Planar motion hexapod walking machines: a new configuration

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ABSTRACT

The present paper develops a new configuration for walking machines which is in a way an hybrid between rigid-frames and zoomorphic walkers. It hopefully shares the advantages of both: the complexity is only marginally higher than that of rigid-frames walkers, while the performances may be similar to those of the more complex machines. The legs are essentially made of linear actuators moving in the vertical direction, like in rigid-frames machines. They are carried at the end of pantograph mechanisms which allows the feet to move along a straight line parallel to the longitudinal axis of the machine. The total number of degrees of freedom goes from 8 in the simplest form to 13 in the most complex one. The paper describes the layout of the machine, with particular reference to a small prototype for planetary exploration or other applications like archaeological survey or humanitarian demining.

1 INTRODUCTION

In spite of the advantages of walking machines for a variety of tasks, spanning from off-road locomotion to rescue tasks in unstructured environment, from planetary exploration to earth moving machines, very seldom any of them did show an actual competitive edge in practical applications. Almost all the self-moving machines marketed and used are either wheeled or tracked: perhaps the main reason is the fact that wheeled vehicles have a tradition that cannot be matched by other configurations so that the designer may refer to 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. But it is not only a matter of a consolidated design practice: legged vehicles usually have reciprocating parts which undergo to a high number of fatigue cycles, are usually highly stressed, require complex control systems and often have a higher energy consumption, in spite of a greater theoretical efficiency. Even when the difficulties encountered in achieving high speeds are of no concern like in planetary rovers, whose velocity is strongly limited by other considerations (1), (2), walking machines are seldom considered at the application stage.

Most walking machines are based on zoomorphic configurations, trying to match the very high performances of living beings. However this approach has never been really successful and may well be a losing strategy when dealing with many applications which do not require such high performances. One of the reasons is 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 characteristics 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. 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 when there is no possibility of repair and maintenance. All organisms shaped by evolution are expendable, since what matters is the species and not the individual, and reliability is a secondary factor: no artificial device with legs as delicate as those of a horse, for example, may be considered acceptable. The possibility of self-repair of biological materials must also be added: bones and muscles remodel and repair themselves in a way impossible for 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 must finally be noted that usually the number of degrees of freedom of each leg in a zoomorphic configuration is 3, which yields a minimum of 18 degrees of freedom for a hexapod machine and of 12 for a quadruped. However, very seldom the number of degrees of freedom of animals is limited to that: legs have usually a further degree of freedom and the body is articulated, particularly in quadrupeds. To achieve really zoomorphic performances the number of required degrees of freedom is much higher than that reported above.

The above mentioned reasons suggest to use non-zoomorphic, highly simplified layouts. Twin rigid-frames machines proved to be simpler and solved some problems related to mechanical reliability and autonomous working, while reducing the performances mainly for regarding the maximum speed (4), (5). The seven-legged Walking Beam (3) is a very good example of twin-rigid frames rover and WALKIE 6 is a more recent proposal (6), (7), (8).

The experience accumulated in the design of several versions of WALKIE 6 and their operation for long periods of time did show that this approach may overcome the reliability problems, while reducing control problems without penalising too much performances. WALKIE 6.2 is one of the few walking machines able to perform autonomously (the power and the control systems are on board and needs no umbilical) for prolonged time without maintenance. Its low power requirements (less than 3 W at 52 m/h on level ground) remain unmatched (8).

The aim of the present paper is developing a new configuration which is in a way an hybrid between rigid-frames and zoomorphic machines, hopefully sharing some of the advantages of both: complexity is only marginally higher than that of the former, while performances may be similar to those of more complex machines with a larger number of degrees of freedom.

2 PANTOGRAPH LEGS

The uncoupling of the vertical and horizontal motions of each foot is very important to relieve the control system from the duty of generating the correct foot trajectories and, above all, to reduce the energy consumption. Here most walking machine deviate from really zoomorphic layout since in no animal such uncoupling is present. This is made possible by the high computational power supplied by even the simplest brain and by the ability of muscles of carrying the load without consuming much energy and at the same time supplying the required compliance.

In a walking machine powered by electric motors, a similar solution requires that the electric motors supply a torque during the stance phase without producing a rotation and hence consume power without producing useful work.

To uncouple the horizontal and the vertical motion of the feet, pantograph mechanisms have been several times proposed and used (9). The large *Adaptative suspension vehicle* of the Ohio State University, for instance , uses six 'mammalian' pantograph legs located in an almost vertical plane (Figure 1a). Points A, B and C are always on a straight line and the foot duplicates exactly the horizontal motion of point B and the vertical motion of point A, with a constant amplification given by ratio AB/BF.

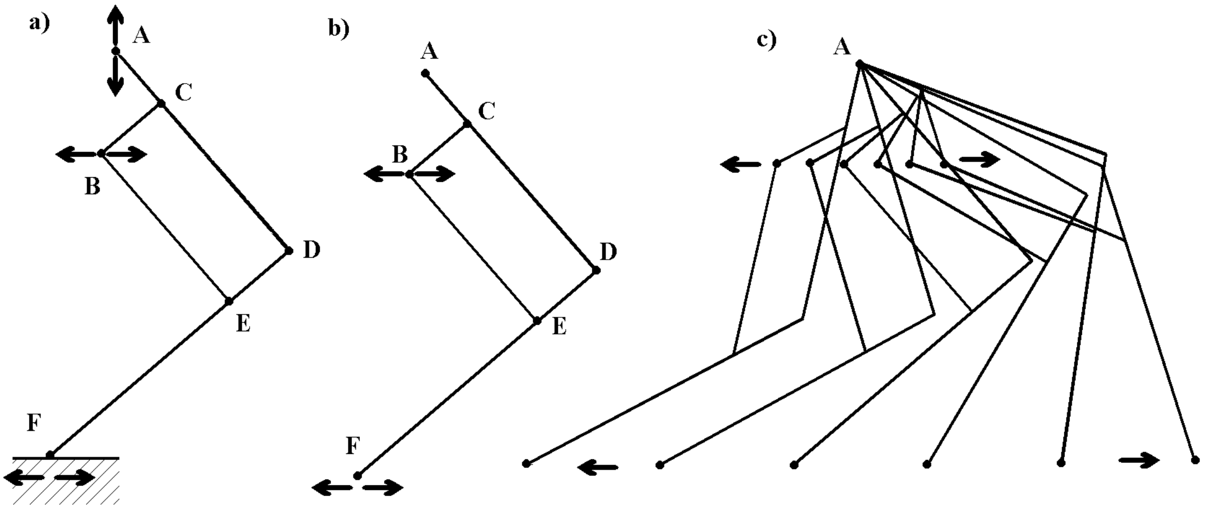

Figure 1. Pantograph legs. a): a two degrees of freedom 'mammalian' leg seen in the vertical plane. The actuators are located in A and B and move the foot F in vertical and horizontal direction. b): a 'reptilian' leg seen in the horizontal plane. The actuator in B move point F in which the vertical actuator is located in a direction parallel to the longitudinal axis of the machine. c): the pantograph in b) seen in different positions.

The problems linked with a solution of this type, common to almost all pantograph legs, is the fact that the horizontal guide of point B must carry the load acting on the leg, amplified by a factor which changes during the stance phase. The vertical guide of point A is also loaded in a direction perpendicular to that of the motion, in all positions except when the line ABC is vertical. The pantograph configuration may be further made complex, giving two degrees of freedom to point A, i.e. adding an out-of-plane motion (3D pantograph). However, the difficulties above described become in this case even greater.

A new configuration is here suggested. Each leg is made by a single-degree of freedom pantograph located in a horizontal plane (Figure 1b). Point A is the cylindrical hinge in which the leg is articulated to the body, while point B moves in longitudinal direction, being guided along a straight line. The foot is carried by a vertical linear actuator located in point F, in a way which is identical to rigid-frames walking machines. As clearly shown in Figure 1c, the longitudinal foot movement follows the movement of B, suitably magnified.

Like in rigid frames machines, the vertical and horizontal motions of each foot are uncoupled from each other, and if the body is always maintained in an horizontal position even when walking on a slope, the direction of the linear actuators is always vertical, while the motion of all the pantographs occur in a horizontal plane (hence the definition of *planar-motion walking machines*).

Since no forces (except inertia forces which in low speed walking are very low) act in the horizontal plane, the guide used to allow point B to move along a straight line has to withstand no force in a direction perpendicular to the motion. Also the actuator which moves point B has to supply only the power needed to overcome friction (always neglecting inertia forces) but performs no useful work. All loads act in a direction perpendicular to the plane of the pantograph, generating bending moments in the beams and torques in the joint, whose vector however is always perpendicular to the axis of the hinge.

It is possible to design the leg in such a way that all loads are carried by beams AD and DF (for instance by using spherical joints in points C and E) so that bars BC and BE are just push-pull rods, not loaded in bending. In this way the bending moment in D is simply the load on the foot multiplied by distance DF and that in A is the load multiplied by distance AF. These bending moments are not constant, since the load on the foot is not constant during walking, but their variation is neither large nor quick, as occurs for the loads in many elements of walking machines of different type.

If legs built in this way are used for a hexapod walking machine, the six pantographs may be moved by a single actuator, realising a type of motion and a gait (alternate tripod gait) which is exactly the same of rigid-frames machines. As an alternative, six independent actuators may operate them, allowing to walk with any type of gait like more complex zoomorphic machines and allowing the body to move at a constant speed (unlikely rigid-frames machines which undergo an acceleration-deceleration cycle at each step).

3 GENERAL LAYOUT

A basic layout for a hexapod walking machine of this type is shown in Figure 2. Note that the right and the left legs are hinged in the same points R, S and T (or better, in points which are on the same vertical line). The legs are numbered from 1 to 6, the full forward position are indicated with letter A, while the full backward positions with letter B. The total stroke of the legs has been assumed to be equal to the length of the body, i.e. to the distance RT.

Assume that an alternating tripod gait, performed with the same control architecture used in rigid frames machines, is chosen. Each step can be subdivided in six phases. Assuming that at the beginning all feet are on the ground, legs 1, 3, 5 are in forward (A) position and legs 2, 4, 6 are in backward (B) position,

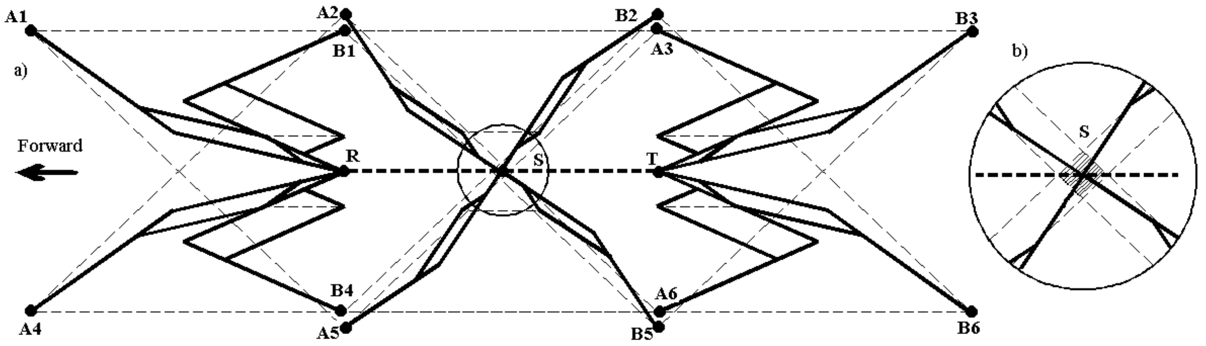

Figure 2. Hexapod planar motion walking machine. a):extreme positions of the six pantograph legs. b): Enlargement of the zone included in the circle around point S.

1. Legs 2, 4, 6 are raised. (the vehicle is supported by legs 1, 3, 5, and the centre of gravity must be over triangle B1B3B5);
2. Legs 2, 4, 6 move forward and legs 1, 3, 5 move backward (with the respect to the body). The body moves forward and the centre of gravity at the end of the phase must be over triangle A1A3A5;
3. Legs 2, 4, 6 are lowered to the ground in positions A2A4A6;
4. Legs 1, 3, 5 are raised. (the vehicle is supported by legs 2, 4, 6, and the centre of gravity must be over triangle A2A4A6);
5. Legs 1, 3, 5 move forward and legs 2, 4, 6 move backward (with the respect to the body). The body moves forward and the centre of gravity at the end of the phase must be over triangle B2B4B6;
6. Legs 1, 3, 5 are lowered to the ground;

The body moves forward only in phases 2 and 4, while in all other phases only the vertical actuators move. To ensure static equilibrium in all phases the centre of gravity must be over the intersection of the four aforementioned triangles. Such intersection is represented in the enlarged view of Figure 2b) (shaded area). Note that this area is quite small: it reduces to a single point (point S) if the stroke of the legs is equal to the length RT and the track of the central legs is equal to that of the front and rear legs. The useful area for the centre of mass increases by:

- decreasing the stroke of the legs;
- decreasing the track of the front legs with respect to that of the central ones (or increasing the latter with respect to the former).

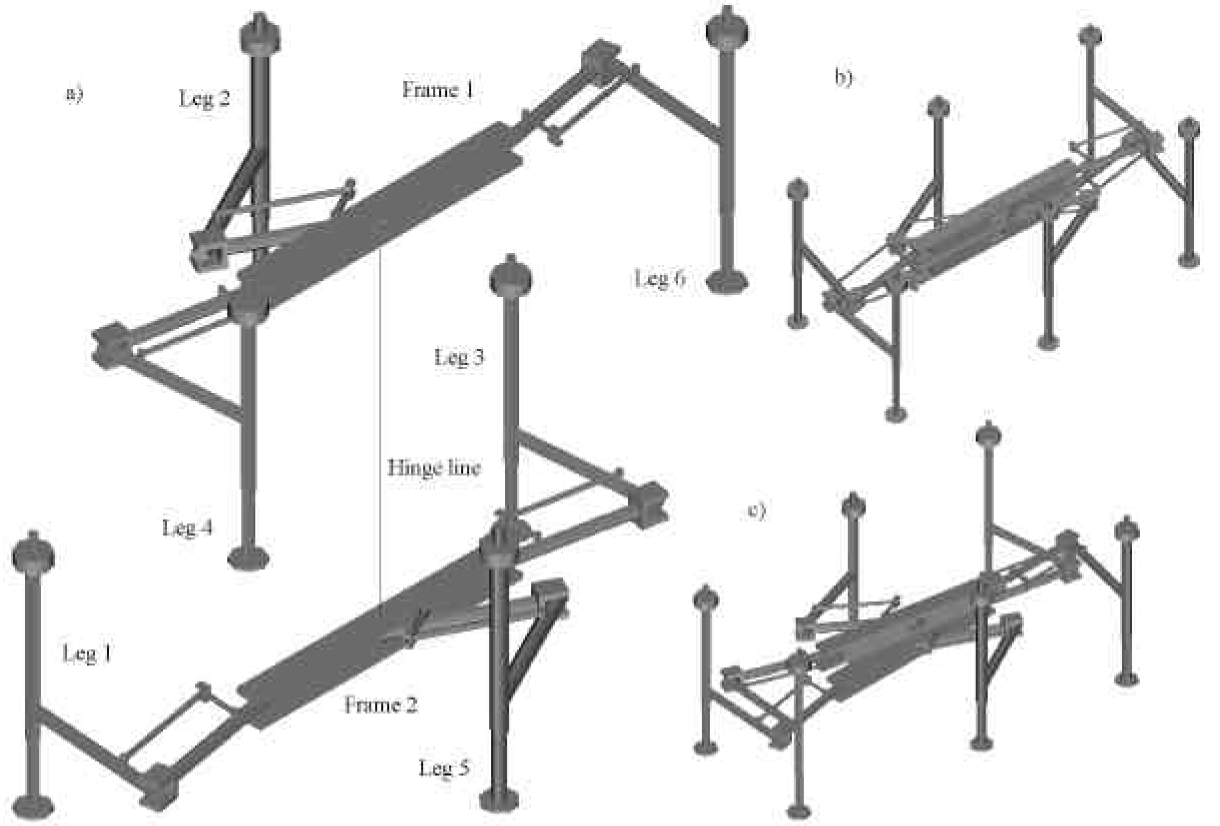

Figure 3. a): Exploded view of the two parts of the body, which are hinged to each other; b): Sketch of the hexapod walking machine with the legs in an intermediate position and c) with the two frames rotated by 10° with respect to each other.

Note that this type of gait and control strategy is the worst choice for what static equilibrium is concerned, but allows to control the vehicle using simple on-off switches and requires no velocity control on the actuators. The number of total degrees of freedom is 8 (the 8th degrees of freedom is used for rotation, see below) since, even if the six pantographs are operated by six separate electric motors, they may be controlled by a single driver: the machine is exactly equivalent to a twin frames walker, with the difference that only cylindrical hinges are used, no slider guide operating under load is present and the stroke may be longer and hence the machine can move faster. If the electric motors are controlled separately, a machine with 13 degrees of freedom is obtained, it is possible to have a continuous motion of the body, with no acceleration-deceleration cycle and any of the gaits which have been studied for hexapod machines can be used.

Steering may be implemented in two different ways, either by having the feet moving on curved trajectories or by making the body in two parts, one articulated on the other, with three legs each. The first solution allows to walk on any curved trajectory, as zoomorphic machines, but makes it necessary to use six additional degrees of freedom, while the second one, which is identical to the strategy used in twin frames machines, requires a single additional degree of freedom but compels to stop the machine for changing the direction of the motion while walking occurs only on a straight path.

The layout for the legs shown in figures 2 and 3, although being not symmetrical with respect to *xz* plane (this deviation from bilateral symmetry is another non-zoomorphic characteristic of this machine), allows to ensure that the centre of gravity doesn’t shift straight during motion, when the alternate-tripod strategy described above is adopted. It has the added advantage of having 6 identical legs (even if 3 of them are assembled in a way which is specular with respect to the other 3) and two identical (not specular) halves of the machine. This should simplify construction and reduce costs (Figure 3a).

The pantographs may be actuated in two different ways: linear actuators moving point B (figure 1b and 4a) or a rotational actuator acting in point A in the same figure (1b and 4a). The first alternative can be implemented using a screw actuator, which may be given the two tasks of moving the linkage and of guiding point B along a straight line. The latter task is made possible by the very low forces which act between the pantograph and the guide in a direction perpendicular to the motion. If a linear actuator is used, the motion of the foot is proportional to that of the actuator and, if a screw is used, to the rotation angle of the electric motor. If on the contrary the mechanically simpler alternative of a rotational actuator in point A is followed, a nonlinear relationship exists between the motion of the foot and the rotation of the actuator; this relationship is different for the three pairs of legs.

Moreover, not in all configurations a rotational actuator may be used. The relationship between the displacement of the foot (point F) in x direction and angle q (see Figure 4a) is

$$x = l_1 \sin(J) - l_2 \sin\left\{ \arccos\left[\frac{d}{l_2} - \frac{l_1}{l_2} \cos(J) \right] \right\} \tag{1}$$

The relationship between angle θ and the displacement x of the foot (in nondimensional form) for two legs of the machine of Figure 2 is shown in Figure 4b. While the relationship for leg 2 is nonlinear, but the derivative dx/dq is always limited, in the case of leg 3 such derivative becomes infinite in a position. In this case it is impossible to drive the pantograph directly with a rotational actuator, while the use of a linear actuator moving point B in x direction is always possible.

If the use of a rotational actuator is possible, there is no difficulty in measuring the displacement of the foot by measuring the position of point B along the guide and consequently controlling the actuator in a closed loop, but this increases the complexity of the control system. If a simple alternate tripod gait is chosen and the machine behaves like a rigid frames machine, this would add much to the complexity of the system; if a more sophisticated control is anyway present, the additional complexity is small.

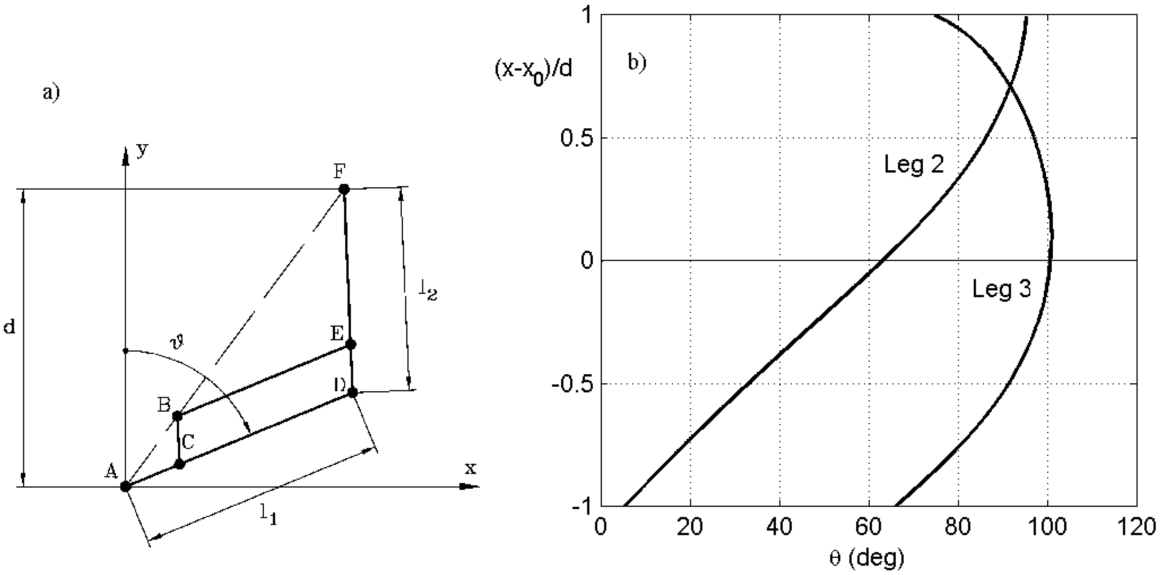

Figure 4. a) Geometrical definition of a pantograph leg. b) relationship between angle q **and the displacement** x **of the foot for two legs of the machine of Figure 2.** x_0 **is the value of** x **at the centre of the stroke.**

Finally, all the considerations regarding the position of the centre of gravity have been obtained assuming that the area of the foot is very small, and the contact with the ground occurs in a single point. In an actual case the contact area depends on the type of terrain for which the machine has been designed: an increase of the size of the foot reduces the problems linked with static equilibrium but may cause also a reduction of the stroke, to avoid contact between two feet. The foot must also be connected to the vertical actuators in such a way that it can rotate about a vertical axis, since the vertical actuators rotate with respect to the ground together with the beam DF.

Two sketches of the machine are shown in Figure 3b) and c): all feet are on the ground and the legs are in an intermediate position; the two frames are straight in one case and rotated by 10° in the other one.

4 CONCLUSIONS

An unconventional leg configuration for multi-legged walking machines is here described. It has the following advantages with respect to other, more zoomorphic configurations (referred to an hexapod machine):

1. The horizontal and vertical foot motions are uncoupled (advantage shared with all pantograph configurations).
2. The guides of the pantograph are not loaded in a direction perpendicular to the motion, except than by inertia forces and lateral forces.
3. The joints of the legs are loaded by bending moments with a vector acting always perpendicular to the hinge axis (they do not perform work; the only energy required in straight level walking is that to overcome friction). These moments are much smaller and less variable in time than in other configurations.

4. The body may be maintained in a horizontal position.
5. The same simple on-off controller used in rigid frames machines can be used, if an alternate tripod gait with stops at end of the phases of longitudinal motion is accepted (like in rigid frames machines)
6. The total number of actuators is only 13 and the number of controlled degrees of freedom may be reduced to 8. If 13 degrees of freedom are controlled separately, all the different gaits of zoomorphic hexapods are possible.

The disadvantages are mainly 2

1. The maximum achievable speed is lower than that of zoomorphic machines, and particularly it is difficult to see how running might be possible. However, even zoomorphic configurations have very seldom the ability to reach high speed (not to mention running), for other reasons (power limitations, high stressing, control problems, etc.)
2. Vertical linear actuators must be used for the vertical motion of the feet. They are slower and add much to the mass of the legs, two factors which are the main responsible of the above mentioned limited maximum speed.

Most of the advantages and drawback are similar to those of rigid frames machines, but the proposed configuration has much more flexibility and may be seen as an intermediate layout between very simple rigid frames machines and much more complicated zoomorphic machines. Moreover, from a research viewpoint, it can be built initially using many components, including the control system, of rigid frames machines and later its characteristics can be improved by introducing changes in the control system. If a digital controller is used, this means simply by improving the software.

A full scale demonstrator for a planetary microrover based on the WALKIE 6 machine is at present under study.

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