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Conference Paper · July 2007

DOI: 10.1109/MED.2007.4433829 · Source: IEEE Xplore

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Proceedings of the 15th Mediterranean Conference on
Control & Automation, July 27 - 29, 2007, Athens - Greece

A Design of a New Leg-Wheel Walking Robot

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Abstract—**In this paper the analysis and design are presented for a 1-DOF (Degree-Of-Freedom) leg-wheel walking machine. A preliminary prototype of a low-cost robot, which is capable of a straight walking with only one actuator, has been designed and built at LARM: Laboratory of Robotics and Mechatronics in Cassino. Simulation and experimental validation have been carried out to verify the operation of the prototype.**

I. INTRODUCTION

The walking in nature is a very flexible and complex task. For example, in generating a trajectory several parts/systems are involved: muscle as actuators, bones as linkages, nerves as sensors and brain as a complex control system [1]. Moreover, locomotion type depends on several variables. For example, one of the most influent aspects ca be considered the environment characteristics. While the legged locomotion is more adaptable in a wide range of ground, the wheeled locomotion is faster but only on smooth surfaces. The most common walking machines are wheeled and tracked systems, but large interest is also focused on legged machines. A leg should generate an approximately straight-line trajectory of a foot point with respect to the body, as outlined in references [1-5].

The use of legs and wheels can be a good compromise for a walking machine combining the advantages of the both locomotion types. An interesting application can be, for example, the improvement of the mobility of a wheelchair with a four-link mechanism obtaining a staircase-climbing wheelchair [6]. Another useful application can be the use of mobile robotic systems in rough, unstructured terrain, such as underground mines, forests, disaster sites, and planetary explorations as outlined in [7].

In this paper a new prototype of leg-wheel walking robot is proposed with low-cost easy-operation features. The leg structure, shown in Fig. 1, has one DOF (degree of freedom) and it is possible to have one actuator moving both legs while wheels are passive.

In the paper a kinematic analysis of the leg structure is proposed and the results of a numerical simulation are reported with design and operation considerations.

Then, the design of the 1 DOF hybrid robot prototype is presented together with simulations of operations. Finally a built prototype is presented together with experimental tests, and considerations on its behaviour are outlined.

II. A 1-DOF LEG FOR WALKING MACHINE

A. Design of the leg

The leg architecture is composed by a Chebyshev mechanism and a Hart mechanism and it is shown in Fig.1. The Chebyshev mechanism generates an approximately straight-line trajectory. The lengths of the links are determined in such a way that the shape of the leg end point trajectory is similar to the shape of a man's ankle. Moreover, the straight part of the trajectory is very accurate. It is an important aspect in order to avoid the body raising during the walk. The Hart mechanism inverts and amplifies the trajectory, as shown in Fig. 2. The amplification factor, from point B to point A, is approximately of 2. Thus, the body can move horizontally by moving the feet and legs.

Several walking robots have a design containing a pantograph as fundamental mechanism and even Chebyshev linkage has been used for actuator purposes [8-9], as experienced at LARM in Cassino, [10-17].

In Table 1 design parameters of the leg system in Fig. 1 are reported as calculated through repeated analysis procedures and parametric calculations. The values of transmission angle, velocity and acceleration of significant points, and design leg parameters have been determined through a parametric study of kinematic performance of the system via simulations.

B. A Kinematic model

A kinematic analysis has been developed in order to evaluate and simulate performances and operations of the leg system. A fixed reference system C**XY** has been considered attached at body in point C, as shown in Fig.1. The actuated link is LE. The position of point B with respect to C**XY** frame can be evaluated as a function of the input crank angle α and kinematic parameters of the Chebyshev mechanism LEBDC in the formletters for

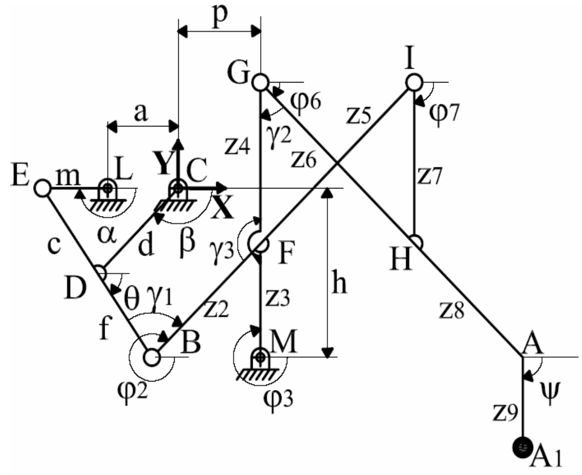


Figure 1. A kinematic scheme for the new 1-DOF leg

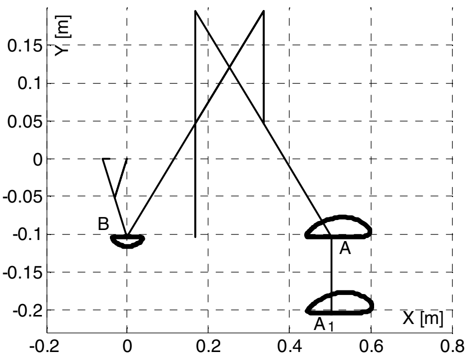


Fig 2. Simulated trajectories for leg operation in leg mechanism in Fig.1.

table footnotes (Table I).

$$X_B = -a + m\cos\alpha + (c+f)\cos\theta$$
$$Y_B = -m\sin\alpha - (c+f)\sin\theta \tag{1}$$

The position of point A with respect to the fixed frame can be given as

$$X_A = X_M - (z_3+z_4)\cos\varphi_3 + (z_6+z_8)\cos\varphi_6$$
$$Y_A = Y_M + (z_3+z_4)\sin\varphi_3 - (z_6+z_8)\sin\varphi_6 \tag{2}$$

The position of point A1 with respect to the fixed frame can be given as

$$X_{A1} = X_A + z_9\cos\psi$$
$$Y_{A1} = Y_A - z_9\sin\psi \tag{3}$$

The transmission angles shown in Fig. 1 can be evaluated as

$$\gamma_1 = -\theta + \varphi_2 - \pi$$
$$\gamma_2 = \varphi_3 - \varphi_6 - \pi \tag{4}$$
$$\gamma_3 = \varphi_3 - \varphi_2 + \pi$$

The velocity of points B, A and A1 can be evaluated by using time derivatives from Eqs. (1) to (3).

Angles θ, φ_2, φ_3 and φ_6 can be evaluated as

$$\theta = 2\tan^{-1}\left(\sin\alpha - \frac{\sqrt{\left((\sin\alpha)^2 + B^2 - D^2\right)}}{B+D}\right)$$

$$\varphi_2 = 2\tan^{-1}\left(-K_2 + \frac{\sqrt{K_2{}^2 - 4K_1K_3}}{2K_1}\right)$$

$$\varphi_3 = 2\tan^{-1}\left(-L_2 + \frac{\sqrt{L_2{}^2 - 4L_1L_3}}{2L_1}\right) \tag{5}$$

$$\varphi_6 = 2\tan^{-1}\left(-M_2 + \frac{\sqrt{M_2{}^2 - 4M_1M_3}}{2M_1}\right)$$

where

$$B = \cos\alpha - \frac{a}{m}$$

$$D = \frac{a}{c}\cos\alpha - \frac{a^2 + m^2 + c^2 - d^2}{2md}$$

$$K_1 = -2X_B z_2 + 2X_M z_2 + X_B^2 + X_M^2 +$$
$$z_2^2 + Y_B^2 + Y_M^2 + z_3^2 - 2X_B X_M - 2Y_B Y_M$$
$$K_2 = +4Y_B z_2 - 4Y_M z_2$$
$$K_3 = 2X_B z_2 - 2X_M z_2 + X_B^2 + X_M^2 +$$
$$z_2^2 + Y_B^2 + Y_M^2 + z_3^2 - 2X_B X_M - 2Y_B Y_M$$
$$L_1 = 2X_M z_3 - 2X_B z_3 + X_B^2 + X_M^2 +$$
$$z_3^2 + Y_B^2 + Y_M^2 - z_2^2 - 2X_B X_M - 2Y_B Y_M$$
$$L_2 = -4Y_B z_3 + 4Y_M z_3 \tag{6}$$

$$L_3 = -2X_M z_3 + 2X_B z_3 + X_B^2 + X_M^2 +$$
$$z_3^2 + Y_B^2 + Y_M^2 - z_2^2 - 2X_B X_M - 2Y_B Y_M$$
$$M_1 = -2X_G z_6 + 2X_I z_6 + X_G^2 + X_I^2 +$$
$$z_6^2 + Y_G^2 + Y_I^2 - z_7^2 - 2X_G X_I - 2Y_G Y_I$$
$$M_2 = -4Y_G z_6 + 4Y_I z_6$$
$$M_3 = 2X_G z_6 - 2X_I z_6 + X_G^2 + X_I^2 +$$
$$z_6^2 + Y_G^2 + Y_I^2 - z_7^2 - 2X_G X_I - 2Y_G Y_I$$

The acceleration of point A1 can be obtained, with respect to the fixed frame

$$\ddot{X}_{A1} = \dot{\varphi}_3^2(z_3+z_4)\cos\varphi_3 + \ddot{\varphi}_3(z_3+z_4)\sin\varphi_3 +$$
$$-\dot{\varphi}_6^2(z_6+z_8)\cos\varphi_6 - \ddot{\varphi}_6(z_6+z_8)\sin\varphi_6 +$$
$$-\dot{\varphi}_6^2 z_9\cos(\varphi_6+\psi) - \ddot{\varphi}_6(z_6+z_8)\sin\psi \tag{7}$$
$$\ddot{Y}_{A1} = -\dot{\varphi}_3^2(z_3+z_4)\sin\varphi_3 + \ddot{\varphi}_3(z_3+z_4)\cos\varphi_3 +$$
$$+\dot{\varphi}_6^2(z_6+z_8)\sin\varphi_6 - \ddot{\varphi}_6(z_6+z_8)\cos\varphi_6 +$$
$$+\dot{\varphi}_6^2 z_9\sin(\varphi_6+\psi) - \ddot{\varphi}_6 z_9\cos\psi$$

The proposed analysis formulation has been considered for numerical simulations. Numerical results have been obtained without considering the leg's interaction with the ground.

An amplification factor equal to 2 has been chosen to obtain a foot trajectory with suitable step size, as shown in

TABLE I.
THE DESIGN PARAMETERS IN MM FOR KINEMATIC MODEL OF FIG.1

a	m	c	d	f
45	15	60	60	60
p	h	z2	z3	z4
168	104	225	150	150
z5	z6	z7	z8	z9
225	225	150	225	100

Fig. 2. The above-mentioned parametric study has been carried out by looking specifically at plots like those in Figs. 3 to 5, which show final results.

Figure 3 shows a numerical simulation for transmission angles γ_1, γ_2 and γ_3 as function of the input crank angle α. Fig. 4 shows results of the numerical simulation for the velocity of points B, A and A_1 respectively, that have been obtained when the angular velocity ω of the input crank is chosen with a constant value equal to 1.0 rad/sec. Figure 5 shows numerical simulation of the acceleration of points B, A and A_1.

C. Design consideration

A basic goal for a mobile robot is to perform a walking operation without the need of an external control unit. One way to get this goal is to build light and simple architectures with limited number of DOFs, [14].

Furthermore, basic considerations for a leg design can be outlined as follows: the leg end point trajectory should lie on a straight-line; the leg should have a fairly simple mechanical design; the leg should have the minimum number of DOFs to ensure suitable motion capability.

According to those basic requirements a leg has been designed by considering compactness, modularity, light weight, reduced number of DOFs as basic characteristics for an easy-operation walking. Furthermore, the mechanical design has been conceived by using linkage architecture in order to build a low-cost prototype, as shown in Fig. 6. Aluminium alloy has been selected to build the prototype of the leg because of its lightness and easy machining.

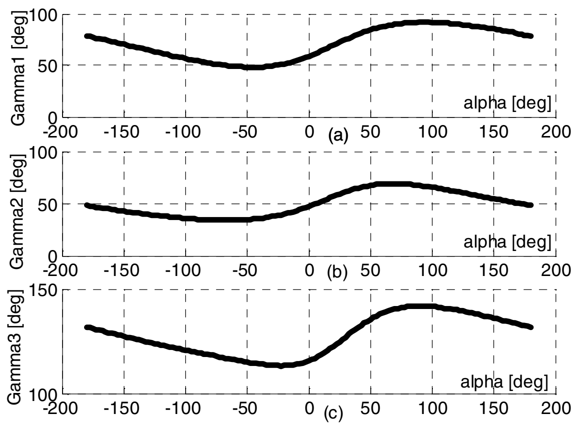


Figure 3. Numerical simulation for the transmission angles in degrees: a) angle $\gamma 1$; b) angle $\gamma 2$; c) angle $\gamma 3$.

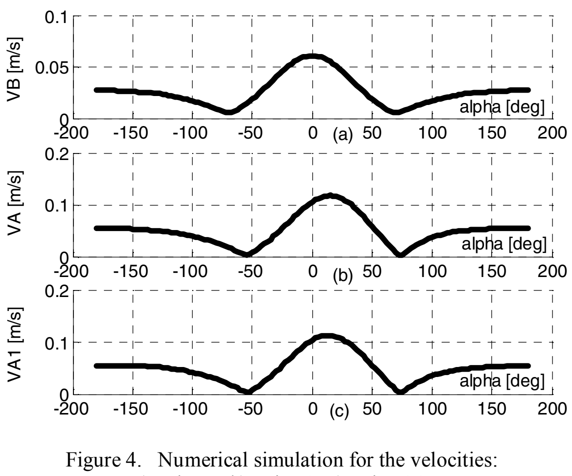


Figure 4. Numerical simulation for the velocities: a) point B; b) point A; c) point A1.

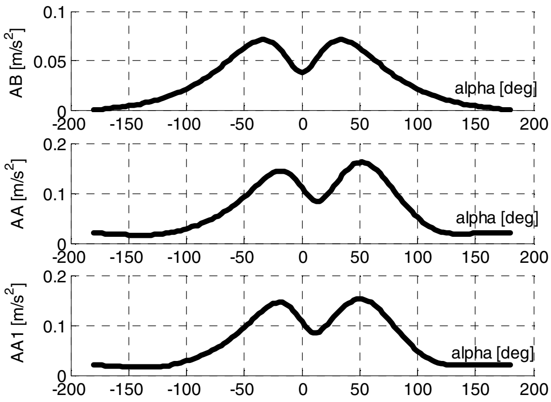


Figure 5. Numerical simulation for the accelerations of point B, point A and point A_1.

III. DESIGN AND SIMULATION OF THE LEG-WHEEL WALKING ROBOT

The mechanical design of the walking robot is the main issue of a project with the aim to obtain a simple system, that is able to walk in several environmental conditions.

The designed prototype consists of a biped module, whose two active legs are designed as described in Section II, a DC motor for actuation, and two passive wheels. The leg-wheel mobile robot design and simulation are shown in Figs. 6 and 7.

Each leg has been provided by suitable foot, which has been rigidly installed at the leg tip, for walking in both flat and rough terrains. In particular, in Fig.7 simulations of the robot walking are presented. They have been used to determine and check the feasibility the mechanical design. for each quantity that you use in an equation.

The actuation is transmitted to the two active legs through a gear transmission system. The body of the mobile robot has been conceived in order to be able to

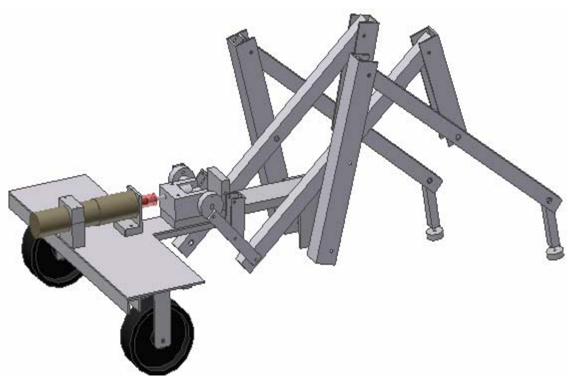


Figure 6. Mechanical design of the leg-wheel walking robot.

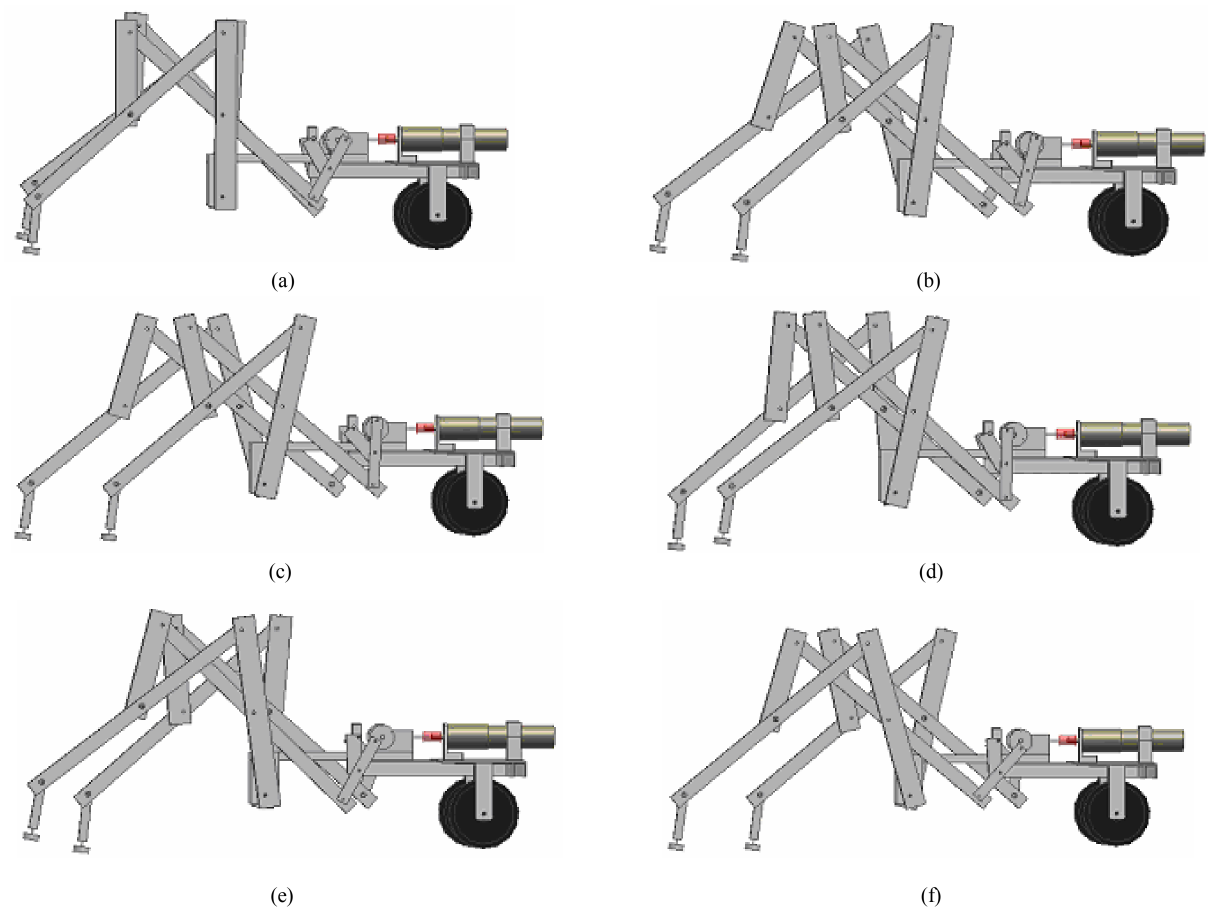


Figure 7. A sequence of movements of the designed prototype as function of the input crank angle: a) α=360 deg; b) α=310; deg; c) α=270 deg; d) α=210 deg; e) α=150 deg; f) α=90 deg.

carry batteries and a suitable PLC (Programmable Logic Controller) for operating the robot.

Furthermore, it allows the installation of suitable sensors and acquisition system on board.

IV. EXPERIMENTAL RESULTS

A prototype of the leg-wheel walking robot has been built at LARM for first experimental validation. It is shown in Fig. 8.

The prototype has been built by considering several aspects that can be outlined as follows:

- modularity of the prototype by considering future development;
- autonomy. In this first phase, the robot will walk without sensors and control unit. The body has been designed with a shape allowing installation of batteries;
- low-cost.

Several parts in the prototype are low-cost commercial components, easily available.

Body and legs have been made of an aluminium alloy with the aim to have a limited weigh and also to facilitate the machining of the parts.

The actuation system, shown in Fig. 9, consists of an electrical DC motor that is installed on the body of the leg-wheel walking machine. It drives the two legs through a gear transmission system, while the wheels are passive.

During the walking the prototype has always a leg and two wheels in contact with the ground. The mass distribution and body shape give that the projection of the barycentre is always in the area that is limited by the elements in contact with the ground.

The velocity is constant during the walking on flat terrain, and it depends on the friction between foot and ground. The walking sequence in Fig. 10 corresponds satisfactorily to the design sequence in Fig. 7.

Characteristic dimensions of the prototype are 0.500 x 1.000 x 0.400 m and mass of 9 kg (batteries not included).

The step of the robot has a maximum height of 0.03 m and a length of 0.16 m, and its shape allows the prototype to walk over terrains of various nature.

The prototype has been tested by walking forward and backward on flat terrain.

The prototype has been tested also in a slope of about 20 deg, as shown in Figs.11 and 12. The backward walk has been obtained more efficiently than in the case of pulling walk mode. The difference can be explained by considering the position of the mass centre and friction of the floor plane.

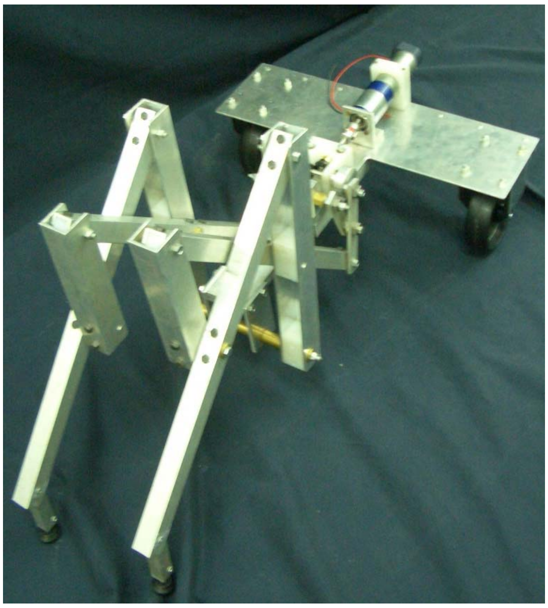


Figure 8. Built prototype of the hybrid walking robot at LARM as based on the scheme of Fig.1.

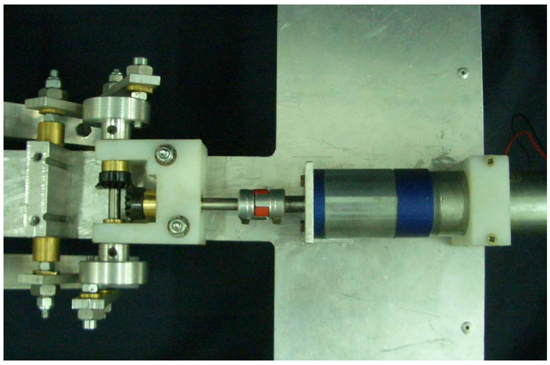
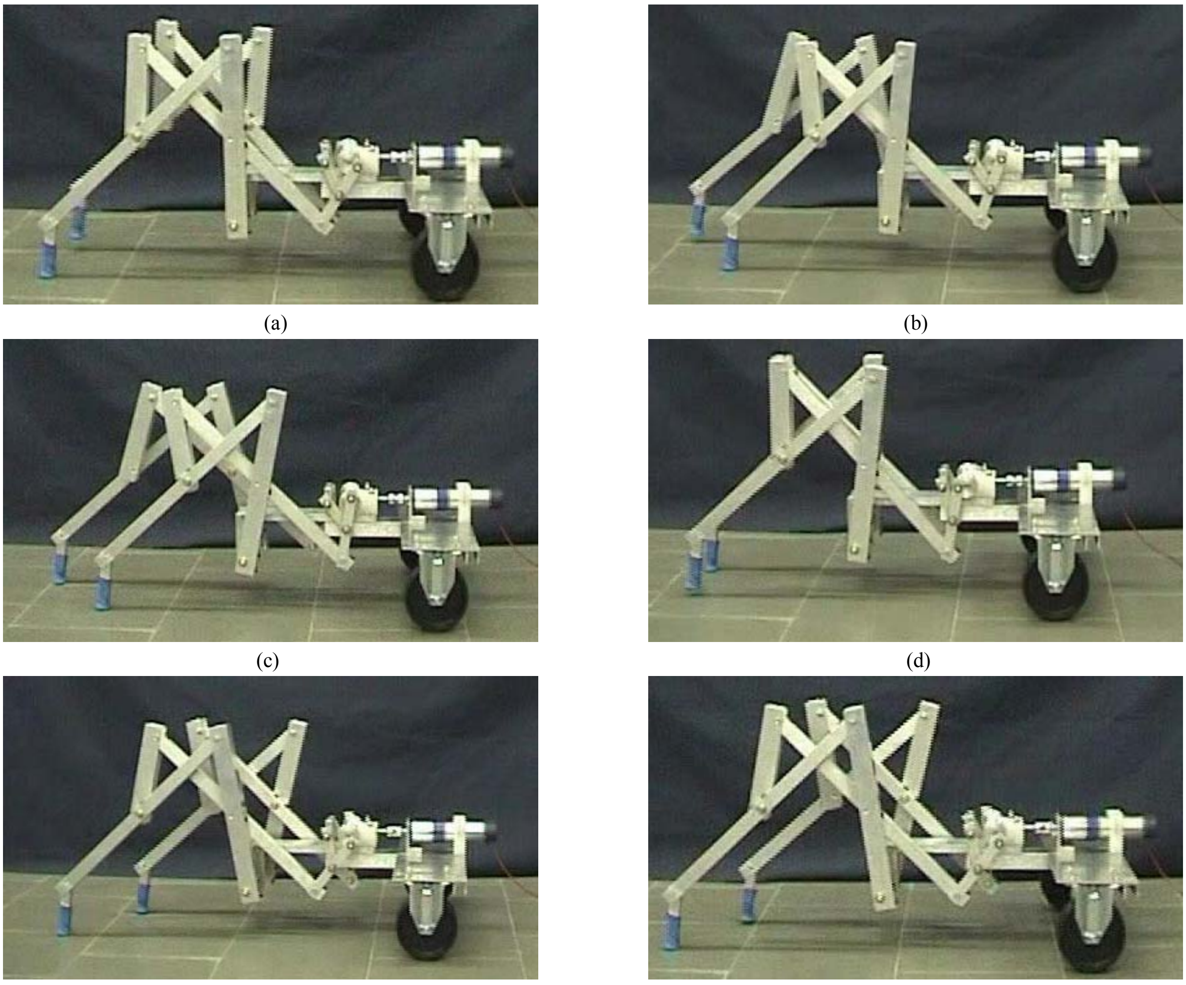


Figure 9. Transmission system of the built prototype.

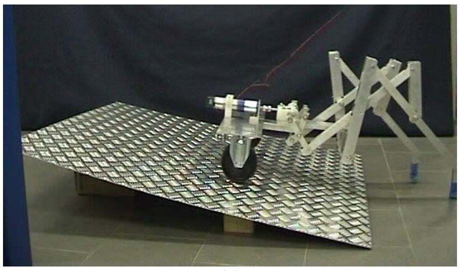
The velocity reaches a maximum value equal to 0.07 m/sec. it decreases depending on the slope of the ground, because of the masses distribution, and on terrain nature, because of the friction.

The prototype has been designed and built in order to have a low-cost, easy operating system able to walk on several terrains as, for example, in case of planetary explorations and disaster sites.

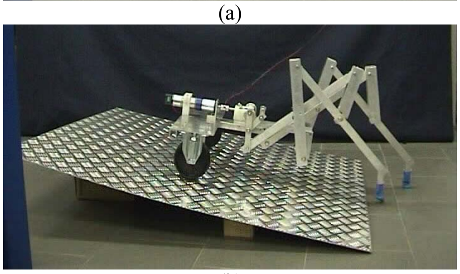


(a) (b) (c) (d) (e) (f)

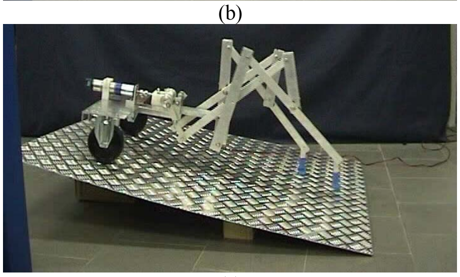
Figure 10. A sequence of movements of the built prototype as function of the input crank angle: a) α=360 deg; b) α=310; deg; c) α=270 deg; d) α=210 deg; e) α=150 deg; f) α=90 deg.



(a)

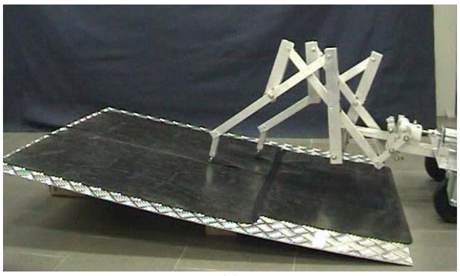


(b)

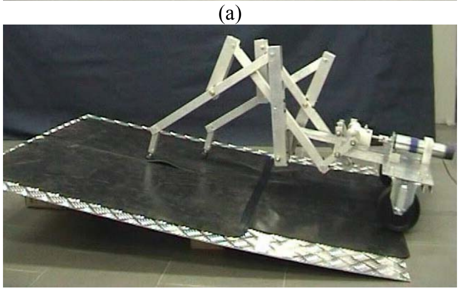


(c)

Fig 11. The built prototype while climbing a slope of 20 deg in pushing walk mode for legs.



(a)



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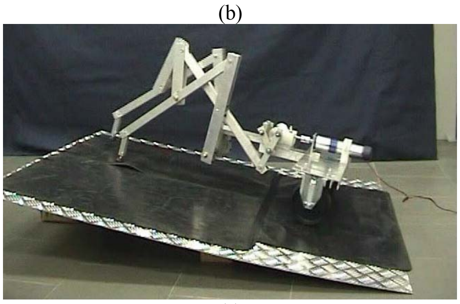

(c)

Fig 12 The built prototype while climbing a slope of 20 deg in pulling walk mode of legs.

V. CONCLUSION

In this paper a new prototype of leg-wheel walking robot is proposed with low-cost easy-operation features. A suitable kinematic model has been presented for a 1-degree of freedom leg with a fully-rotative actuation. A kinematic analysis has been carried out in order to evaluate and simulate performance and operations of the leg system. A low-cost leg-wheel machine has been built at LAboratory of Robotics and Mechatronics in Cassino by using the proposed 1-degree of freedom leg. First experimental results have been obtained successfully by testing the prototype over several terrains.

In order to obtain a more flexible walking robot, as future development, the prototype can be improved by adding more leg modules, sensors and a device that allows turning.

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