

A new articulated leg for mobile robots

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Purpose: The paper presents a new mechanical scheme for a leg to be included in legged vehicles that aims to simplify the control actuations along the stride.

Design/methodology/approach: The scheme includes three four-bar links grouped in two mechanisms: the first one that decouples the vertical and horizontal movements of the foot and the second ones that produces a constant horizontal foot velocity when the corresponding motor is actuated with a constant speed reference. A hybrid locomotion robot has been simulated and constructed to validate the leg performance.

Findings: The gait control requires only five commands to the electronic cards to control the cycle of a leg. Decoupling vertical and horizontal movements allows a more adequate selection of actuators. Additional mechanical benefits, such as higher robustness and lower inertia are obtained.

Research limitations/implications: A hybrid robot improves the stability with respect to a legged robot. This way the lateral movement is not a concern, and therefore it has not been tested yet.

Originality/value: This new scheme obtains a quasi-Cartesian behaviour for the foot movement that drastically simplifies the walking control. Although the decoupling between movements has already been presented in previous papers, these schemes seemed not to guarantee a constant horizontal velocity under constant speed reference of the corresponding motor. These schemes were also suitable for crab-like gaits, not mammal-like ones.

Abstract: This paper presents the design, simulation and experimental tests on a new articulated leg that can be used either for legged or hybrid mobile robots. In particular, the synthesis of the so-called primary and secondary mechanisms constituting the leg has been performed with the main objectives of obtaining: a) fast and easy-controlled motion in obstacle free environment and b) flexible and robust motion in uneven terrain or obstacles. In order to pursue these targets we have proposed a synthesis of the primary mechanism to get an almost straight line trajectory during the support phase and the synthesis of the secondary mechanism to obtain a constant velocity of the leg-tip point during the support phase by means of a constant input angular velocity. Simulations have been carried out in ADAMS environment to verify the results of the synthesis procedures and a prototype has been built and tested providing first experimental results.

Keywords: Mobile Robots, Legged Robots, Kinematic Analysis and Synthesis.

1. Introduction

Many walking robots have been developed in the last decades. They can be classified according to the type of locomotion they perform as: wheeled, tracked, legged or hybrid robots (Sandin, 2003). A number of developed prototypes tried to mimic the walking in nature that is a complex task involving mechanics, electronics, sensing and control. Wheeled and tracked mobile robots can perform fast and robust motion on flat terrain, but they are ineffective in overpassing obstacles that are greater, or even near, than the radius (dimension) of the wheel (track). In principle, legged robots can go where wheeled ones cannot, so they have a potential utility that justifies the extra effort required to control their locomotion.

Legs are a flexible and effective option and allow the robot to move on uneven terrain and natural environments, since they can easily adapt to the geometry of the terrain. They can also move on soft terrains like sand or mud.

Legged robots are therefore considered promising systems but their design and control can be very complex, furthermore, energy consumption is often high. Several examples of legged robots can be found in the literature with four, six or more legs, examples are TITAN (Hirose et al., 1991, Palmer and Orin, 2006). Most of these systems use quasi-static locomotion (Song and Waldron, 1989) Statically stable locomotion requires at least four legs and usually the number of legs is high for many reasons, but mainly for increasing the speed of locomotion and stability (Cobano 2008). Furthermore, the gait is a sequence of static-equilibrium configurations, which means high robustness, safety and adaptability to the geometry of the terrain; and the control of the gait is easier than for dynamic gaits (Figliolini and Rea, 2007). In addition, if particular gait schemes are adopted, e.g., double-tripod gait, the “quasi-static” motion is achieved without any need of assessing the robot equilibrium at the different gait configurations (Gonzalez de Santos et al., 2005; Figliolini et al., 2006).

Furthermore, the biped locomotion can be considered one of the most sophisticated forms of motion. From a dynamic point of view performing a gait synthesis on biped robots is a useful way for understanding the dynamic principles of human walking. In (McGeer, 1990) the concept of Passive Dynamic Walkers (PDW) was introduced to show that it is possible to perform stable bipedal walking without any actuation or control. A passive motion considered as “natural” usually meet requirements of energy optimality, therefore, the investigation of such motions may potentially lead to develop control strategies useful for active walking machines.

A number of researchers focused their attention to extensions of this concept. In this line of work, the concept of Controlled Passive Walking was introduced in (Van Ham et al., 2007) during the design of a biped robot with mechanically adjustable compliance. Also the concept of Limit Cycle Walking has been introduced to expand the concept of PDW to actuated biped robots (Hobbelen et al., 2008).

It is evident by reported works and literature, that legged robots have favorable characteristics for obtaining flexible and robust motion, but suffers of some drawbacks, such as energy consumption but also stability and locomotion speed, both if we are dealing with two, four, six or more legs. Legs therefore need to have a workspace that ensures them a foothold (taking forbidden zones into consideration), to support both body and payload, and to cross over obstacles (Gonzalez de Santos et al., 2005; Figliolini et al., 2009).

A successful example of legged locomotion in rough terrain is obtained by the BigDog (Raibert et al., 2008), for which a dynamically balanced trot gait is adopted. BigDog balances using an estimate of its lateral velocity and acceleration, determined from the sensed behavior of the legs during stance combined with the inertial sensors.

Hybrid systems were developed to exploit the terrain adaptability of legs in rough terrain and simpler control as well as high speed related with wheels. From an historical point of view, a system using both legs and wheels was not new, because the wheel barrow and bullock cart have been used since the early days of civilization. However, legged animals were an integral part of these systems and the design of fully artificial hybrid systems started much later.

There are two types of hybrid systems. The first solution makes use of wheels and articulated legs working independently. An articulated leg can provide traction for obstacle climbing when the wheel cannot. This scheme is used for example in (Guccione and Muscato, 2003), in which two driven wheels and pneumatic legs are used in order to improve its all-terrain capability. The prototype proposed in (Ottaviano et al., 2004) is a low-cost 1-DOF hybrid robot with two legs and two passive wheels. The prototype proposed in (Wellman et al., 1995) consists of a four-wheel wheelchair with two legs for obstacle climbing. An innovative prototype of a wheelchair capable of climbing stairs has been proposed in (González et al., 2007).

A second type of hybrid locomotion robots uses a wheel that is installed at the extremity of an articulated leg. The articulated leg is used to locate the wheel in a suitable place avoiding

surfaces with slopes that cannot be climbed by the wheel traction. This scheme is explained in (Grand et al., 2004) in which a prototype is proposed with passive wheels that can roll like a skater or walk like a legged robot. The prototypes reported in (Aarnio et al., 2000; Halme et al., 2003) are rovers with four driving wheels located at the end of the legs. The rovers are able to move in highly unstructured environments. In (Yuan and Hirose, 2005) a solution is proposed as a leg-wheel hybrid stair climbing wheelchair, which consists of eight independent prismatic-joint legs and eight wheels. This prototype can perform safe stable three-dimensional motion. The prototype in (Hirose and Takeuchi, 1996) is a robot able to walk using legs as a conventional legged robot and is also able to skate with passive wheels attached to the end of each leg. The robots in (Wilcox et al., 2007; Germann et al., 2005) are big sized hybrid locomotion robots.

A different scheme of hybrid legged-wheel approach is presented in (Eich et al., 2009) that uses one rotating actuator for driving one or more legs around one axis.

In this paper we present a kinematic analysis, synthesis and simulation of a new articulated leg to be used for mobile robots, either legged or hybrids, with the main objective of obtaining a fast and low energy consumption motion both on flat and uneven terrain (with obstacles). According to the classification presented in (Kar, 2003) the leg design falls into the gravitationally decoupled mechanisms, and with the advantages of a three-dimensional pantograph leg.

Unlike the traditional decoupled configurations (Hirose et al., 1991; Baños et al., 1992; Adachi et al., 1988), the leg is not laterally connected to the hip (like a crab), but in a vertical way (like mammals). This configuration adds new features to the structure from the point of view of the capacity load and leg workspace. Another advantage is that the linear actuator requiring a faster performance has been replaced into a rotational one, as in the small low-cost robot presented in (Ottaviano et al., 2004), that uses a pantograph mechanism and a Chebyshev linkage.

However the main contribution of the presented design over decoupled configurations is the proportionality between the horizontal movement speed and the corresponding actuator speed. This feature, together with the decoupled operation, facilitates the control of the trajectory, reduces the energy loss and allows a more adequate selection of actuators (Hirose et al., 1991).

Section 2 presents the leg design and describes its degrees of freedom and characteristics.

Section 3 describes the synthesis process of the primary mechanism for horizontal and vertical movements.

Section 4 describes the synthesis process of the secondary mechanism to move the leg tip at a constant velocity.

Section 5 shows the simulation results that validate the synthesis analysis.

In section 6, first experimental results are shown for a built prototype of a hybrid robot named as LEBREL, standing for LEg Bioinspired Robot with Efficient-operation Limbs.

Finally in section 7, the conclusions of the work are presented.

2. A new articulated leg for mobile robots

The proposed leg mechanism has been synthesized in order to obtain: a) fast and easy controlled walking operation in obstacle-free environment and b) flexible and robust motion in uneven terrain. The first goal requires simple inverse kinematic functions as references for the motors control laws, but at the same time the leg must be efficient even when dealing with obstacle avoidance. In general, if the control operation is easier, the motion can be performed in a faster way and the speed of the legged robot would be considerable increased, which is one of the crucial issues in legged robots.

The leg mechanism must have also flexible operation in order to behave in several environments, such as unstructured terrains, stairs and obstacles. According to these requirements the leg mechanism has been designed with 3 DOF in order to achieve a flexible operation. The 3

DOFs allow positioning the leg-tip P in any point of its workspace. According to the scheme of Fig. 1, 2 DOFs are required to obtain vertical (a) and horizontal (b) motion of the leg in the sagittal plane. This result has been achieved by considering one revolute (I) and one prismatic (II) actuators placed at point H and at link 4, respectively, while the transversal motion (c) can be obtained through another prismatic actuator (III) placed between links 1 and 2 (Gonzalez et al., 2009).

The mechanism for vertical and horizontal movements of point P has been designed as a planar mechanism with 2 DOFs, as it is shown in Fig. 1, it will be called as “primary mechanism”. The plane of the movement is parallel to the direction of movement and contains the leg-tip point P and the hip point H. The actuation of the above-mentioned planar mechanism can be obtained by means of an electric motor (I) and a linear actuator (II). This mechanism will be synthesized to provide an approximate straight trajectory segment during the support phase. In this phase only the active revolute joint (I) is operating, while the linear actuators (II) and (III) remain inactive, as it is shown in Fig. 1a). Point P can be lifted using the linear actuator (II) during the swing phase, as it is shown in Fig. 1b). The third DOF allows rotating the plane of movement with respect to an axe parallel to the sagittal plane and containing the hip, and it is driven by the linear actuator (III), as it is shown in fig 1c).

Once the vertical, lateral and horizontal movements of the leg-tip P are decoupled, different maximum velocities, torques and forces for the actuators can be chosen for every movement, according to the proposed scheme. This is an important advantage since the requirements for speed and force are different depending on the kind of movement. Therefore, motors with less power and weight can be used to drive a robot if a correct reduction gear is used.

In particular, during the support phase and mainly the swing phase, the rotational actuator (I) should provide a large velocity if a fast motion is desired for the robot, although not an important torque is required for this movement. In contrast, actuator (II) must deliver a high force to withstand the whole robot weight plus payload, and in this case the ascent/descent leg velocity is not a major concern. With regard to the linear actuator (III), their desired characteristics are similar to the actuator (I).

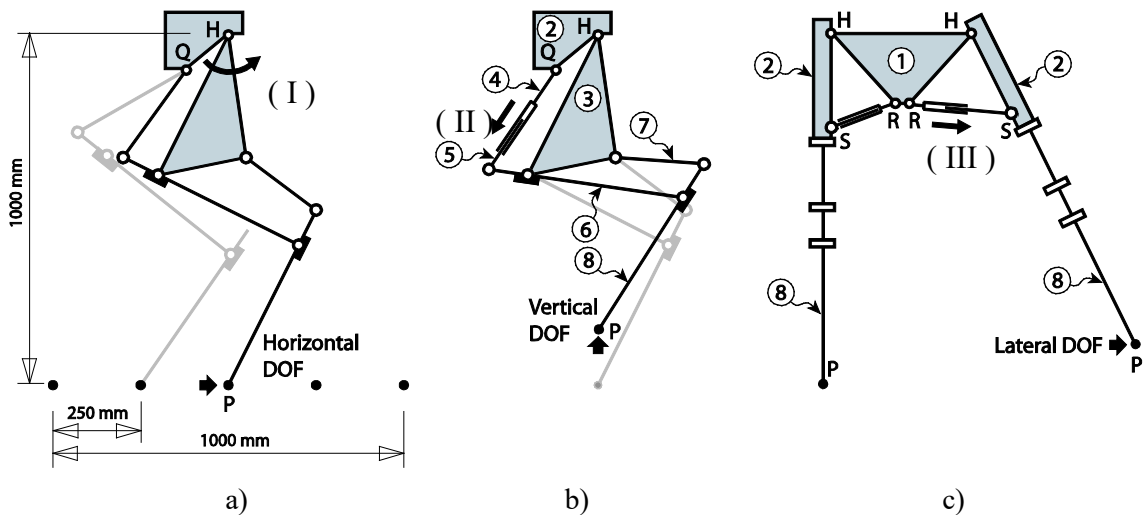


Figure 1 A scheme for the proposed articulated leg (primary mechanism): a) Horizontal DOF of the proposed leg and position precision points for synthesis; b) Vertical DOF and labels for leg's links; c) a scheme for the lateral DOF.

A drawback of the above mentioned solution is that the leg-tip point P follows a suitable trajectory but does not possess constant velocity during the support phase. The operation of the leg mechanism in Fig. 1 can be improved by adding a new four bar mechanism (links labelled 9 and 10 in Figure 2), that is the so called “secondary mechanism”. The new four bar mechanism

has been included in order to provide a quasi-constant velocity at leg-tip point P, when the input link 10 of the mechanism has a constant angular velocity. According to the scheme of Fig. 2 the actuation (I) has been moved from link 3 (point H) to link 10 (point T). The advantage of considering a secondary mechanism can be recognized as obtaining a quasi-constant velocity at point P during the support phase by providing a constant input angular velocity of the actuator (I) as shown in Fig. 2.

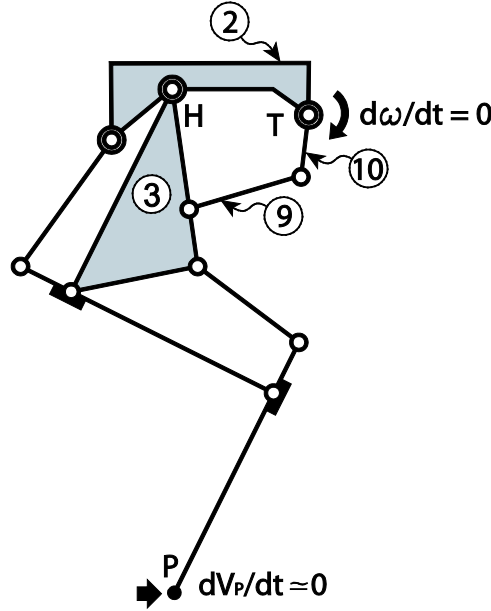


Figure 2. A scheme of the additional four-bar mechanism (links 2, 3, 9, 10) called as “secondary mechanism” to achieve a constant velocity at point P with constant velocity at point T.

3. Synthesis of the primary mechanism for horizontal and vertical movements

To perform the synthesis of the primary mechanism, the position analysis will be carried out according to the scheme in Fig. 3. The goal of the synthesis is to obtain a mechanism that provides an approximate straight line trajectory segment of the leg-tip P. It is worth to note that the motion is achieved by actuator (I) while the prismatic one (II) is locked. The linear actuator (II) is modeled by the vector $\mathbf{r}_2$ in Fig. 3. The length of this segment changes when the P point follows a vertical movement, but for the synthesis of the support phase, the module of vector $\mathbf{r}_2$ remains constant, in this way the mechanism will be synthesized as 1 DOF mechanism.

Indeed, the system in Fig. 3 is composed by two four bar mechanisms: the first one can be modeled by vectors $\mathbf{r}_1$, $\mathbf{r}_2$, $\mathbf{r}_3$ and $\mathbf{r}_5$; the second one can be modeled by vectors $(\mathbf{r}_3 - \mathbf{r}_4)$, $\mathbf{r}_6$, $\mathbf{r}_7$ and $\mathbf{r}_9$. The input link of the first four-bar mechanism (vectors $\mathbf{r}_3$ and $\mathbf{r}_4$) is the frame of the second one, and the coupler of the first four-bar mechanism (vector $\mathbf{r}_5$) is joined to the input link of the second one (vector $\mathbf{r}_6$, where $\mathbf{r}_5$ and $\mathbf{r}_6$ are collinear). The goal of the synthesis problem is to provide a 1m approximate straight segment for the trajectory of point P in support phase.

The second DOF of the mechanism is provided by a linear actuator (II) that allows changing the length of the output link of the first four bar mechanism (vector $\mathbf{r}_2$), as it is shown in Fig. 1b). This second DOF is responsible for the vertical movement of the foot.

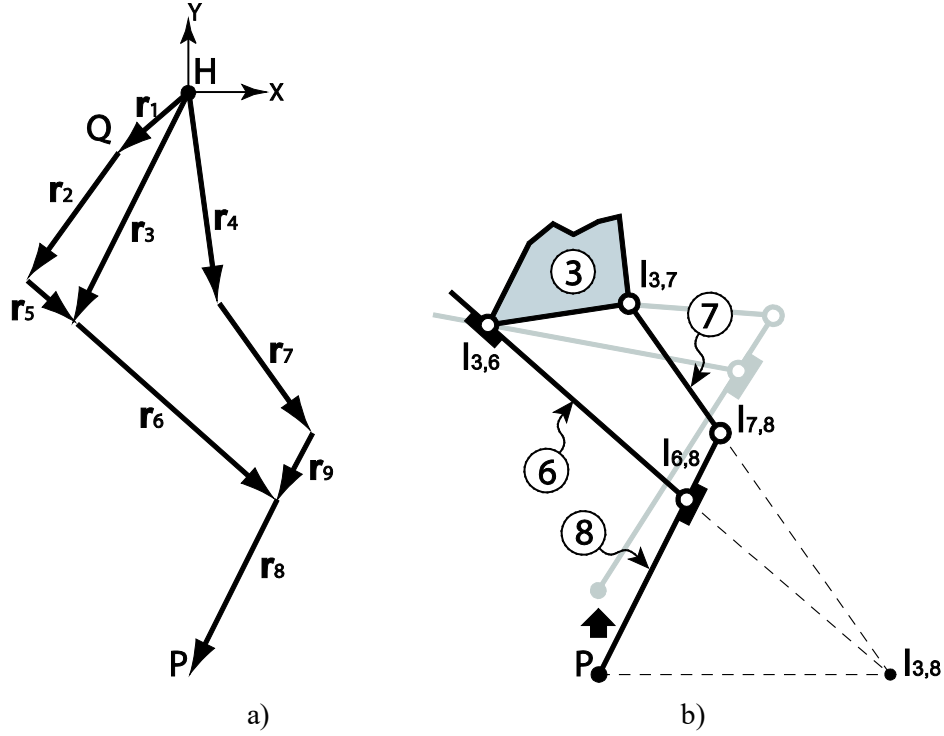


Figure 3. A scheme for the primary mechanism: a) Vectors used in the synthesis problem; b) Position of the Instantaneous Centre of Rotation of link 8 respect to 3 to obtain a vertical movement at the center of the point P trajectory.

The synthesis of the primary mechanism can be performed by using five precision points. Vectors will be labeled as $\mathbf{r}_{jk}$ where j is the index of the vector as shown in Fig. 3; and k refers to the precision point where the point P is located. The precision points are shown in Fig. 1a).

Vectors $\mathbf{r}_{jk}$ can be expressed as $\mathbf{r}_{jk} = \rho_j \exp(i\theta_{jk})$. Obviously ρ_j only has an index because lengths of vectors are the same for all precision points.

According to the scheme in Fig. 3a) where the origin is placed at point H and assuming a vertical coordinate of -1m for the precision points, the position equations can be expressed as (for $j = 1, \dots, 5$)

$$\begin{aligned} \mathbf{r}_{1j} + \mathbf{r}_{2j} + \mathbf{r}_{5j} + \mathbf{r}_{6j} + \mathbf{r}_{8j} &= -\mathbf{i} - 0.5 + (j-1) \cdot 0.25 \\ \mathbf{r}_{1j} + \mathbf{r}_{2j} + \mathbf{r}_{5j} - \mathbf{r}_{3j} &= 0 \\ \mathbf{r}_{3j} + \mathbf{r}_{6j} - \mathbf{r}_{4j} - \mathbf{r}_{7j} - \mathbf{r}_{9j} &= 0 \end{aligned} \quad (1)$$

Equations (1) represent a system of 15 complex equations, which become 30 scalar equations. The number of unknowns is 54, where 9 unknowns are ρ_j and 45 unknowns are θ_{jk} .

The number of unknowns can be reduced:

- If one considers $\mathbf{r}_{1k}$ fixed, then $\theta_{1k} = \theta_{11}$ for $k = 2, \dots, 5$. Therefore the number of unknowns is reduced by 4.
- Vectors $\mathbf{r}_{5k}$, $\mathbf{r}_{6k}$ are imposed to be collinear, and vectors $\mathbf{r}_{8k}$, $\mathbf{r}_{9k}$ are also collinear, in this way $\theta_{5k} = \theta_{6k}$ and $\theta_{8k} = \theta_{9k}$ with $k = 1, \dots, 5$. This reduces the total number of unknowns by 10.
- Vectors $\mathbf{r}_{5k}$, $\mathbf{r}_{6k}$ belong to the same link (link number 3) this consideration gives four constraint equations $\theta_{3k} - \theta_{4k} = \theta_{31} - \theta_{41}$. where $k = 2, \dots, 5$. Therefore, it results in 34 equations and 40 unknowns.

- In this context we have imposed 5 lengths of the links of the mechanism as: $\rho_3 = 0.4$ m, $\rho_5 = 0.1$ m, $\rho_6 = 0.4$ m, $\rho_8 = 0.4$ m, $\rho_9 = 0.1$ m.

A last condition will be imposed to the mechanism. When point P is placed at precision point 3 and actuators change length of vector $\mathbf{r}_2$, point P must describe a vertical trajectory. This condition is equivalent to the condition of horizontality of segment $PI_{3,8}$, where $I_{3,8}$ is the instantaneous centre of rotation of link 8 with respect to link 3. This is due to the fact that the point P will have a velocity with respect to the link 3 (which is the fixed bar in this configuration) perpendicular to segment $PI_{3,8}$. The above-mentioned configuration is shown in Figure 3b).

This condition can be expressed by using the sine theorem. It gives

$$\rho_9 \frac{\sin(\theta_{73} - \theta_{93})}{\sin(\theta_{63} - \theta_{73})} = \rho_8 \frac{\sin(\theta_{93})}{\sin(\theta_{63})} \quad (2)$$

Solving these 35 equations with 35 unknowns all vectors can be determined for the 5 precision points for P. Remaining vectors modules and angle of the fixed link 1 can be evaluated as:

$$\begin{aligned} \rho_1 &= 0.1153 \text{ m} \\ \theta_{11} &= 4.4313 \text{ rad} \\ \rho_2 &= 0.2268 \text{ m} \\ \rho_4 &= 0.3664 \text{ m} \\ \rho_7 &= 0.3194 \text{ m} \end{aligned}$$

4. Synthesis of the secondary mechanism to move the leg tip at a constant velocity.

The additional four-bar linkage (secondary mechanism) in Fig. 2 has been considered to give to point P a constant velocity during the support phase when a constant velocity is provided at the input link 10. An optimization algorithm has been used in order to obtain the smallest variation of velocity of point P, when the actuation is placed at point T with a constant angular velocity.

With this aim, a constant velocity at point P has been imposed, obtaining the corresponding angular velocity at link 3. This angular velocity will be called as ω^* . Figure 4 shows ω^* when a constant velocity of 150 mm/s is given to point P. The function ω^* in Fig.4 is obtained with an ADAMS simulation of the leg mechanism. Therefore horizontal velocity of point P will be constant velocity when the angular speed of link 3 in Fig. 2 were ω^* . The four bar mechanism has been synthesized to give rise to this speed for link 3 when a constant velocity is given to the input link of the four bar mechanism (labeled 10 in Fig. 2).

For the leg design the secondary mechanism has been synthesized with the following constraint: a constant velocity for a trajectory segment of 0.6 m centered with respect to the approximate straight trajectory of point P. This segment corresponds to an initial value $\theta_{3\text{initial}} = 4.826$ rad and final value $\theta_{3\text{final}} = 5.408$ rad of the link 3 rotation.

An optimal synthesis procedure has been used with the objective of obtaining a secondary mechanism that gives a profile of angular velocity for link 3 as close as possible to profile ω^* , as shown in Fig. 4, in which β is shown in Fig. 5a).

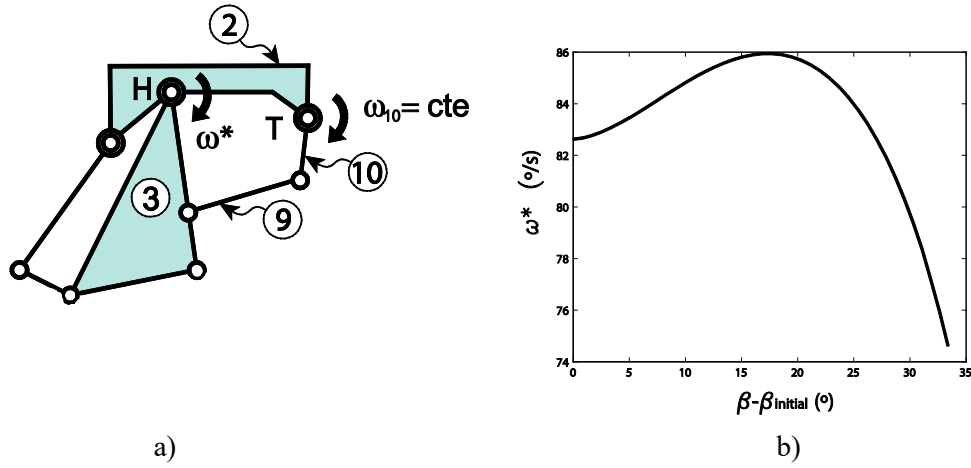


Figure 4. Secondary mechanism: a) A scheme; b) Angular velocity ω^* of link 3 obtained when a constant velocity of 150 mm/s is given to P.

The angular velocity of link 10, ω_{10} , can be expressed as a function of angular position of link 3, ω_{10} , by using the instantaneous centre of rotation of link 3 with respect to link 10 ($I_{3,10}$) [Eardman & Sandor, 1998]. Since the relative linear velocity $V_{I_{3,10}}$ with respect to link 3 can be evaluated as $\omega_3(L+a)$ (see Fig. 5), and with respect to link 10 can be evaluated as $\omega_{10}L$, one can write

$$\omega_3 = \frac{L+a}{L} \omega_{10} \quad (3)$$

By using the cosine theorem one can write

$$(M+c)^2 = (L+a)^2 + d^2 - 2d(L+a)\cos(\pi - \beta) \quad (4)$$

$$r^2 = b^2 + c^2 - 2bc \cos \gamma \quad (5)$$

$$L^2 = b^2 + M^2 - 2bM \cos(\pi - \gamma) \quad (6)$$

where a , b , c , L , M , β and γ are shown in Fig. 5b). L can be obtained as

$$L = \frac{AB + (c^2 + r^2 - b^2)\sqrt{Ar^2 - AB^2}}{(c^2 + r^2 - b^2)^2 - 4c^2B^2} \quad (7)$$

with

$$\begin{aligned} r &= \sqrt{a^2 + d^2 + 2ad \cos \beta} \\ A &= 2b^2c^2 + 2b^2r^2 + 2c^2r^2 - b^4 - c^4 - r^4 \\ B &= A + d \end{aligned} \quad (8)$$

When L is known, ω_3 can be evaluated using expression (3).

An error function E can be introduced. It depends on the geometry of the four-bar mechanism in Fig. 5b) as $E = E(a, b, c, d, \varphi)$. Since the relationship between ω_3 and ω_{10} does not depend on the overall size of the mechanism, one can impose one parameter. Therefore, we consider $b = 0.143$ m.

An optimization algorithm is implemented by considering the minimization of the error as

$$E = \int_{\beta_{initial}}^{\beta_{final}} (\omega_3 - \omega^*) d\beta \quad (9)$$

where $\beta_{initial} = \theta_{3initial} - \pi - \varphi$ and $\beta_{final} = \theta_{3final} - \pi - \varphi$, according to the scheme of Fig. 5a).

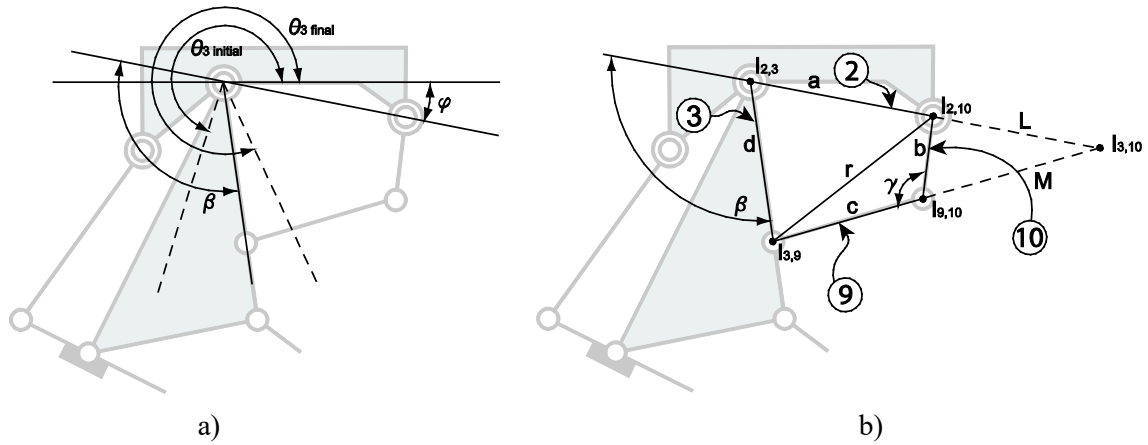


Figure 5. A scheme for: a) Angle β used in the optimization process. b) Positions of the Instantaneous centers of rotation.

An optimization algorithm has been implemented in Matlab environment according to the above-mentioned formulation. The results of the optimization process are the length of parameters of the secondary mechanism. The solution obtained is $\varphi = 0.151$ rad, $a = 0.340$ m, $c = 0.348$ m and $d = 0.250$ m.

5. Simulation of the Proposed Leg.

According to the results of the synthesis of the primary and secondary mechanisms reported in the previous Sections, simulations have been carried out to study the motion of leg-tip P. A CAD model has been designed. Then the geometry has been exported to ADAMS environment. The first tests have been carried out to obtain the workspace of the leg mechanism. To get this result, both actuators of the primary mechanism have been moved from their initial position to their maximum strokes. The resulting workspace shown in Fig. 6 is sufficient to overcome obstacles higher than 500 mm. In this figure the origin is located at the hip point H.

The centre line within the workspace is the trajectory of the point P when a movement starts from the third precision point. This movement is obtained by using only the actuator (II) for the vertical motion, while actuator (I) remains inactive.

In order to verify the result of the synthesis for the primary mechanism, a trajectory has been generated to pass through the precision points. For this trajectory only the actuator (I) is active, while the actuator (II) is locked.

Figure 7 shows the trajectory of point P obtained during this simulation. Deviation from a straight line trajectory during the support phase is less than 2 mm with respect to the imposed value of 0.6 m, representing an error less than 0.4%.

Figure 7 shows also the velocity of point P when the motor for horizontal movement provides a constant speed of 150 deg/s for a step of 0.6 m, thus resulting in a velocity of point P of 1.5 m/s. In this case the velocity variation is about 0.1 m/s which represent an error of 7%.

These small variations can be considered fully assumable, but error in velocity of point P may even be reduced with a more compliant control of the horizontal motion motor when the point P is in contact with the ground.

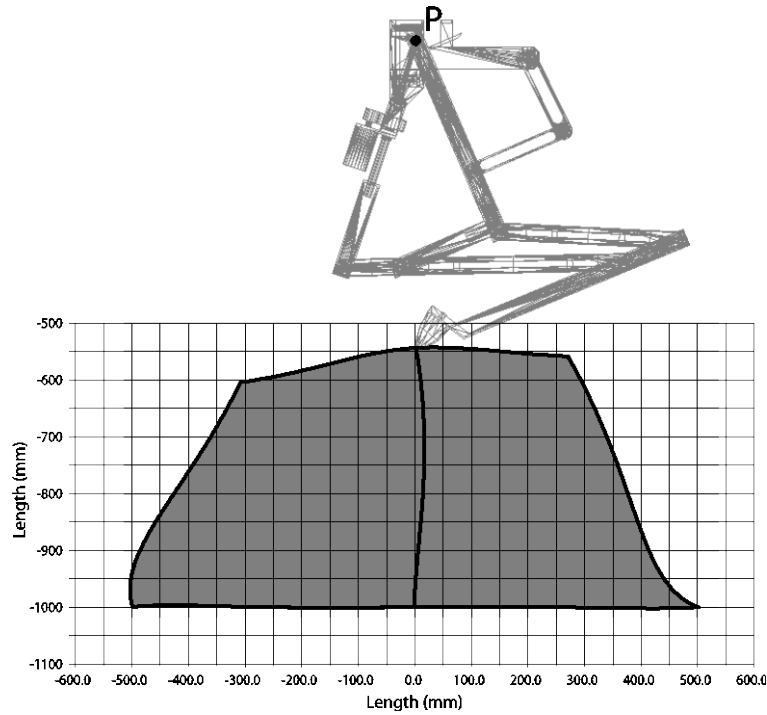


Figure 6. Workspace of the proposed leg obtained with ADAMS.

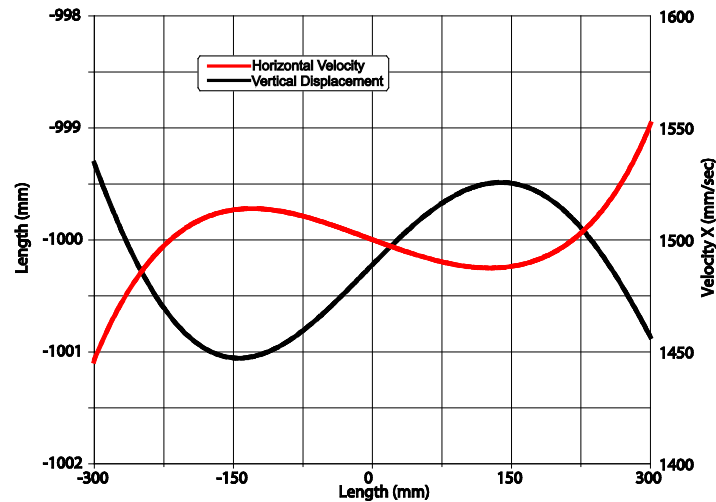


Figure 7. Trajectory and velocity of point P when the actuator for the vertical motion is extended and the motor for horizontal motion provides a constant angular velocity of 150 deg/s.

According to the simulation of the new articulated leg, a hybrid mobile robot has been developed to explore its behaviour during a walking operation. The robot, shown in Fig. 8, is composed by a chassis, two articulated legs and two passive wheels. The walking operation has been executed with simple control signals. These signals, shown in the Fig. 9, can be summarized as (Gonzalez et al.,2009):

- The actuator for the horizontal motion provides a constant speed when the foot is in contact with the ground, while the actuator for the vertical motion is inactive.
- When the leg reaches the end of the step the actuator for the vertical movement begins to raise the leg and the horizontal motor changes the direction of the speed for the swing phase.
- In the middle of the swing phase, the motor for the horizontal motion begins to slow down the horizontal velocity and, simultaneously, the actuator for the vertical movement starts the descent of the leg.
- When the point P starts the contact with the ground it has the required horizontal speed to start the next step.

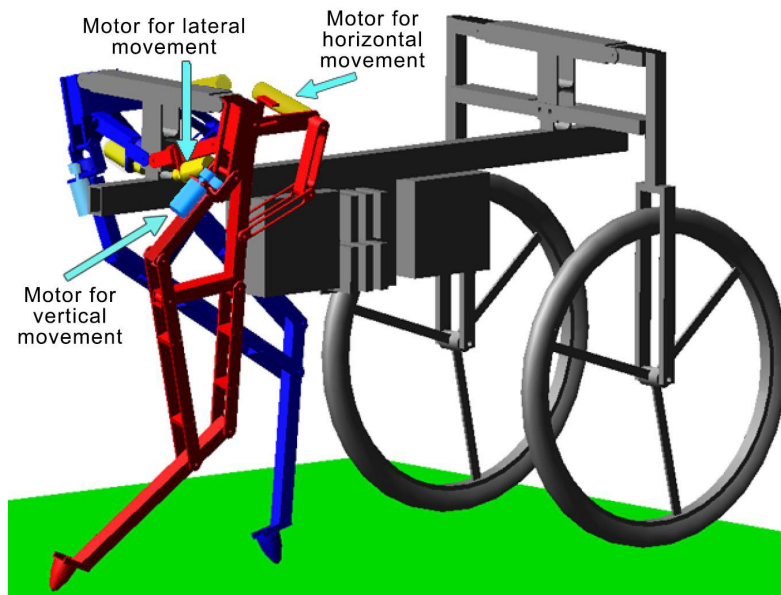


Figure 8. A hybrid mobile robot to simulate the behavior of the proposed articulated leg.

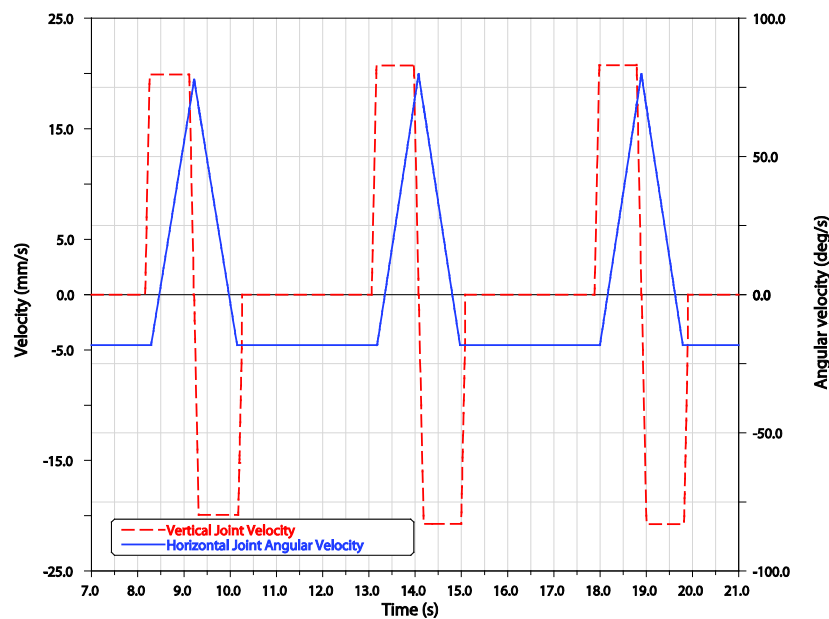


Figure 9. References values the actuators for vertical and horizontal motions.

The input signals in Fig. 9 have been used as references for the PI controllers that establish the forces and torques for the leg actuators. Figure 10 shows simulated velocities of point P with respect to time obtained in ADAMS environment. In Fig. 11 the trajectory of the point P is shown.

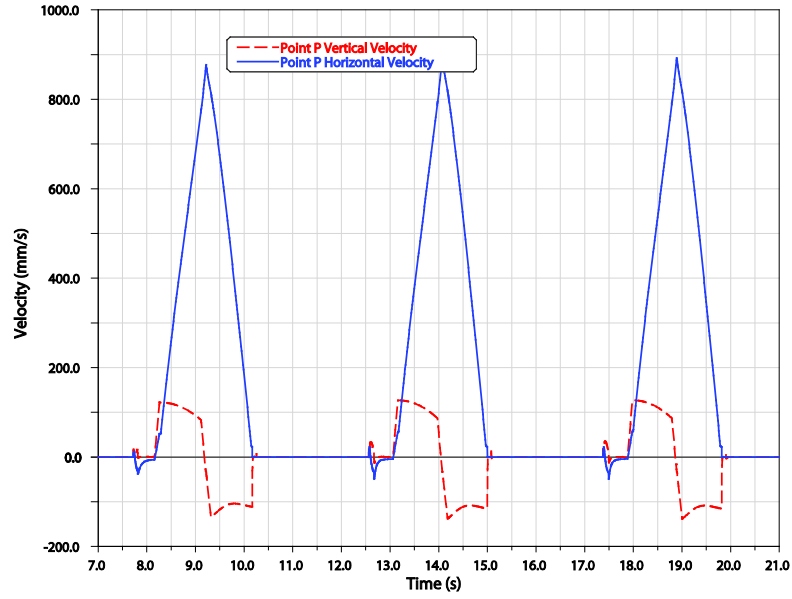


Figure 10. Simulated velocities of point P when actuators (I) and (II) have the reference velocities reported in Fig. 9.

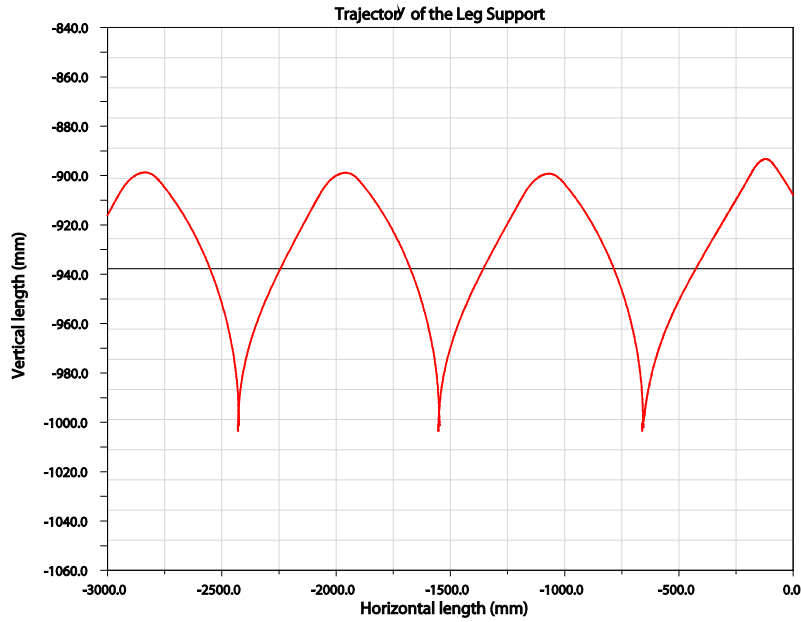


Figure 11. Trajectory of point P obtained in ADAMS environment.

6. Experimental results

A prototype of the proposed articulated leg has been built for experimental testing according to the results of the synthesis and simulations reported in previous Sections. Four legs have been built; two legs ended in two rubber feet and two legs ended in two wheels. This way, the quadruped robot named as LEBREL has been built (see Fig. 12a)). Maxon motors with suitable electronic boards are used to drive the legs. It is worth to note that the reference signals used to drive the robot are those used in the ADAMS simulation of Fig.9.

Experimental tests have been carried out in laboratory environment and the steps have been recorded with the Optotrack system. This system uses infrared markers whose position is recorded by three cameras. Figure 12b) shows the robot and the cameras used in experimental tests. An infrared marker was placed at point P of one leg. Figure 13 shows the horizontal and vertical coordinates of point P with respect to time. Figure 14 shows the velocity of point P. These plots show how simple control signals allow the robot to walk smoothly.

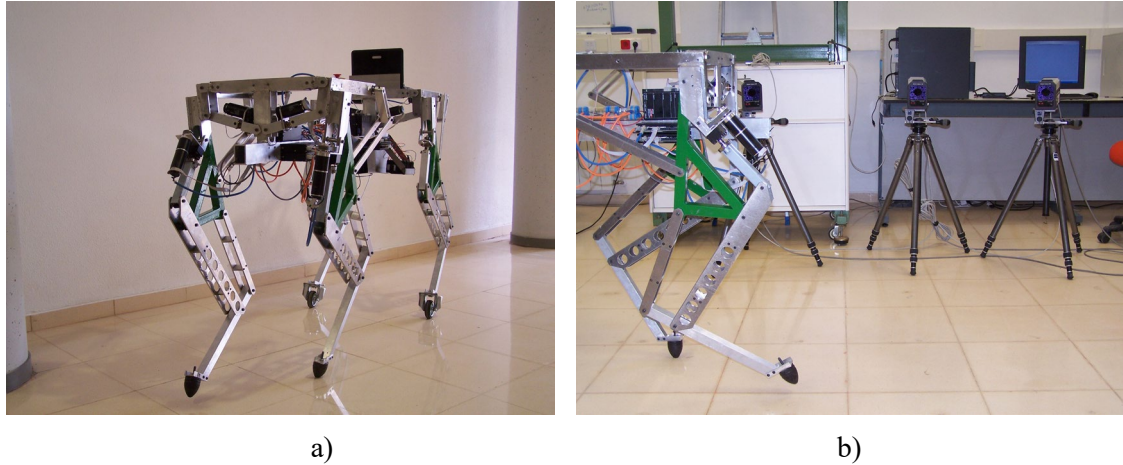


Figure 12. Robot LEBREL: a) a prototype; b) set up for the experimental tests with Optotrack system.

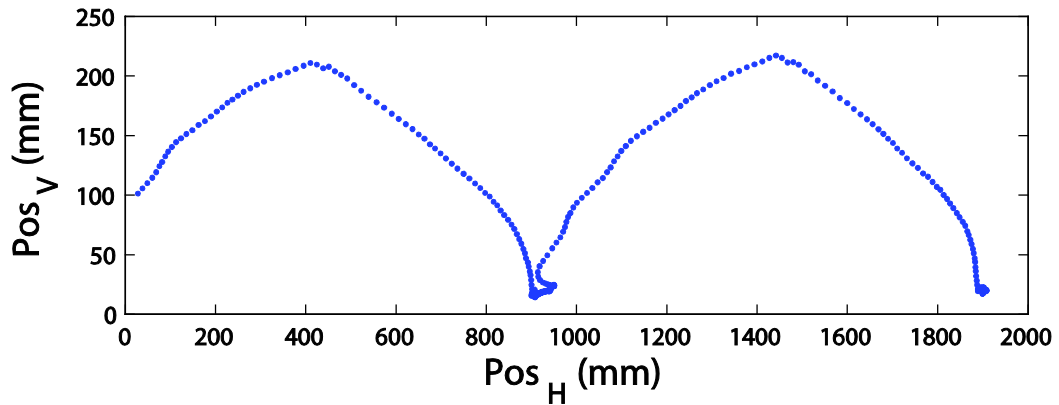


Figure 13. Horizontal and vertical coordinates of point P obtained with the Optotrack system in Fig. 12.

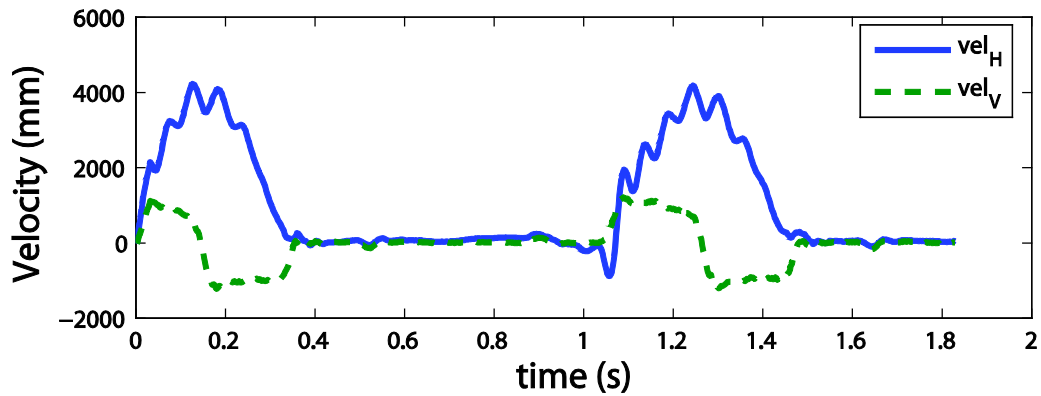


Figure 14. Experimental results of the leg end-point P velocity obtained with Optotrack system.

7. Conclusions

In this paper the synthesis, design and simulation results are presented for an articulated leg that can be used for legged or hybrid mobile robots. The proposed leg has been synthesized having three DOFs and being easy to control in flat terrain. To accomplish the last requirement the leg has been synthesized to provide an almost straight line segment during the support phase, by actuating over only one motor (the first actuator). In addition, during the support phase the leg design pursues to obtain a proportionality between the actuator angular speed and the foot linear speed. With these features, the control system operations can be greatly simplified.

A second actuator is responsible for the leg vertical movements, and its long stroke will allow the leg to overpass high obstacles. The third actuator allows the leg turning and it will be used to achieve the lateral stability of the legged robot.

In essence, the leg mechanism is composed by a primary and secondary mechanism. Both of them have been synthesized to let the leg being suitable for walking on flat or uneven terrains. Another advantage of the proposed solution is that the actuation choice is optimized for each kind of movement. In order to verify that the articulated leg accomplishes these requirements, numerical simulations and experimental tests have been carried out. Simulations have been performed by means of a hybrid robot with two wheels and two legs. The reported simulations have proved that the system operates with a control system that can greatly simplify the coordination of the actuation system. A first prototype of a quadruped mobile robot named as LEBREL has been built for laboratory tests, which show successful results and good match with numerical ones.

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