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Mantis: hybrid leg-wheel ground mobile robot

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Abstract

Purpose – The aim of the research is the development of a small-scale ground mobile robot for surveillance and inspection; the main design goals are mobility in indoor environments with step climbing ability, pivoting around a vertical axis and without oscillations for stable vision, mobility in unstructured environments, low mechanical and control complexity.

Design/methodology/approach – The proposed hybrid leg-wheel robot is characterized by a main body equipped with two actuated wheels and two praying Mantis rotating legs; a rear frame with two idle wheels is connected to the main body by a vertical revolute joint for steering; a second revolute joint allows the rear axle to roll. The geometrical synthesis of the robot has been performed using a nondimensional approach for generality's sake.

Findings – The experimental campaign on the first prototype confirms the fulfilment of the design objectives; the robot can efficiently walk in unstructured environments realizing a mixed wheeled-legged locomotion.

Practical implications – Thanks to the operative flexibility of Mantis in indoor and outdoor environments, the range of potential applications is wide: surveillance, inspection, monitoring of dangerous locations, intervention in case of terroristic attacks, military tasks.

Originality/value – Different from other robots of similar size, Mantis combines high speed and energetic efficiency, stable vision, capability of climbing over high steps, obstacles and unevenness.

Keywords Surveillance, Hybrid locomotion, Mobile robotics

Paper type Research paper

1. Introduction

The world market of service robotics is expected to grow remarkably in the next 20 years, surpassing the market of industrial robotics in terms of units and sales (International Federation of Robotics, 2012; Prassler and Kosuge, 2008; EURON and EUROP, 2009). Mobile robots moving on ground are the most widespread category of service robots; in particular, ground mobile robots for defence or field applications represent today the 75 percent of the total unit sales of professional service robots. Besides military aims (Playter *et al.*, 2006), important applications are homeland security (Murphy, 2004), surveillance (Quaglia *et al.*, 2011), intervention in case of terroristic attacks (Birk and Carpin, 2006; Snyder, 2001), recognition in dangerous locations, for example in case of radioactive or chemical contamination (Hamel and Cress, 2001).

In this scenario, the research about innovative locomotion architectures with high operative flexibility, designed to operate efficiently both in structured and in unstructured environments, assumes paramount importance.

It is very complex to outline concisely the state-of-the-art of locomotion systems for ground mobile robots: several mechanical architectures have been proposed by academic and industrial researchers, which are characterized by various combinations of advantages and drawbacks (Siegwart and Nourbakhsh, 2004; Seeni *et al.*, 2008). In Bruzzone and Quaglia (2012) the three main categories of locomotion systems, wheeled (W), tracked (T) and legged (L), and the four hybrid categories derived from combination, legs-wheels (LW), legs-tracks (LT), wheels-tracks (WT), legs-wheels-tracks (LWT), are analysed and compared with reference to several performance features (speed, obstacle climbing, step/stair climbing, slope climbing, walking capability on soft and uneven terrains, energetic efficiency).

Figure 1 shows a very synthetic and qualitative comparison of the different locomotion systems by graphing mobility in unstructured environments (y) vs speed and energetic efficiency (x). Wheeled robots are in the right lower zone (better x, worst y), legged robots are in the left upper zone (worst y, better x), tracked robots are in the middle.

As a matter of fact, locomotion by wheels provides high speed and energetic efficiency because the contact with the terrain occurs without impacts and vibrations; in particular, wheeled robots derived from automotive technology, with car-like suspensions and Ackermann steering, maximize these parameters. On the other hand, wheels are unsuitable for climbing obstacles and irregularities, and this limits the capability of wheeled robots of moving in unstructured environments.

Legged robots are the most suitable for unstructured environments due to their capability to overcome obstacles and irregularities, properly planning their gait; on the other hand, they are relatively slow and have high energy consumption, because their motion is not continuous, as it occurs for wheeled robots.

In the graph of Figure 1, tracked robots are in the middle between wheeled and legged robots, because they can climb obstacles and irregularities better than the wheeled ones thanks to their large contact surfaces; on the other hand, they are subject to vibrations because the track lateral profile is a polygon with moving vertices, and they are rarely equipped

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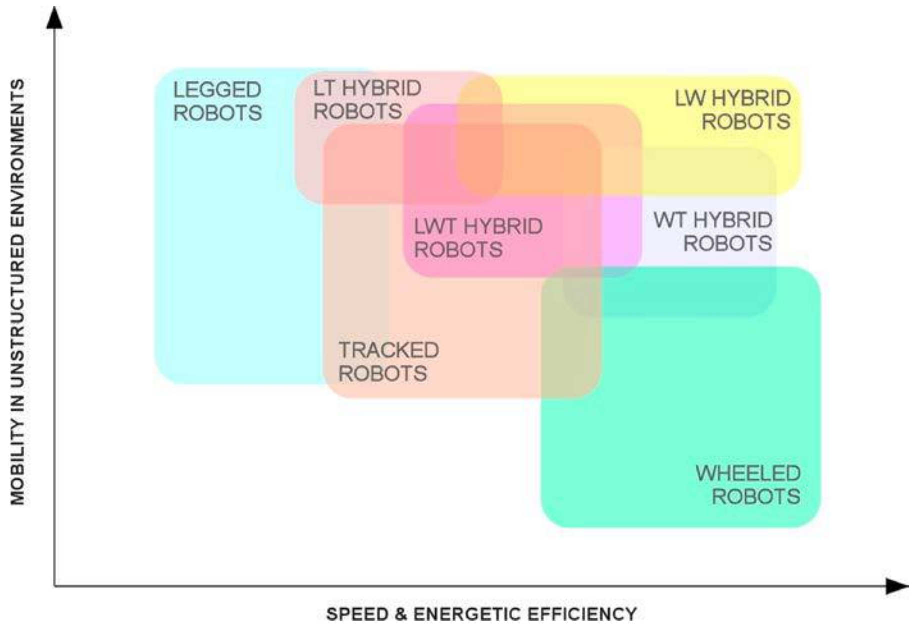
Figure 1 Comparison of the locomotion systems features



Source: Bruzzone and Quaglia (2012)

with damping systems; this limits the maximum speed and lowers the mechanical efficiency.

In the graph of Figure 1 the positioning of the hybrid categories is due to the fact that they aim to join the benefits of the categories from which they derive, but this does not completely occurs: as a matter of fact, the combination of more alternative locomotion devices tends to lower the overall performance, because a non-active device is a non-negligible payload.

The state-of-the-art analysis shows that hybrid LW locomotion systems are suitable when it is required to combine the speed and energetic efficiency of the wheels with the climbing ability and operative flexibility of the legs. In particular, for small and lightweight robots the inertial effects in case of trajectory discontinuities are less dangerous from a structural point of view, and this allows to adopt simplified leg mechanisms while maintaining good dynamic performances. Therefore, hybrid LW locomotion systems do not have in general the high number of actuators and the gait control complexity of legged robots (Raibert, 1986; Manchester *et al.*, 2011), and consequently their cost is usually lower.

Basically, legs and wheels can be combined in four ways:

1 equipping a wheeled robot with additional legs connected to the robot body;
2 combining wheels and legs always acting together during locomotion;
3 using retractable modules that can be used as wheels or as legs; and
4 placing wheels on the leg links (usually at the ends of the legs).

Using approach *a*, the robot design is conceptually simple: legs and wheels are used alternatively, depending on the terrain conditions; the main drawback is that the robot is equipped with two distinct locomotion systems and therefore its mass is higher.

On the contrary, using approach *b*, the wheels are not sufficient for any locomotion mode without the intervention of the legs; examples are the Wheeleg (Guccione and Muscato, 2003) and the RoboTrac (Six and Kecskeméthy, 1999); these robots are usually characterized by a lower number of actuators with respect to approach *a*.

Approach *c* is interesting (Tadakuma *et al.*, 2010), but the mechanical design of the retractable modules is very complex, and this lowers the reliability in dirty environments or in case of shocks.

Approach *d* can be realized in different ways. Alduro (Germann *et al.*, 2005) and Lebrel (Gonzalez Rodriguez *et al.*, 2011) are quadruped robots with wheels placed at the end of the rear legs. Octopus (Lauria *et al.*, 2002) is a mobile robot with a sophisticated locomotion system, characterized by 15 degrees of freedom, with four legs and eight motorized tactile wheels, two per leg. A simpler approach is the *stepping triple wheel* of the Spacecat and Epi.q robots (Siegwart *et al.*, 1998; Quaglia *et al.*, 2011): the locomotion modules, equipped with three wheels carried by three legs placed at 120°, can rotate independently with respect to the main body to climb obstacles, while on flat ground only the wheels are active; the mechanical complexity is intermediate between approaches *a* and *b*.

Another interesting hybrid locomotion system is the *Galileo wheel*, adopted for example in the VIPeR, a mobile platform for surveillance tasks developed by Elbit Systems; the Galileo wheel combines wheel and track in a single group, characterized by extensible crawlers.

In applications with small robot size and payload, e.g. surveillance, another suitable solution is locomotion with rotating legs; for example, RHex is a cockroach-inspired hexapod robot with compliant legs that provide a self-stabilized gait; in spite of its simple mechanical design with one actuator per leg, RHex is capable of walking, running, leaping over obstacles, and climbing stairs (Altendorfer *et al.*, 2001). Whegs is another biologically inspired robot with rotating legs, characterized by three-spoke locomotion units (Quinn *et al.*, 2003); Loper (Herbert *et al.*, 2008) and ASGUARD (Eich *et al.*, 2009) adopt the Whegs locomotion principle with refinements in the design of the legs, which are compliant for shock absorption and specially conceived for stairs climbing.

In the following section the mechanical architecture of the Mantis robot is discussed; it is a small-size hybrid LW robot for surveillance and inspection tasks, characterized by four wheels and two front legs with praying Mantis leg shape, designed to work only in combination with the wheels and not independently.

2. The Mantis architecture

2.1 General specifications

The objective of the research is the development of a small size mobile platform, approximately $350 \times 300 \times 200$ mm, characterized by the following features:

- payload mass of about 1 kg, compatible to a typical surveillance/inspection equipment: camera, microphone, task-oriented additional sensors (for example for detecting chemical or radioactive contamination), wireless communication devices;
- mobility in indoor environments structured for human locomotion, and in particular capability of going up and down stairs with standard-size steps (160 mm of rise) which are the main hindrance for indoor surveillance of buildings with small-scale robots;
- capability of pivoting around a vertical axis on flat grounds to avoid complex manoeuvres with backward motion in narrow spaces;
- locomotion without oscillations on flat grounds to obtain stable camera vision;
- motion capability in unstructured environments characterized by uneven and/or yielding terrains and irregular obstacles; and
- slope climbing ability ≥ 65 percent.

Other general requirements are low control complexity and simple mechanical structure, in order to enhance the overall reliability and to reduce the robot cost, thus widening the range of potential surveillance/inspection applications.

2.2 The Mantis hybrid leg-wheel locomotion system

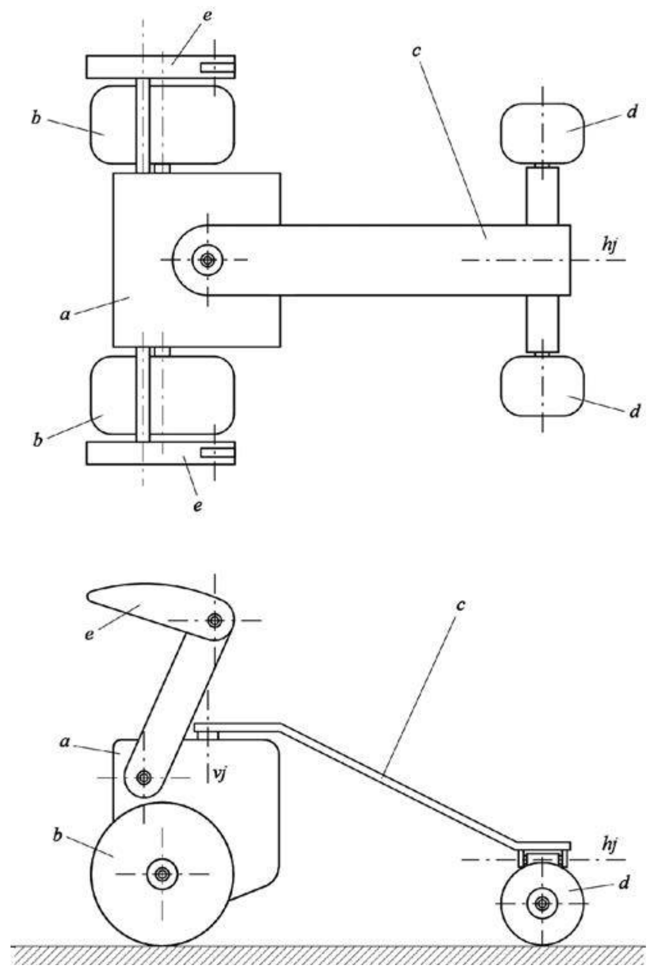
The Mantis architecture has been developed starting from the previously discussed requirements, and in particular considering the ratio between the heights of the robot and of the step which can be climbed. The research has been focussed on hybrid LW architectures to combine good speed and energetic efficiency in wheeled locomotion mode and step and obstacle climbing ability in legged locomotion mode.

The proposed Mantis architecture has been conceived to climb steps higher than the robot body, by adopting legs with two degrees of freedom, one actuated and one passive. Figure 4 shows the main robot parts: the front main body (*a*), two actuated front wheels (*b*), the rear frame (*c*), two rear idle wheels (*d*), two rotating front legs with praying Mantis leg shape (*e*).

On flat and even terrains locomotion is by wheels: the two front wheels perform differential steering, while the two rear wheels passively stabilize the robot. The rear frame is connected to the main body by a revolute joint with vertical axis (Figure 2, *vj*), in order to obtain a relative rotation while steering; a second revolute joint with horizontal axis (Figure 2, *hj*) allows the roll of the rear axle on unevenness.

The main body hosts all the actuators and the control and surveillance equipment; therefore the robot centre of mass is very close to the front axle, and the rear axle is lightly loaded; then the robot can pivot about a vertical axis, by imposing opposite angular velocities to the front wheels; in this case the rear axle slides laterally; therefore, an elastic return is introduced on the vertical joint *vj* to limit its angular excursion while pivoting, as it will be discussed in Section 5.

Figure 2 Architecture of the Mantis robot



In case of terrain unevenness or small obstacles, or in presence of low friction surfaces, when the traction of the front wheels is not sufficient, the front legs rotate performing a hybrid legged-wheeled locomotion (Figure 3(a)); the leg outer surfaces belong to a cylinder with axis on the leg revolute joint centre; the two legs can rotate with different speeds to perform differential steering also in the legged-wheeled mode.

When it is necessary to climb over a step, the legs rotate simultaneously, grasping the top surface of the step and lifting up the robot body to overcome the step (Figure 3(b)); the same movement can be performed to climb over high obstacles with different profiles.

During normal wheeled locomotion the front legs can be positioned pointing backwards in rest position (Figure 4(a)), minimizing the robot height and shifting the robot centre of mass towards the rear axle, which reduces the risk of overturn in deceleration; on the contrary, going down a step or a steep slope, legs can be positioned pointing forward to avoid overturn (Figure 4(b)).

Figure 3 Leg action in case of terrain unevenness (a) or step climbing (b)

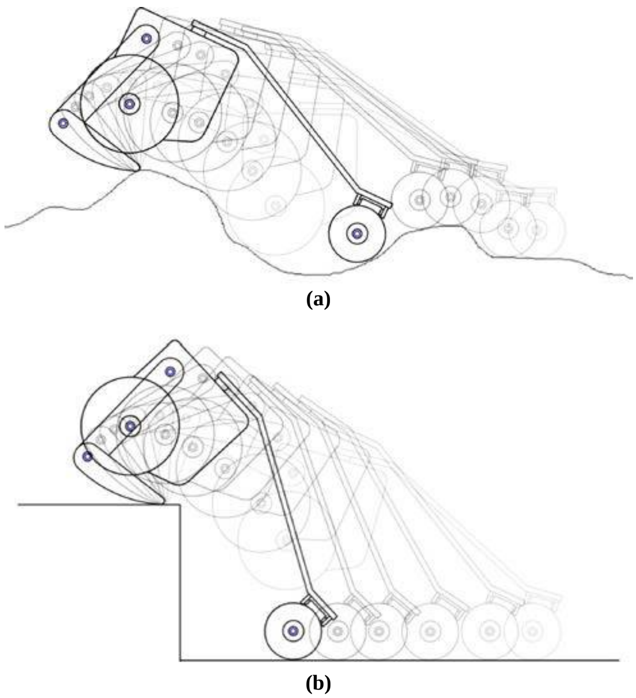
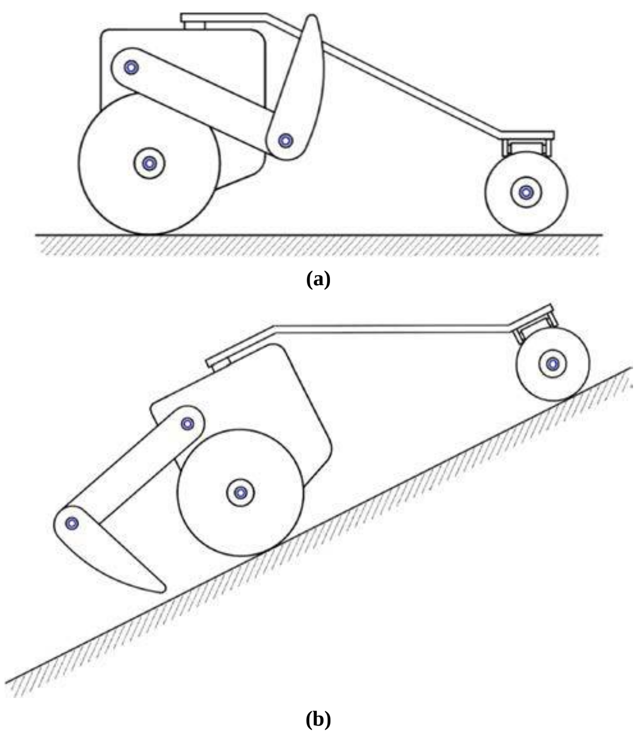
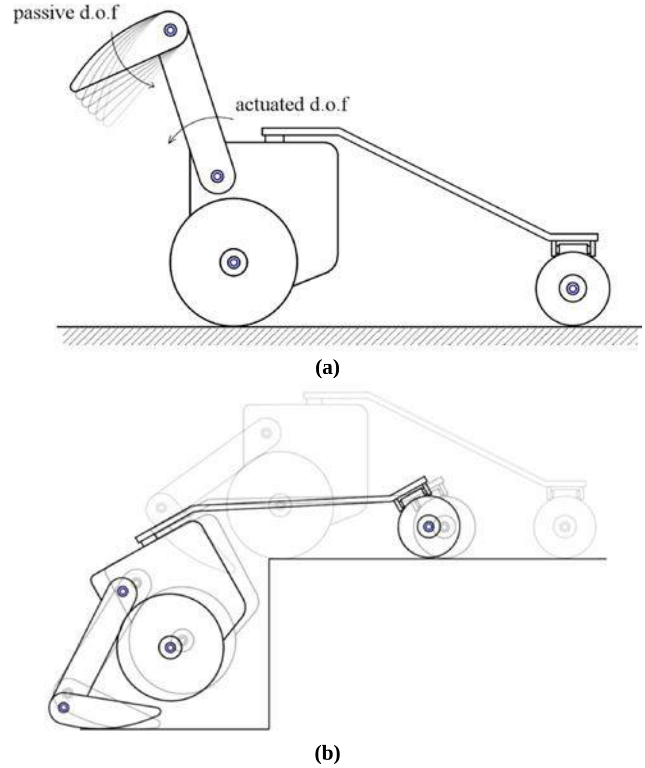


Figure 4 Legs in rest position (a) and in downhill-deceleration position (b)



For the step descent, a passive degree of freedom has been added to the legs to reduce impacts: the end of the leg can bend internally, rotating with respect to the rest of the leg with elastic return force, realizing a sort of shock absorber (Figure 5).

Figure 5 The leg passive degree of freedom with elastic return force (a) absorbs the impacts during the step descent (b)



2.3 Comparison with other locomotion systems for small-scale robots

On flat and even terrains the proposed locomotion system requires a simple control strategy with differential steering, similarly to Epi.q robots with stepping triple wheel and epicyclical transmission, to VIPeR with Galileo wheels and to robots with rotating legs; in case of obstacles or terrain unevenness, the legs intervention must be commanded by the control system. On the contrary, the Epi.q system performs both wheeled and legged movements using a single actuator per locomotion unit, and does not require the active control of the transition between the two modes, which is driven by the dynamic and friction conditions (Quaglia *et al.*, 2011). This simplifies the control strategy, but on the other hand reduces the capability of managing the robot dynamics; in particular, in unfavourable friction conditions the wheel sliding can stop the step climbing with an unwanted transition from legged to wheeled mode. The stepping triple wheel with four actuators per locomotion unit of Spacecat (Siegwart *et al.*, 1998) enhances the control of the robot attitude, but with more actuators and higher control complexity.

With the stepping triple wheels the maximum step which can be climbed is about 85-88 percent of the locomotion unit height for evident geometrical reasons: the upper wheel has to grasp the step edge. Similarly, robots with Galileo wheel or rotating legs are higher than the maximum step which they can climb. On the contrary, Mantis can climb obstacles higher than its height with its legs in rest position.

Using the hybrid legged-wheeled mode on uneven terrains and obstacles, the Mantis locomotion is similar to that of RHex, Loper and ASGUARD, but differently from those, Mantis can

Industrial Robot: An International Journal
Volume 41 · Number 1 · 2014 · 26–36

reach high speed with good energetic efficiency in the wheeled mode; from this point of view, it is even better than Epi.q robots, due to the simplest mechanical transmission; moreover, similarly to robots with stepping triple wheel, but differently from robots with rotating legs, the locomotion without vibrations assures a steady camera vision.

3. Functional design

The geometrical synthesis of the robot is based on several different requirements, and in particular on the analysis of step climbing, which is the most critical issue due to the complex interaction between wheels and legs.

The main geometrical parameters of the robot are shown in Figure 6: r_f, r_r and r_l are, respectively, the radii of the front and rear wheels and of the legs; i is the wheelbase; x'_l and z'_l are the constant coordinates of O_l, which is the intersection of the axis of the actuated leg revolute joints, with the $z'x'$-plane (the robot reference frame (x', y', z') has the third axis perpendicular to the drawing of Figure 6, and its origin is on the robot symmetry plane).

Considering also the step height h, it is possible to define the following geometric ratios:

$$\alpha = \frac{2r_f}{h} \tag{1}$$

$$\beta = \frac{r_r}{r_f} \tag{2}$$

$$\gamma = \frac{i}{r_f} \tag{3}$$

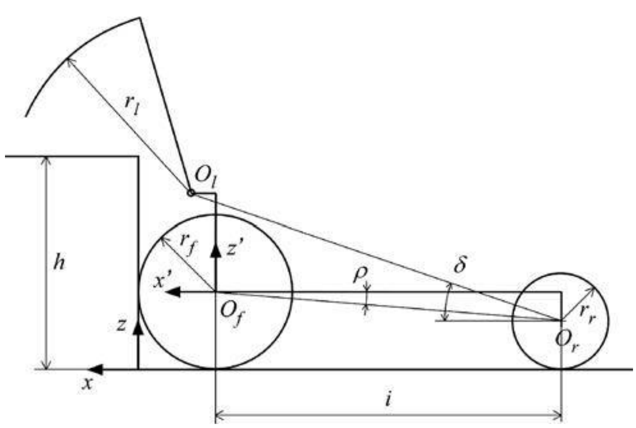
$$\xi_l = \frac{x'_l}{r_f} \tag{4}$$

$$\psi_l = \frac{z'_l}{r_f} \tag{5}$$

$$\gamma_l = \frac{r_l}{r_f} \tag{6}$$

The parameter α defines the robot size with respect to the maximum step which can be climbed; on the contrary, the parameters β, γ, ξ_l, ψ_l, γ_l depend only on the robot geometry and determine the constant frame angles ρ and δ (Figure 6).

Figure 6 Main geometrical parameters of the Mantis robot



During step climbing, the robot trajectory is determined by the coordination between wheels and legs; it is possible to distinguish four phases of the front wheels step climbing (Figure 7):

1 horizontal approach to the step by wheels;
2 vertical lift of the robot body by legs with the front wheels in contact with the step vertical surface;
3 rotation of the front wheels around the step edge; and
4 robot lift of the robot body with the leg outer surface in contact with the step upper surface.

If the front wheels touch the step at the end of phase A (Figure 8, left), the front wheels remain in contact with the step for all phase B, because the legs grasp the step upper surfaces and lift the robot while pulling it forward; on the contrary, if phase A ends without contact with the step, the first contact between front wheels and legs occurs in the middle of phase B (Figure 8, right); in any case, phase B ends when the front wheels touch the step edge. The transition between phases C and D occurs when the front wheels lose contact with the step, and the robot remains suspended on the legs.

During phase D, the pitch angle θ, which is the relative rotation between the robot and the absolute reference frames shown in Figure 6, is maximum when the leg revolute joint is on the vertical projection of the contact point between leg outer surface and step upper surface (Figure 9, left). In this position the gravity force is not sufficient to outbalance the elastic preload of the leg passive degrees of freedom. The maximum pitch angle is expressed by the following equation:

$$\begin{aligned}\theta_{\max} &= \varphi_{\max} - \delta \\ &= \arcsin\left(\frac{\gamma_l + (2/\alpha) - \beta}{\sqrt{(\gamma+\xi_l)^2 + (\psi_l + 1 - \beta)^2}}\right) \\ &\quad - \arctan\left(\frac{\psi_l + 1 - \beta}{\gamma + \xi_l}\right)\end{aligned} \tag{7}$$

The maximum pitch angle and the coordinates of the robot center of mass G (including payload) in the robot reference frame influence the possibility of overturn during step climbing. According to equation (7), the maximum pitch angle can be reduced by increasing the robot length (higher γ), but this lowers the robot agility and hinders pivoting around a vertical axis. Another way to decrease θ_{max} is by adopting $\xi_l > 0$. The three-dimensional graph of Figure 10 shows the values of θ_{max} as a function of γ and ξ_l, for $\alpha = 0.69$, $\beta = 0.82$, $\psi_l = 1.45$, $\gamma_l = 2.90$. On this basis, during the geometrical synthesis, positive values of ξ_l have been selected, because placing the leg revolute joint axis slightly forward than the front axle helps to avoid overturn while maintaining low values of γ.

The static stability margin (SSM) for a given support polygon is defined as the smallest of the distances from the center of mass projection to the edges of the support polygon, and the static stability condition is SSM > 0 (Garcia *et al.*, 2002). In the maximum pitch angle position (Figure 9, left), this stability condition is verified if:

$$\delta_G + \theta_{\max} = \arctan\left(\frac{\psi_G + 1 - \beta}{\gamma + \xi_G}\right) + \theta_{\max} < \frac{\pi}{2} \tag{8}$$

Figure 7 Step climbing phases

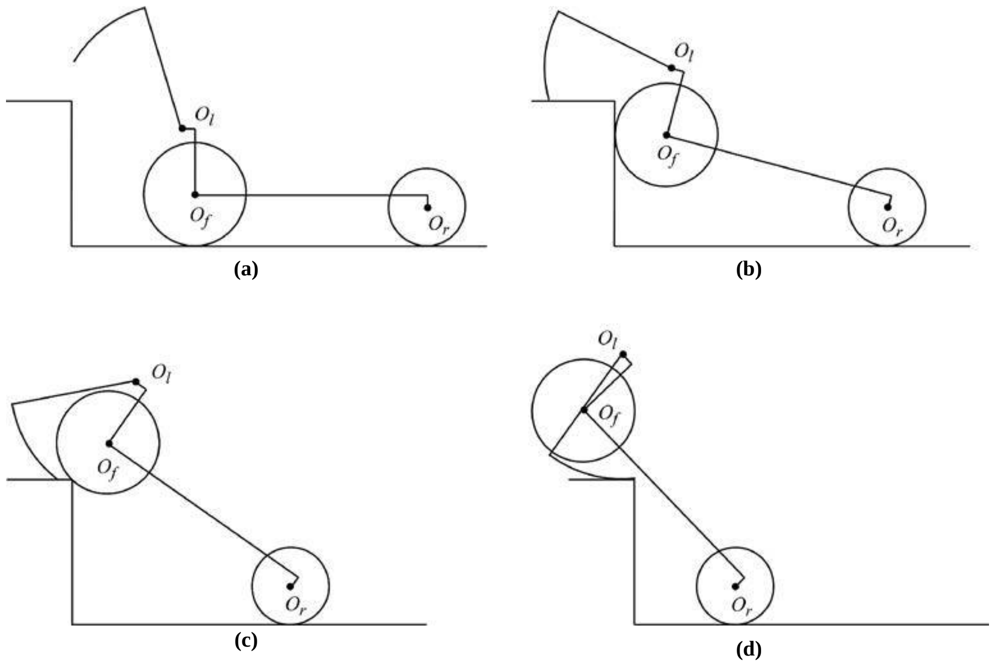


Figure 8 First contact between front wheels and step at the end of phase A (left) or in the middle of phase B (right)

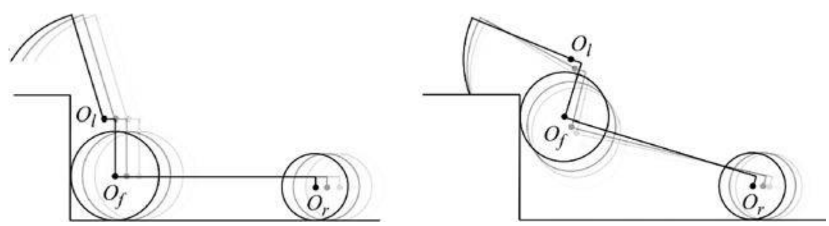


Figure 9 Maximum pitch angle position (left); final position of the step climbing, with the robot suspended on the front wheels and on the legs (right)

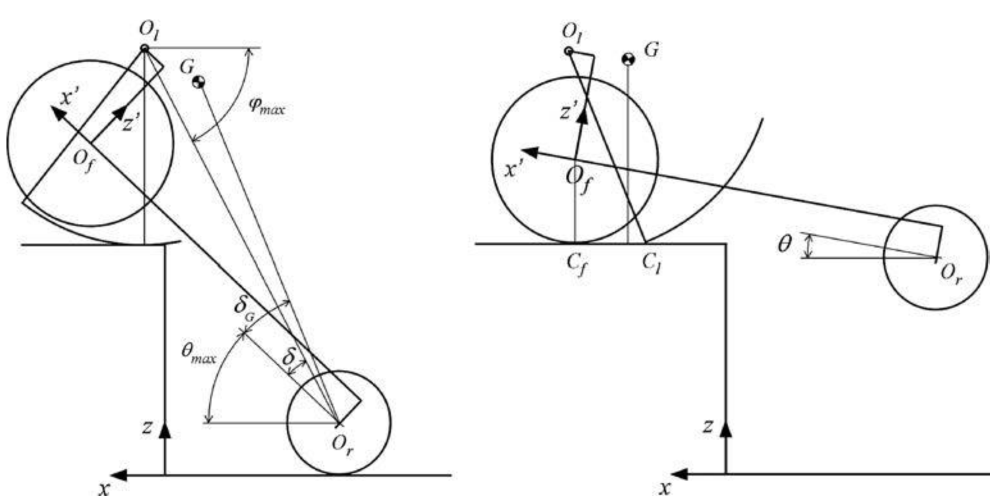
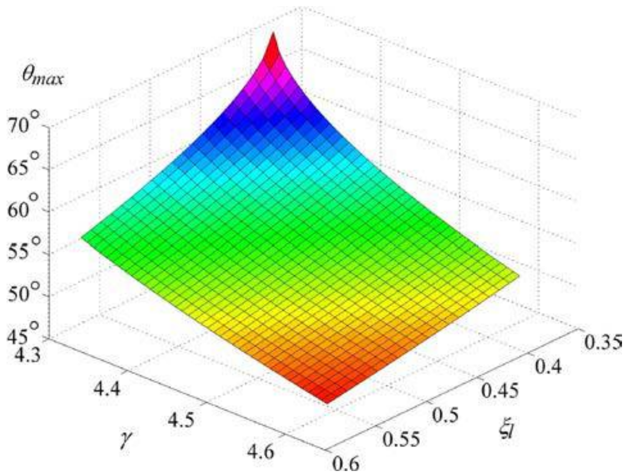


Figure 10 Maximum pitch angle θ_{max} as a function of γ and ξ_l



where:

$$\xi_G = \frac{x'_G}{r_f} \quad (9)$$

$$\psi_G = \frac{z'_G}{r_f} \quad (10)$$

As it will be discussed in Section 5, at the end of phase D, when the front wheels touch the upper step surface, it is necessary to invert the sense of rotation of the legs to lift the rear axle. In this phase (Figure 9, right) the stability condition is verified if the center of mass vertical projection lies between the contact points of front wheels and legs with the step upper surface (C_f and C_l), that is:

$$x_{C_l} < x_G < x_{C_f} \quad (11)$$

Considering the geometry of Figure 9, right, and using the previously defined geometric ratios, it is possible to express the inequalities (10) as follows:

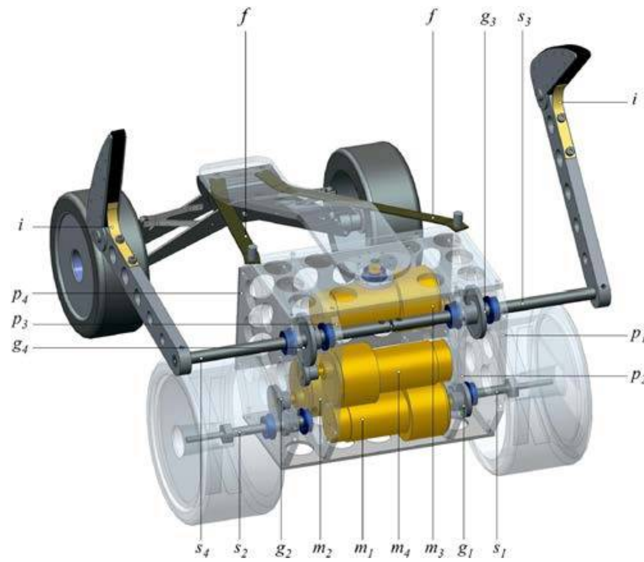
$$\begin{aligned} 0 &< \psi_G\sin(\theta) - \xi_G\cos(\theta) \\ &< \psi_l\sin(\theta) - \xi_l\cos(\theta) \\ &+ \sqrt{\gamma_l^2 - (1 + \psi_l\cos(\theta) + \xi_l\sin(\theta))^2} \end{aligned} \quad (12)$$

4. Embodiment design

The embodiment design and the functional design of the robot are interrelated, because the embodiment design determines the position of the center of mass and therefore the stability conditions discussed in Section 3; therefore the design process has been performed iteratively, starting the functional design with approximated mass properties; then, after implementing the embodiment design, the functional design has been refined on the basis of the actual mass properties. At the end of the design process, the following values of the main geometrical ratios have been selected: $\alpha = 0.69$, $\beta = 0.82$, $\gamma = 4.35$, $\xi_l = 0.58$, $\psi_l = 1.45$, $\gamma_l = 2.90$.

Figure 11 shows the internal layout of the main body of the first Mantis prototype. The gearmotors m_1 and m_2 actuate the front wheels independently, while m_3 and m_4 actuate the legs independently.

Figure 11 Embodiment design: front view

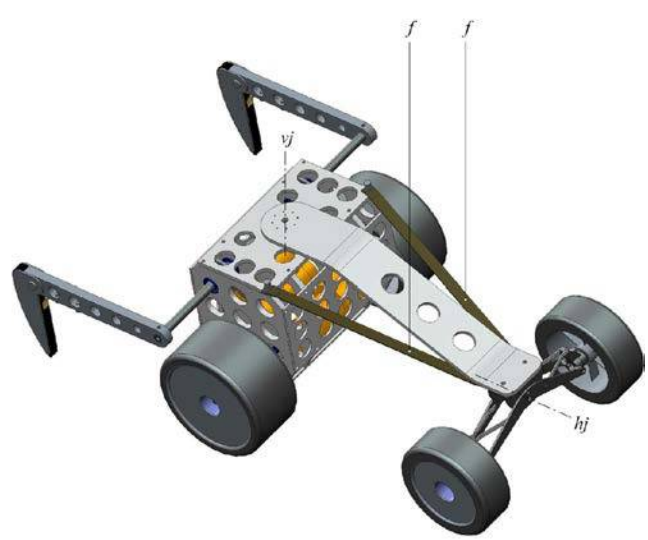


The frame of the main body is characterized by four vertical plates ($p_1 \ldots p_4$), realized in aluminium alloy with lightening holes; the four gearmotors are fixed to the internal plates p_2 and p_3; the shafts of the wheels (s_1, s_2) and of the legs (s_3, s_4) are connected to the internal and external plates by ball bearings. Four gear pairs ($g_1 \ldots g_4$), placed in the two spaces between the internal and external plates, realize the transmission between the output shafts of the gearmotors $m_1 \ldots m_4$ and the shafts $s_1 \ldots s_4$. Also the motor drives and the control system are hosted in the main body.

The elastic bands f (Figures 11 and 12) limit the rotation of the vertical joint vj while the robot pivots around a vertical axis. The flexible elements i (Figure 11) realize the elastic return force for the leg passive degrees of freedom, for shock absorption during step descent (Figure 5).

Figure 13 shows the first Mantis prototype. With its legs placed backward in rest position (Figure 4(a)), the robot overall dimensions are 335 mm (length) × 298 mm

Figure 12 Embodiment design: rear view



Industrial Robot: An International Journal
Volume 41 · Number 1 · 2014 · 26–36

(width) × 160 mm (height). The overall mass is 3.2 kg including a surveillance camera and a 2600 mAh LiPo battery.

The maximum pitch angle during step climbing is influenced by the position of the robot center of mass *G*. The limit of stability can be obtained from the inequality (8) by imposing $\delta_G + \theta_{max} = \pi/2$. The payload influences the coordinates of *G* in the robot reference frame, and consequently the maximum pitch angle. Figure 14 shows the pitch angle at the limit of stability for the Mantis prototype as a function of the payload, considering a payload center of mass located in [0, 0, 125] mm in the robot reference frame (Figure 6), which is a suitable position for the camera. It is worth noting that a large variation in palyoad mass (from 0 to about 25 percent of the robot mass) causes a limited variation of the maximum pitch angle.

5. Experimental tests

The frame sequences of Figures 15-18 show Mantis locomotion features. In particular, Figure 15 shows Mantis climbing a step of 200 mm, 25 percent higher than the robot in rest position; this is the maximum square step that can be climbed, with the robot very close to the limit of stability (Figure 15, frame 5).

Figure 13 The first Mantis prototype

Figure 14 Pitch angle at the limit of stability as a function of the payload

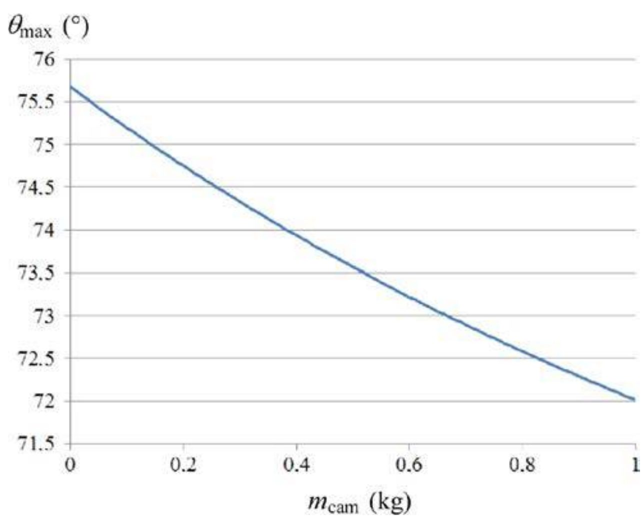
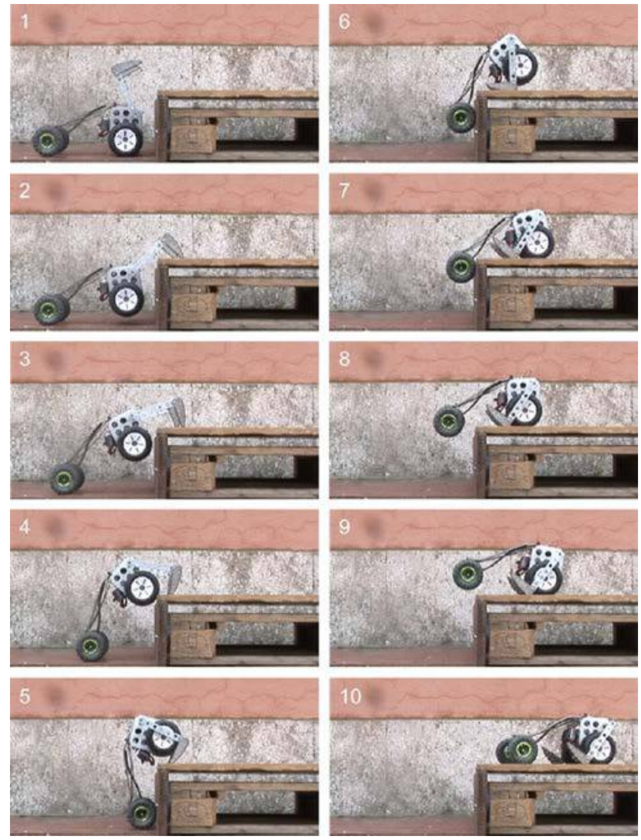


Figure 15 200 mm step climbing (frame interval: 1 s)



The last frames show that after the front wheels touch the upper step surface (frame 7) it is necessary to:

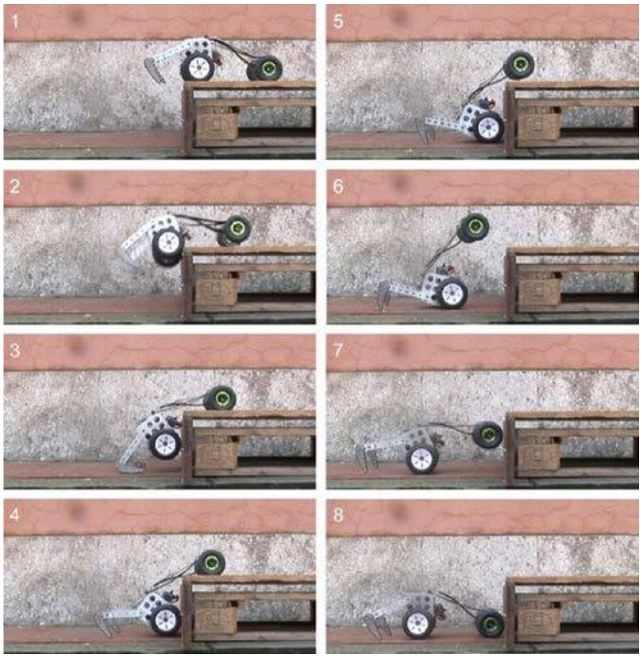
- invert the sense of rotation of the legs to lift the rear axle, and simultaneously move forward the robot by means of the front wheels with the rear axle lifted up, until it is positioned above the step upper surface (frames 8-9);
- lower the rear axle by rotating the legs forward (clockwise in the figure, frame 10).

Figure 16 shows the forward step descent, which exploits the shock absorption of the leg passive degrees of freedom (frames 2-3); after the contact with the terrain, the legs rotates backwards until the front wheels touch the terrain (frames 4-5); then the front wheels move the robot forward (frame 6); when the robot is at a sufficient distance from the step, the rear axle can be lowered by rotating the legs forward (frames 7-8).

The step descent can be carried out also by inverting the climbing procedure (backward descent). With the backward descent, shocks are eliminated; however, shock absorption has been introduced in the legs in order to allow the forward descent for the following reasons:

- if the robot is remotely controlled by using camera vision, the backward descent is possible only if the robot is equipped at least with two cameras, one pointing forward and one pointing backward;
- pivoting before step or obstacle descent may be critical in narrow spaces or in case of uneven terrains;
- stability in the maximum pitch position (Figure 15, frame 5) is more critical in backward descent than in step

Figure 16 200 mm forward step descent (frame interval: 1 s)



climbing, because in the descent the friction of the idle wheels causes overturn; therefore the maximum step in backward descent (about 170 mm) is lower than the maximum step in ascent (about 200 mm); on the contrary, with forward descent it is possible to perform the same step in both directions.

Figure 17 shows the mixed legged-wheeled locomotion on uneven grounds and irregular obstacles. Thanks to the independent rotation of the legs it is possible to realize differential steering also in the legged-wheeled locomotion mode, coping with terrain irregularities. The experimental tests have confirmed the effectiveness of the leg differential steering, which greatly improves the robot manoeuvrability in case of obstacles with asymmetrical shape. See for example Figure 17, frames 7-10: the right leg rotates faster than the left one to correct the trajectory deviation due to an inclined stone. In similar situation it would be impossible to control the trajectory without the differential action of the legs.

Mantis maximum speed is 2.3 km/h on flat ground with the values of gear ratios selected to obtain a high maximum slope climbing ability: 71.5 percent (35.6°) in favourable friction conditions (static friction coefficient between front wheels and terrain ≥ 0.77). Obviously, with different gear ratios it is possible to increase the maximum speed, sacrificing the slope climbing ability.

On indoor floors, imposing the same speed with opposite directions to the front wheels, the robot pivots around a vertical axis which intersects the front axle, assuring maximum manoeuvrability in narrow spaces (Figure 18); at the end of the turn, thanks to the elastic return force of the vertical joint *vj*, the relative rotation of the rear frame with respect to the main body is small (Figure 18, frame 7), and this increases the robot stability in the following motion.

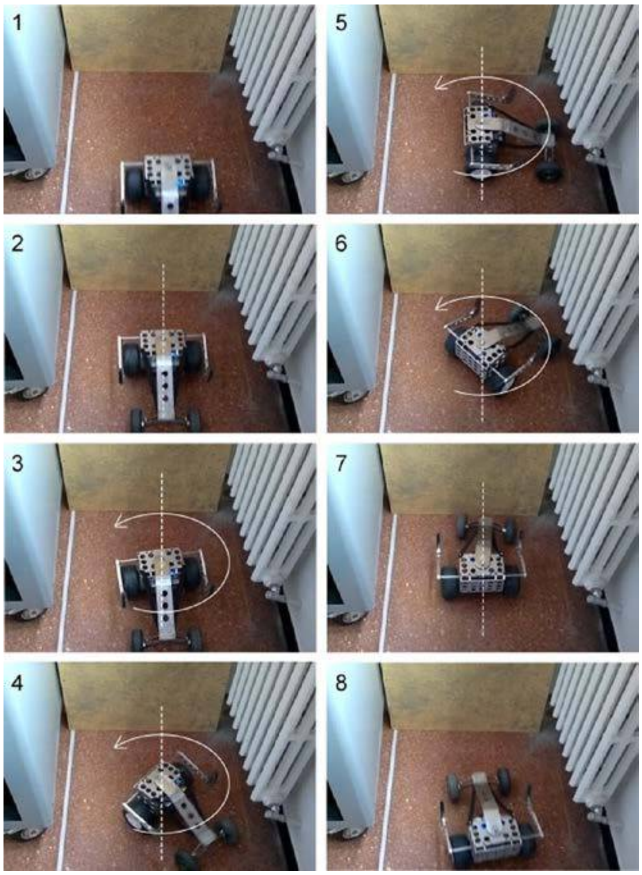
Figure 17 Mixed legged-wheeled locomotion on uneven terrains (frame interval: 1 s)

6. Conclusions

An innovative hybrid leg-wheel, small-scale ground mobile robot for surveillance and inspection, named Mantis, has been designed and tested. Its architecture is characterized by a front main body with two actuated wheels and two actuated rotating legs with praying Mantis leg shape; the rear frame with two idle wheels is connected to the main body by a revolute joint to realize a relative rotation during steering, and a second revolute joint allows the rear axle roll on uneven terrains.

The results of the experimental campaign on the first prototype show that the main design objectives have been fulfilled. In the wheeled locomotion mode the robot moves with high energetic efficiency without oscillations, providing a steady camera vision; this represents an advantage with respect to robots with rotating legs like RHex, Loper, ASGUARD. Moreover, thanks to the elastic return of the vertical revolute joint of the rear frame, the robot is capable of

Figure 18 Robot manoeuvrability in narrow spaces, pivoting around a vertical axis (frame interval: 1 s)



pivoting around a vertical axis on flat grounds, improving the manoeuvrability in narrow indoor environments.

Using its legs, Mantis can climb square steps 25 percent higher than itself with its legs in rest position; this is an advantage with respect to robots with rotating legs or stepping triple wheel, like Epi.q and Spacecat; this feature allows conjugating the climbing ability with the ability of exploring constricted tunnels or interspaces.

In case of uneven, yielding or grassy terrains, traction can be enhanced using the mixed legged-wheeled locomotion mode, realizing a gait similar to small robots with rotating legs. Similarly to Spacecat, the transition from wheeled locomotion to hybrid legged-wheeled locomotion must be actively controlled on the basis of the terrain configuration, and this increases the control complexity with respect to Epi.q and robots with rotating legs.

For its capability of facing a wide range of situations, from indoor structured environments with steps to unstructured outdoor surroundings, and for its peculiar combination of agility, energetic efficiency and mechanical simplicity, Mantis seems to be an efficient and flexible general-purpose mobile platform, suitable for a wide range of potential surveillance, security and intervention applications requiring small tools or miniaturized robot arms (the first prototype has been designed for a maximum payload of 1 kg).

Further research will be focussed on the design of a larger prototype, in order to verify if the proposed hybrid locomotion system is effective also for medium-sized mobile robots with 2-3 kg payload, suitable for a wider range of intervention tasks.

In the development of the following prototypes, alternative mechanical schemes of the rear axle will be tested. The experimental tests have shown that the elastic return force on the vertical joint of the robot improves the robot manoeuvrability in narrow spaces on even grounds, causing a lateral skid of the rear axle that keeps it rather aligned with the main body at the end of a pivoting (Figure 18), and this is positive for the robot stability in continuing the motion. Nevertheless, alternative solutions for the rear axle can be tested in order to obtain a kinematically correct steering, such as a single rear spherical wheel or a single rear castor wheel.

Furthermore, future investigations will be focussed on the development of an automatic navigation system (the first Mantis prototype is radio-controlled by a human operator); to this aim, one of the main issue is the definition of a control strategy capable of coordinating wheels and legs in case of step climbing and step descent or in case of irregular obstacles. Moreover, a fully autonomous navigation system for unstructured environments requires the adoption of efficient visual odometry and terrain reconstruction algorithms, which are today an important research area. These scene interpretation techniques are not related to a specific locomotion type; however, the integration between the scene interpretation and the Mantis locomotion planning is a challenging research topic.

References

Altendorfer, R., Moore, N., Komsuoglu, H., Buehler, M., Brown, H.B. Jr, McMordie, D., Saranli, U., Full, R. and Koditschek, D.E. (2001), "RHex: a biologically inspired hexapod runner", *Autonomous Robots*, Vol. 11 No. 3, pp. 207-213.

Birk, A. and Carpin, S. (2006), "Rescue robotics: a crucial milestone on the road to autonomous systems", *Advanced Robotics*, Vol. 20 No. 5, pp. 596-605.

Bruzzone, L. and Quaglia, G. (2012), "Locomotion systems for ground mobile robots in unstructured environments", *Mechanical Sciences*, Vol. 3, pp. 49-62.

Eich, M., Grimminger, F. and Kirchner, F. (2009), "Adaptive compliance control of a multi-legged stair-climbing robot based on proprioceptive data", *Industrial Robot: An International Journal*, Vol. 36 No. 4, pp. 331-339.

EURON and EUROP (2009), *The Strategic Research Agenda for Robotics in Europe*, Technical Report, EUropean RObotics research Network, European RObotics technology Platform, available at: www.robotics-platform.eu/sra

Garcia, E., Estremera, J. and Gonzalez de Santos, P. (2002), "A classification of stability margins for walking machines", *Robotica*, Vol. 20, pp. 595-606.

Germann, D., Hiller, M. and Schramm, D. (2005), "Design and control of the quadruped walking robot ALDURO", *Proceedings of the 22nd International Symposium on Automation and Robotics in Construction, ISARC 2005, Ferrara, Italy, September 11-14*.

Gonzalez Rodriguez, A., Gonzalez Rodriguez, A. and Rea, P. (2011), "A new articulated leg for mobile robots", *Industrial Robot*, Vol. 38 No. 5, pp. 521-532.

Guccione, S. and Muscato, G. (2003), "The Wheeleg robot", *IEEE Robotics & Automation Magazine*, December, pp. 33-43.

Hamel, W.R. and Cress, R.C. (2001), "Elements of telerobotics necessary for waste clean up automation", *Proceedings of the IEEE International Conference on Robotics and Automation*, pp. 393-400.

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Herbert, S.D., Drenner, A. and Papanikolopoulos, N. (2008), "Loper: a quadruped-hybrid stair climbing robot", *Proceedings of the 2008 IEEE Conference on Robotics and Automation, Pasadena, CA, May 19-23*.

International Federation of Robotics (2012), *World Robotics 2012 – Service Robots*, available at: www.ifr.org/service-robots/statistics/ (accessed 13 November 2013)

Lauria, M., Piquet, Y. and Siegwart, R. (2002), "OCTOPUS: an autonomous wheeled climbing robot", *Proceedings of 5th International Conference on Climbing and Walking Robots (CLAWAR)*, pp. 315-322.

Manchester, I.R., Mettin, U., Iida, F. and Tedrake, R. (2011), "Stable dynamic walking over uneven terrain", *International Journal of Robotics Research*, Vol. 30 No. 3, pp. 265-279.

Murphy, R.R. (2004), "Rescue robotics for homeland security", *Communications of the ACM – Homeland Security*, Vol. 47 No. 3, pp. 66-68.

Playter, R., Buehler, M. and Raibert, M. (2006), "Bigdog", *Proceedings of the SPIE Defense&Security Symposium, Unmanned Systems Technology*.

Prassler, E. and Kosuge, K. (2008), "Domestic robotics", in Siciliano, B. and Khatib, O. (Eds), *Springer Handbook of Robotics*, Springer, Heidelberg, pp. 1253-1281.

Quaglia, G., Bruzzone, L., Bozzini, G., Oderio, R. and Razzoli, R. (2011), "Epi.q-TG: mobile robot for surveillance", *Industrial Robot*, Vol. 38 No. 3, pp. 282-291.

Quinn, R.D., Nelson, G.M., Bachmann, R.J., Kingsley, D.A., Offi, J.T., Allen, T.J. and Ritzmann, R.E. (2003), "Parallel complementary strategies for implementing biological principles into mobile robots", *International Journal of Robotics Research*, Vol. 22 No. 3, pp. 169-186.

Raibert, M.H. (1986), *Legged Robots That Balance*, MIT Press, Cambridge, MA.

Seeni, A., Schafer, B., Rebele, B. and Tolyarenko, N. (2008), "Robot mobility concepts for extraterrestrial surface exploration", *Proceedings of the IEEE Aerospace Conference*, pp. 1-14.

Siegwart, R. and Nourbakhsh, I.R. (2004), *Introduction to Autonomous Mobile Robots*, MIT Press, Cambridge, MA.

Siegwart, R., Lauria, M., Maeusli, P.A. and Van Winnendael, M. (1998), "Design and implementation of an innovative micro rover", *Proceedings of Robotics 98, the 3rd Conference and Exposition on Robotics in Challenging Environments*.

Six, K. and Kecskeméthy, A. (1999), "Steering properties of a combined wheeled and legged striding excavator", *Proceedings of the 10th World Congress on Theory of Machines and Mechanisms, Oulu, Finland, June 20-24*, Vol. 1, pp. 135-140.

Snyder, R.G. (2001), "Robots assist in search and rescue efforts at WTC", *IEEE Robotics and Automation Magazine*, Vol. 8 No. 4, pp. 26-28.

Tadakuma, K., Tadakuma, R., Maruyama, A., Rohmer, E., Nagatani, K., Yoshida, K., Ming, A., Shimojo, M., Higashimori, M. and Kaneko, M. (2010), "Mechanical design of the wheel-leg hybrid mobile robot to realize a large wheel diameter", *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp. 3358-3365.

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3. Jean-Christophe Fauroux, Frédéric Chapelle, Belhassen-Chedli Bouzgarrou, Philippe Vaslin, Mohamed Krid, Marc DavisMechatronic Design of Mobile Robots for Stable Obstacle Crossing at Low and High Speeds 567-630. [CrossRef]