination, gait, obstacle avoidance, and recovery from anomalies.

Each automaton acts on its own DC motor, controlled via simple on-off drivers. The leg can thus either raise to begin the step or to avoid obstacles, lower down to the ground or remain still to bear the rover and payload weight.

The automaton also measures leg elongation via an incremental encoder and leg pressure on the ground by detecting the motor current. The latter information is used to detect when the leg hits the ground at whatever height it is, either level, or on a stone, or in a hole, while leg elongation is used to detect when the leg is over a canyon and has no ground to touch. In the latter case, the rover retracts and changes direction.

Actually the rover control system is implemented on a commercial microcontroller, interfaced with sensors and actuators through two programmable VLSI logic arrays. In order to increase the Walkie 6 performance from a control system point of view some improvements are actually under research:

- Control system electronics can be integrated on a single custom chip to reduce both the power consumption and size of electronics boards. This miniaturization allows to minimize also the rover size and weight.
- Artificial vision can improve obstacle avoidance algorithms allowing to discover an obstacle without touching it as needed with the present Walkie 6 tactile sensors. In order to implement artificial vision, the microcamera images are processed by the rover electronics to detect obstacle borders and other relevant terrain characteristics.

Performance and size

Owing to the above mentioned considerations, it is possible to expect a minimum size in the centimetric range for machines of the type here considered. A twin frame walking machine of this size however cannot deal with obstacles larger or higher than a few centimeters and its speed is limited to a few meters per hour, giving them a very small usefulf range. This means that centimetric microrover can be used only for very specific tasks, both in exploration and commercial missions.

In the case of long range missions, i.e. missions towards the satellites of the giant planets, the Pluto-Charon system or other bodies of the Kuiper belt and even bejond, a very small size can be dictated by the need of containing the mass of the rover and of the lander to a minimum. However, the need to resort to energy sources different from solar cell in places so far from the Sun makes the miniaturization even more difficult. RTG are a viable choice, but their bulk and mass compels to resort to rovers of larger size.

In the majority of cases the present size of WALKIE 6 must be regarded as a practical minimum to achieve a good mobility, in terms of obstacle management and speed, while maintaining the ability of carrying a numeber of scientific experiments.

It must be finally stressed that, particularly in the case of low gravity bodies, like small satellites, asteroids and comets, it is possible to increase the size of the microrover without greatly increase its mass or its power requirements. A decimetric size microrover, equipped with highly miniaturized sensors and scientific payload, can be in this case the best choice from the viewpoint of the cost/scientific results ratio.

Conclusions

Twin rigid frames hexapod walking microrovers seem to be very promising for planetary exploration missions. They are best suited to low gravity environment and to low speed requirements, although their speed limitations are less severe than expected.

Microrovers can be further miniaturized, but their performances in terms of mobility and carrying capacity decrease very rapidly with their size, particularly if sub-centimetric size is achieved. Twin rigid frames walking machines do not seem to be a very good choice for this sub-centimetric miniaturization, as telescopic devices appear less suited than articulated ones for very small sizes.

For most scientific missions microrovers in the decimetric range seem to be the best choice. In this size the proposed architecture has several advantages and allows to build very simple and relatively low cost devices. The actual capability of performing a wide variety of tasks depends also on the miniaturization of the instrumentation, control electronics and communication system which is placed on board.

In the case of commercial missions and those aimed to the construction of manned outposts on the Moon or of permanet structures on Mars the required size of the rover can be even larger, up to one meter or more. This can be particularly true if a twin frame walking machine is proposed for tasks as self propelled digging or soil moving machine or for moving and positioning objects or structural elements.

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