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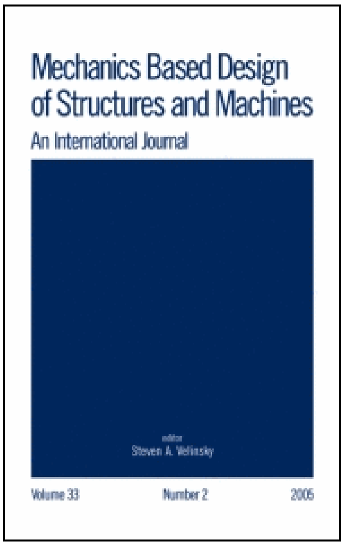
3 authors:


Erika Ottaviano
Università degli studi di Cassino e del Lazio Meridionale


Salvatore Grande
Università degli studi di Cassino e del Lazio Meridionale


Marco Ceccarelli
Università degli studi di Roma Tor Vergata



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Erika Ottaviano[a]; Salvatore Grande[a]; Marco Ceccarelli[a]
[a] LARM: Laboratory of Robotics and Mechatronics, DiMSAT, University of Cassino, Cassino (FR), Italy

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A BIPED WALKING MECHANISM FOR A RICKSHAW ROBOT[#]

Erika Ottaviano, Salvatore Grande, and Marco Ceccarelli
LARM: Laboratory of Robotics and Mechatronics, DiMSAT, University of Cassino, Cassino (FR), Italy

In this paper a 1-DOF- (degree of freedom) biped machine is presented to be used for a rickshaw robot. Main features for the proposed biped walking system are low-cost design and easy-operation in terms of compactness, light weight, and reduced number of DOFs. A numerical characterization is proposed with a suitable kinematic analysis. A prototype has been built and experimental tests have been carried out to validate the proposed design and test its practical feasibility for a rickshaw robot. The robot has been tested in several operating conditions.

Keywords: Biped mechanism; Leg mechanisms: Mechanism analysis; Rickshaw robot; Walking machines.

INTRODUCTION

Mobile robots have a wide range of applications such as: inspection, service, defense, manufacturing, cleaning, remote exploration, and entertainment. Furthermore, due to the rapid development in the related areas of computing, sensing, control, actuation, and artificial intelligence, mobile robots can be also used for intelligent transportation systems (Morecki and Waldron, 1997; Rosheim, 1994). For many of the above-mentioned applications either walking or wheeled robots can be used. Several walking machines and robots have been conceived, designed, and built in the last 20 years with the aim to open new fields of applications, as overviewed by Chernousko (1990).

A number of biped robot designs have an anthropomorphic structure to be used in an environment which contains stairs, obstacles, or slopes. However it is difficult to generate human-like walking motion automatically. To design human-like walking systems, many researchers have developed robots with biped locomotion (Karsten Berns webpage, 2010). Because of the complexity of legged systems, it is often difficult or impossible to directly apply conventional stability concepts. There are three commonly used approaches for defining stability, namely the zero moment point (ZMP), the limit cycle analysis, and the exhaustive

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Correspondence: Marco Cecarelli, LARM: Laboratory of Robotics and Mechatronics, DiMSAT, University of Cassino, Via Di Biasio, Cassino (FR) 46-03043, Italy; E-mail: ceccarelli@unicas.it

simulation/testing. Although the ZMP criterion is a widely used method for guaranteeing stability in humanoid robots, it does not directly correspond to any conventional notion of stability. In addition, it requires large ankle torques and leads to inefficient/unnatural gait. Limit cycle techniques attempt to analyze legged robots by using conventional stability concepts. They can be considered as an extension of the concept of "Passive Dynamic Walking," as pioneered by McGeer (1990), in combination with the typically ZMP concept. Examples of dynamic walking are reported by Vukobratovic et al. (1990), Takanishi et al. (1985), Hirai et al. (1998), Fujimoto and Kawamura (1996), Hobbelen and Wisse (2008), and Hobbelen et al. (2008).

Hybrid systems have been also developed as combination of wheeled and legged solutions with the aim to exploit the advantages of both types of mobile systems. A leg-wheel hybrid stair climbing wheelchair is proposed by Yuan and Hirose (2005), it consists of eight independent prismatic-joint legs and eight wheels. The CALMOS Wheelchair proposed by Gonzalez (2006) has high-load capacity and relevant adaptability to a wide variety of obstacle geometries. A hybrid walking robot is proposed by Tavolieri et al. (2007). The prototype has two legs with one DOF and two passive wheels and it is capable of a straight walking. A new solution is presented to give the robot the turning capability by using an additional DOF, as proposed by Ottaviano et al. (2007).

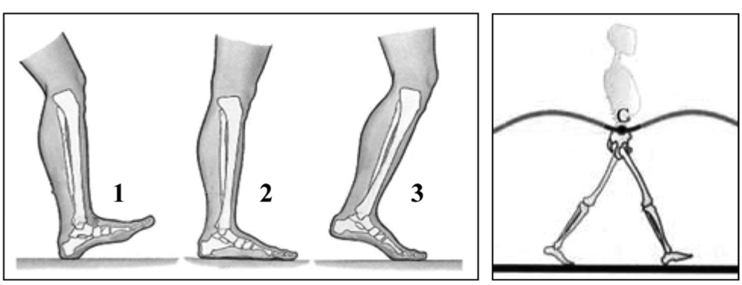
A key issue for the design of a walking robot is the autonomy. Therefore, the need of more payload can be related to the opportunity to have an autonomous robot when the robot itself can carry batteries. The ability to increase the payload can also be related to a specific application, such as for inspection or remote exploration, for which the robot must be able to carry measuring systems and/or instrumentation. The idea of increasing load capacity of walking carrier by using additional wheeled systems is not original. In fact, first solutions go back to Egyptians who used chariots since third millennium B.C. They were used both for transportation and for war purposes by using either horses or human beings as walking carriers. A rickshaw walking robot was presented by Ceccarelli et al. (2000). Rickshaws traditionally refer to a mode of human-powered transport: a runner draws a two-wheeled cart which seats one or two persons. The word rickshaw came from Asia where they were mainly used as means of transportation for the social elite (Modianot-Fox, 2007). Basically a rickshaw is a simple two-wheel chariot that is usually used for ground transportation by pulling and pushing it both for motion and for horizontal positioning.

In this paper we propose a low-cost easy-operation biped mechanism to be used for a rickshaw robot. Basic features of the proposed system are compactness, light weight, and reduced number of DOFs. The prototype must be capable of straight walking with only one actuator and furthermore, it must be capable of carrying loads. Furthermore, the additional passive wheeled system can increase the stability and adaptability of the robot over several types of terrains. A prototype has been built at LARM (Laboratory of Robotics and Mechatronics, in Cassino) and experimental tests have been carried out to test a built prototype in several operating conditions.

BIPED WALKING CHARACTERISTICS

Nature has solved efficiently the problem of biped locomotion, thanks to a long evolution of human being. Therefore, the analysis of basic anthropomorphic walking may be of great interest to tackle the question of biped robot walking operation. Human walking can be very smooth and efficient because humans can make use of gravity effectively and the muscular work is optimized to give the minimum metabolic cost. Basic features that can be deduced from human walking operation in steady state can be found in the work by Morecki (1995).

The walking motion is divided into strides which are themselves divided into steps. Each stride is composed of single and double supports, as shown in Figs. 1(a) and (b), respectively. In the single-support phase the contact begins along the heel then continues on whole sole, and finally it ends along the tip. The walking operation can vary from one individual to another depending on sex, age, weight, and height. An individual may also have various walking patterns depending on learning and tiredness, which are a source of modification of the gait. The displacement parameters can also vary according to the environment characteristics such as obstacles or stairs. The type or objective movement also influences the gait, furthermore, the walking parameters such as step length and speed can be different according to efficiency in covering a long or a short distance. Equilibrium is a key point of both posture and locomotion. Postural static equilibrium is guaranteed when the center of gravity projection on the ground is maintained within the support base. The support base is delimited by the points of the system in contact with the ground, which corresponds to the surface of the convex hull linking the contact points together. Dynamic walking is the normal walking, which can be schematically considered as a fall forward onto the foot receiving the body's weight and the center of gravity projection does not remain inside the support base during the whole movement. To avoid falling the swing foot is placed on the ground, in front of the center of gravity projection. Many studies on biologically inspired mobile robots are concerned with the analysis of the walking in nature also. Terrestrial animals can adopt a wide range of gaits when moving over ground, for example, walking to move at slow speeds and running, trotting, galloping, and hopping for faster locomotion (Morecki and Waldron, 1997). This broad spectrum of gaits raises the question of the factors that govern gait selection.



(a) (b)

Figure 1 Support phases of the human walking: (a) the single support: (1) heel contact; (2) sole contact; (3) tip contact; (b) double support.

(a) (b)

Figure 2 Examples of gait in nature: (a) kinetic energy of limb segments for three strides of an ostrich (Fedak et al., 1982); (b) a sequence of a chicken locomotion.

The leg of an ostrich operates at high speed, although it is almost never fully extended. Indeed, the design of the ostrich leg is common to many birds, which are either flyers or walker/runner. This type of legs can be obtained by connecting two rigid links by a revolute joint and the extremity is connected to the body by means of a spherical joint (Rubenson et al., 2004). The ostriches usually use the legs so that in the final configuration of a movement they are partially folded up. Examples of the gait in nature are shown in Fig. 2, in which the kinetic energy of an ostrich limb movement and a sequence of chicken locomotion are shown. It is worth to note that galliform birds take relatively longer steps because the total of lengths of the leg bones is much greater than hip height.

A NEW KINEMATIC DESIGN FOR A RICKSHAW ROBOT

Basic considerations for a robotic leg design can be outlined as follows: the leg should generate an approximately straight-line trajectory for the foot with respect to the body, as stated by Rosheim (1994) and Morecki and Waldron (1997); the leg should have an easy mechanical design. If it is required it should possess the minimum number of DOFs to ensure the motion capability. In the 1850s Chebyshev proposed a mechanism to allow the walking in such a way that the body can move horizontally by moving the feet and legs in a fixed pattern (Artobolevsky, 1986). The links' lengths can be chosen in such a way that the shape of the end leg point trajectory is similar to the shape of a man's foot trajectory (Yoneda, 2001).

The rickshaw robot should be provided by an additional passive wheeled system to increase both the load to carry and the stability of the whole system of several types of terrains. A wheeled system can be provided of two, three, or four wheels. Two-wheeled systems are simple and can be light; a third wheel can be further used to enhance mainly maneuverability; and four wheels ensure largest payload and stability. Indeed, several wheeled mobile robots have been built and are in use with the above-mentioned architectures. In this paper the rickshaw robot is a hybrid architecture, which consists of a biped robot with one DOF and a

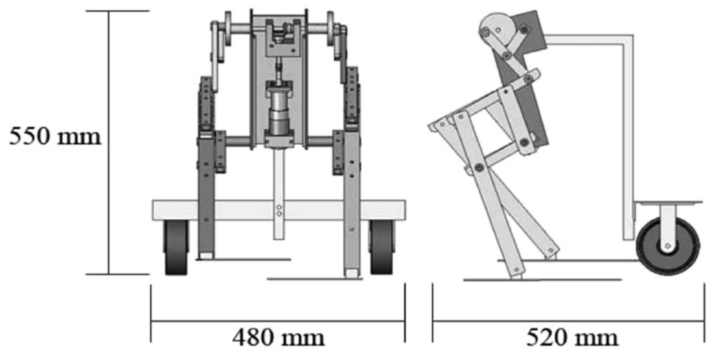


Figure 3 Mechanical design of rickshaw robot with its main dimensions.

chariot. The proposed solution, which is adopted even by human beings, gives high maneuverability, simple use, reduced size, and it does not require high power in operation (Ceccarelli et al., 2000). A sketch of the mechanical design of the proposed rickshaw robot is shown in Fig. 3 with its size. The robot is composed of a low-cost biped mechanism, which has been proposed by Grande and Ottaviano (2008), a passive two-wheeled chariot, and a connecting bar. The low-cost biped mechanism is a robot with one DOF actuated by a DC motor; which is installed on board, together with batteries. A T gear box transmits the motion to two legs, which are composed by a Chebyshev mechanism and a pantograph.

In this section a kinematic analysis of one of the two identical legs is proposed, which is composed by a Chebyshev mechanism and pantograph. Its main characteristic is to possess only one DOF, with many advantages in terms of cost and operation. A sketch for the leg design is reported in Fig. 4. Several solutions can be used to obtain a desired trajectory of point B. For example in the past it was attempted to design a proper cam profile (Lanni et al., 1999), or to use pneumatic actuation. In this paper we have proposed a solution to consider a fully rotative actuation at point L that gives a suitable trajectory of point B. Furthermore, the trajectory of point B, and consequently point *A* can be suitably modified by changing the design parameters shown in Fig. 4.

In particular, it has been shown by Ottaviano et al. (2004) that good features for leg operation can be obtained if the transmission angles γ_1 and γ_2 have suitable values. In particular, a parametric study has been carried out to study the influence of design parameters on the motion capabilities of the 1-DOF leg.

Let us consider a fixed reference system CXY attached at point C, as shown in Fig. 4.

The position of point *B* with respect to CXY frame can be evaluated as a function of the input crank angle α and kinematic parameters of the Chebyshev mechanism LEBDC in the form

$$x_B = -a + m\cos\alpha + (c+f)\cos\theta; \quad y_B = -m\sin\alpha - (c+f)\sin\theta, \tag{1}$$

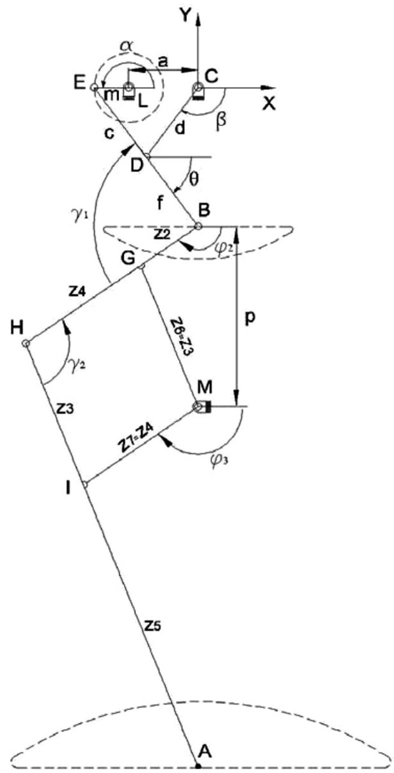


Figure 4 A scheme for the kinematic analysis of 1-DOF leg.

in which

$$\theta = 2\tan^{-1}\left(\frac{-C_2 + \sqrt{C_2^2 - 4C_1C_3}}{2C_1}\right) \tag{2}$$

Coefficients C_1, C_2, and C_3 can be obtained by considering the closure equation of the four-bar linkage CLED in Fig. 4, in the form

$$\begin{aligned} C_1 &= a^2 - d^2 + m^2 + c^2 + 2ac - 2m\cos\alpha(c+a) \\ C_2 &= 4mc\sin\alpha \\ C_3 &= a^2 - d^2 + m^2 + c^2 - 2ac + 2m\cos\alpha(c-a) \end{aligned} \tag{3}$$

Thus, one can obtain φ_2 and φ_3 angles in the form

$$\varphi_2 = 2\tan^{-1}\left(\frac{-K_2 + \sqrt{K_2^2 - 4K_1K_3}}{2K_1}\right); \quad \varphi_3 = \cos^{-1}\left(\frac{-x_B + z_2\cos\varphi_2}{z_3}\right); \tag{4}$$

where

$$\begin{aligned} K_1 &= x_B^2 - z_3^2 + z_2^2 + y_B^2 + p^2 + 2x_B z_2 + 2y_B p, \\ K_2 &= -4(y_B + p z_2), \\ K_3 &= x_B^2 - z_3^2 + z_2^2 + y_B^2 + p^2 - 2x_B z_2 + 2y_B p. \end{aligned} \tag{5}$$

Consequently, the transmission angles γ_1 and γ_2 shown in Fig. 4 can be computed as $\gamma_1 = \theta + (\pi - \varphi_2)$ and $\gamma_2 = \varphi_2 + \varphi_3$. The position of point A with respect to the fixed frame can be obtained as

$$\begin{aligned} x_A &= x_B - (z_2 + z_4)\cos\varphi_2 + (z_3 + z_5)\cos\varphi_3, \\ y_A &= y_B - (z_2 + z_4)\sin\varphi_2 - (z_3 + z_5)\sin\varphi_3. \end{aligned} \tag{6}$$

Figure 5 shows a numerical simulation for points A and B trajectories as functions of the input crank angle. It is worth to note that an amplification factor equal to 2 has been chosen for the pantograph mechanism to reproduce a suitable foot trajectory. The velocity of point A can be computed as

$$\begin{aligned} \dot{x}_A &= \dot{x}_B + \dot{\varphi}_2(z_2 + z_4)\sin\varphi_2 - \dot{\varphi}_3(z_3 + z_5)\sin\varphi_3, \\ \dot{y}_A &= \dot{y}_B - \dot{\varphi}_2(z_2 + z_4)\cos\varphi_2 - \dot{\varphi}_3(z_3 + z_5)\cos\varphi_3. \end{aligned} \tag{7}$$

in which the velocity of point B can be obtained by differentiating Eq. (1) with respect to time.

The acceleration of point A can be obtained by differentiating Eq. (1) two times with respect to time.

The proposed formulation has been considered for a numerical analysis to evaluate basic kinematic performances of each robot leg. In particular, numerical

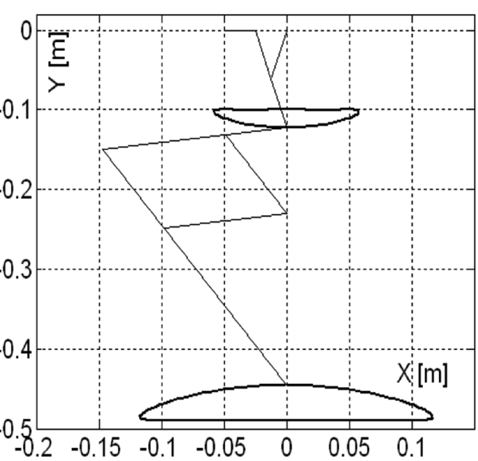


Figure 5 Simulation of trajectories of points A and B of the leg using the design parameters given in Table 1.

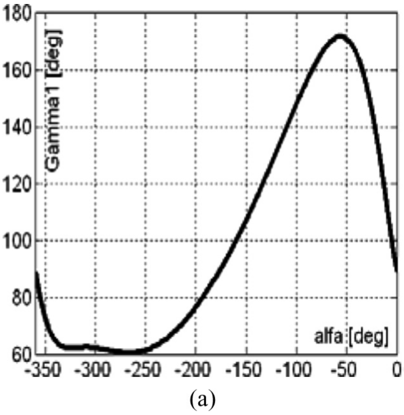


Figure 6 Numerical simulation for the transmission angles in degrees: (a) angle γ_1; (b) angle γ_2.

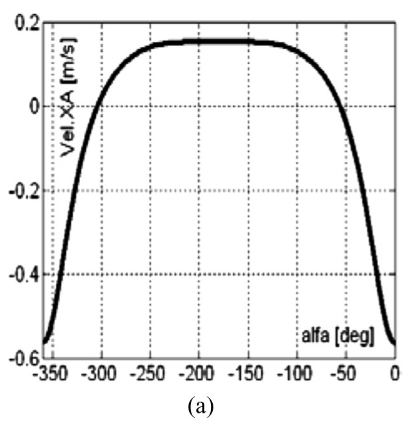


Figure 7 Numerical simulation for the leg: (a) velocity $\dot{x}_A$; (b) velocity $\dot{y}_A$.

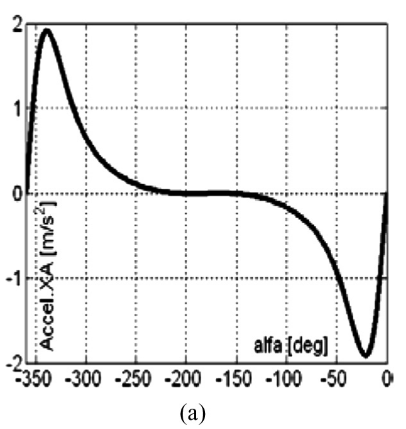


Figure 8 Simulation for the 1-DOF leg: (a) acceleration $\ddot{x}_A$; (b) acceleration $\ddot{y}_A$.

Table 1 Design parameters in mm for the kinematic model of Fig. 4

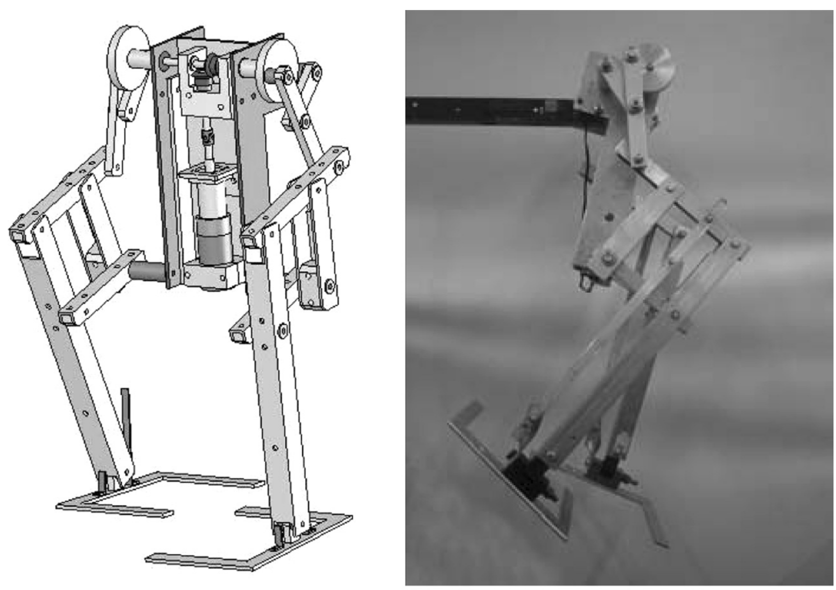
$c = f = d = 62.5$	$a = 50.0$
$m = 25.0$	$p = 230.0$
$z_2 = 50.0$	$z_3 = z_6 = 110.0$
$z_5 = 220.0$	$z_4 = z_7 = 100.0$

results have been obtained without considering the leg's interaction with the ground. Figures 5–8 show numerical results when the design parameters are given in Table 1.

In particular, Fig. 6 shows numerical results for the transmission angles evaluated as functions of the input crank angle α. Figure 7 shows results of the numerical simulation for the velocity of point A that has been obtained when the angular velocity ω of the input crank is chosen with a constant value equal to 1.12 rad/s. Figure 8 shows numerical simulation of point A acceleration when a constant angular velocity is considered.

MECHANICAL DESIGN OF A PROTOTYPE

Many interesting walking machines have been presented, as outlined for example in LARM (2010). One of the main purposes is to achieve a walking operation without the need of an external power supply or connection to an external control unit. One way to get this target is to built light and simple architectures, and to reduce the number of DOFs. Several low-cost walking machines have been built at LARM, as reported in LARM (2010).



(a) (b)

Figure 9 A scheme of 1-DOF-biped robot: (a) mechanical design; (b) built prototype.

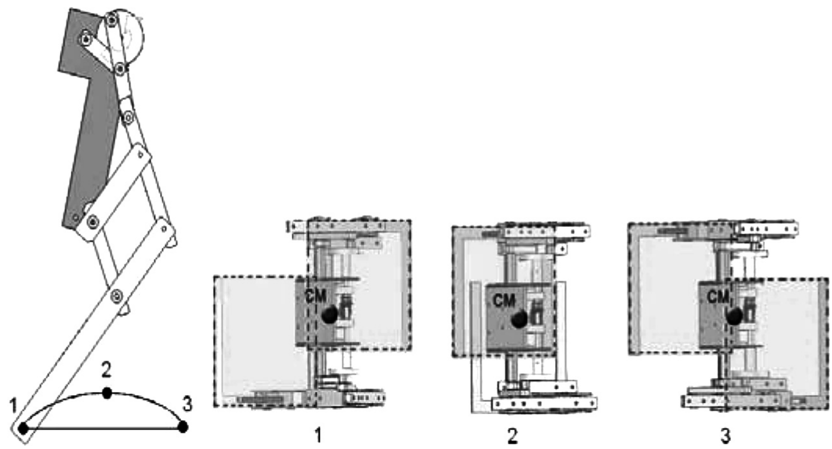


Figure 10 A scheme for the study on biped robot support phases for the foot design.

Furthermore, the mechanical design has been conceived to built a low-cost prototype, as shown in Fig. 9(a). Aluminum was selected to built the prototype in Fig. 9(b) because of its lightness and easy manufacturing.

A preliminary design of foot has been proposed by Grande and Ottaviano (2008). In particular, foot dimensions and ankle rotation limits have been defined according to the scheme in Fig. 10 to guarantee a static walking. Static walking has been chosen in order to have a slow motion of the chariot for safety reasons when instrumentation or monitoring systems have to be carried. According to the scheme in Fig. 10 three different foot configurations have been considered. For each of those configurations it has been verified that the center of mass projection is always inside the contact area (which is delimited by dashed lines). It is worth to note that in configuration 1 and 3 both feet are in contact with the ground, while in the configuration 2 only one foot is in contact with the ground.

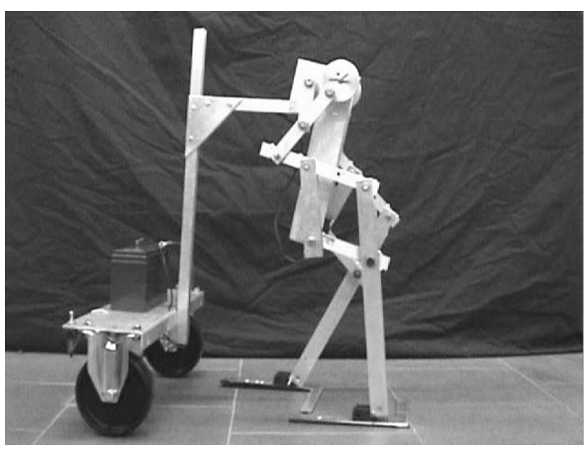
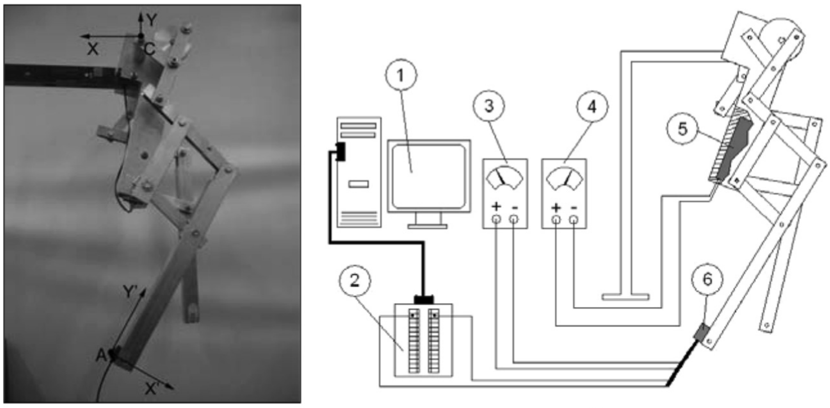


Figure 11 A built prototype of one DOF rickshaw robot at LARM in Cassino.



(a) (b)

Figure 12 Experimental setup at LARM with the low-cost biped machine: (a) a prototype with suitable sensorization (CXY is the fixed frame; AX′Y′ is the moving frame); (b) a scheme of the: (1) PC with LAB view; (2) acquisition board; (3) and (4) power supply; (5) motor; (6) accelerometer.

EXPERIMENTAL TESTS

The biped mechanism has been tested to be used in a rickshaw robot, as shown in Fig. 11. Experimental tests have been carried out at LARM on the built biped walking robot to verify the feasibility of its operation. Although tests were done also outdoor, only indoor tests have been measured and reported in this paper. In particular, indoor tests have been considered, together with experimental analysis of kinematic characteristics of the prototype with suitable sensorization, as shown in the schemes and experimental test-beds of Figs. 12–14.

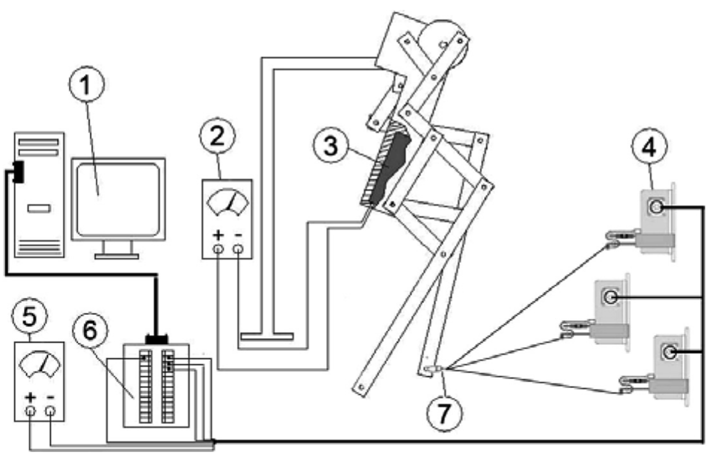


Figure 13 A scheme for experimental setup at LARM with CATRASYS: (1) PC; (2) DC motor power supply; (3) motor of biped robot; (4) and (5) CATRASYS; (6) acquisition board; (7) suitable end effector.

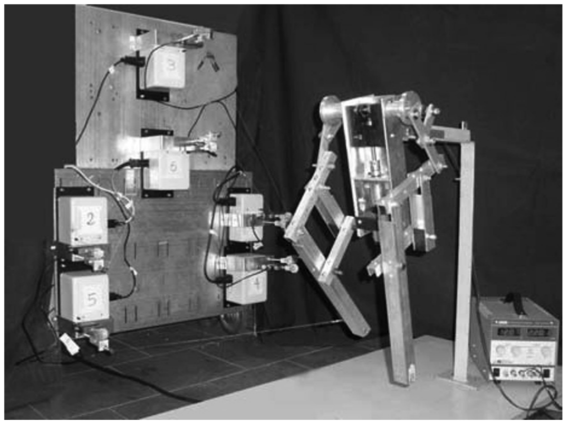
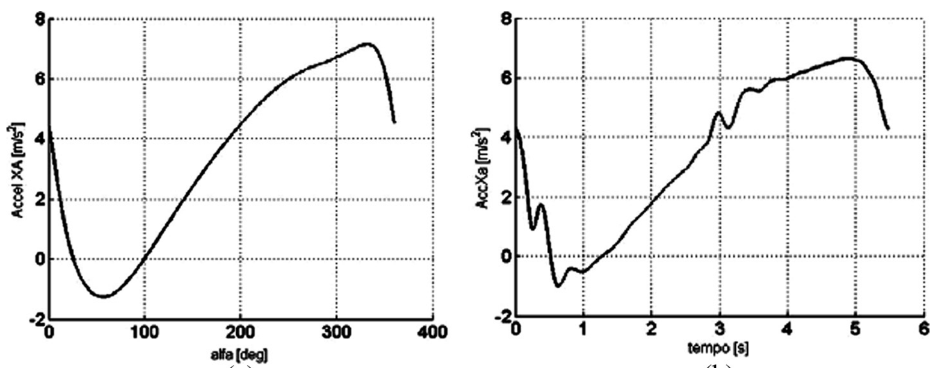
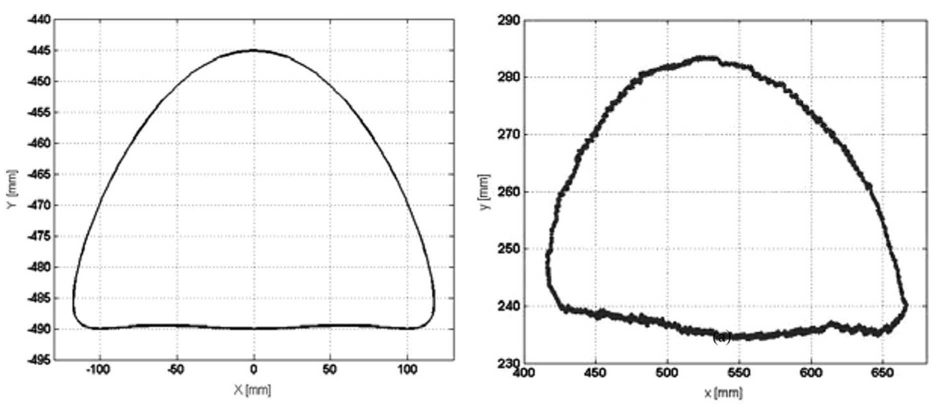


Figure 14 Experimental setup of the low-cost biped machine with CATRASYS system.



(a) (b)

Figure 15 A comparison between numerical and experimental results for the prototype of Fig. 10: (a) simulated acceleration along X′-axis; (b) measured acceleration along X′-axis.



(a) (b)

Figure 16 Point *A* trajectory (a) numerical results; (b) experimental results obtained with CATRASYS.

Characteristic dimensions of the biped robot prototype are $0.350 \times 0.260 \times 0.600$ m and a mass of 5 kg (batteries not included). The gait of the robot has a maximum height of 0.05 m and length of 0.25 m, and its shape allows the prototype to walk over terrains of various nature.

Suitable test-beds have been settled up at LARM, they are shown in Figs. 12–14. Both of them are composed by commercial measuring sensors and LabView software with NI 6024E Acquisition Card. Referring to Fig. 12(a) one accelerometer has been installed at point *A*. It gives the possibility to measure and monitor the acceleration at the extremity of the leg. Referring to Fig. 13 the CATRASYS measuring system (Ottaviano et al., 2002) has been used to experimentally determine the trajectory of point *A*. Numerical results are shown in Figs. 15 and 16. In particular, in Fig. 15 the acceleration component a_{Ax} is expressed in the $AX'Y'$ moving reference frame, as shown in Fig. 12(a). Experimental tests shown in Figs. 15(b) and 16 have been carried out without considering the robot interaction with the ground, as shown in the laboratory layout of Fig. 9(b).

In particular, Figs. 15 and 16 show a good match between numerical and experimental results. It is worth to note that small oscillations on the experimental plot are due to the open loop nature of the robot actuation system.

The rickshaw robot has been also tested on several different terrains. Figure 17 shows a motion sequence for the robot operation on a flat surface in an indoor application. Figure 18 shows a sequence for the experimental tests of the built prototype when climbing a surface with a slope.

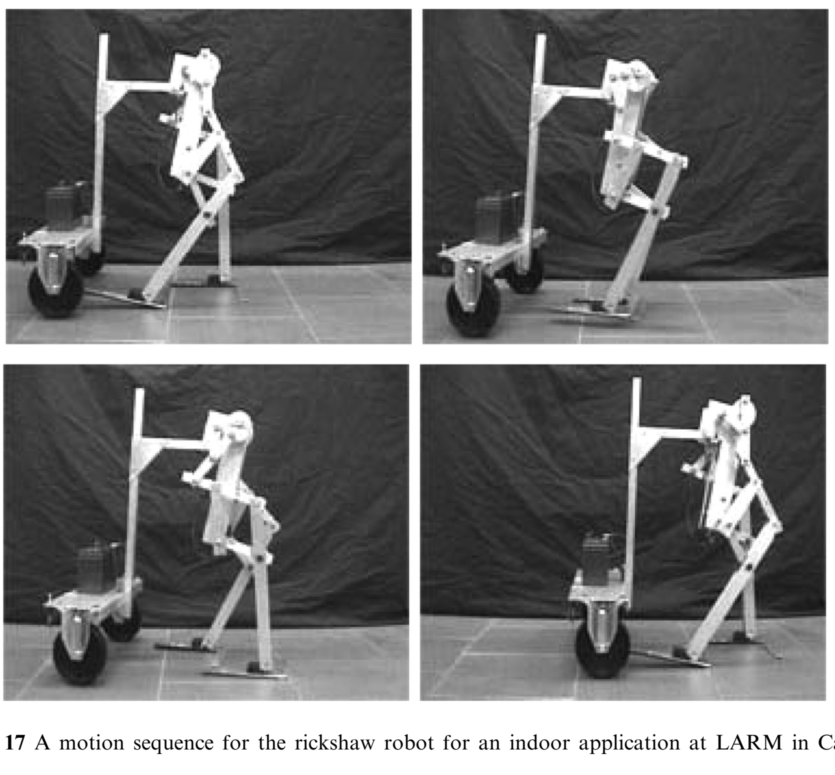


Figure 17 A motion sequence for the rickshaw robot for an indoor application at LARM in Cassino.

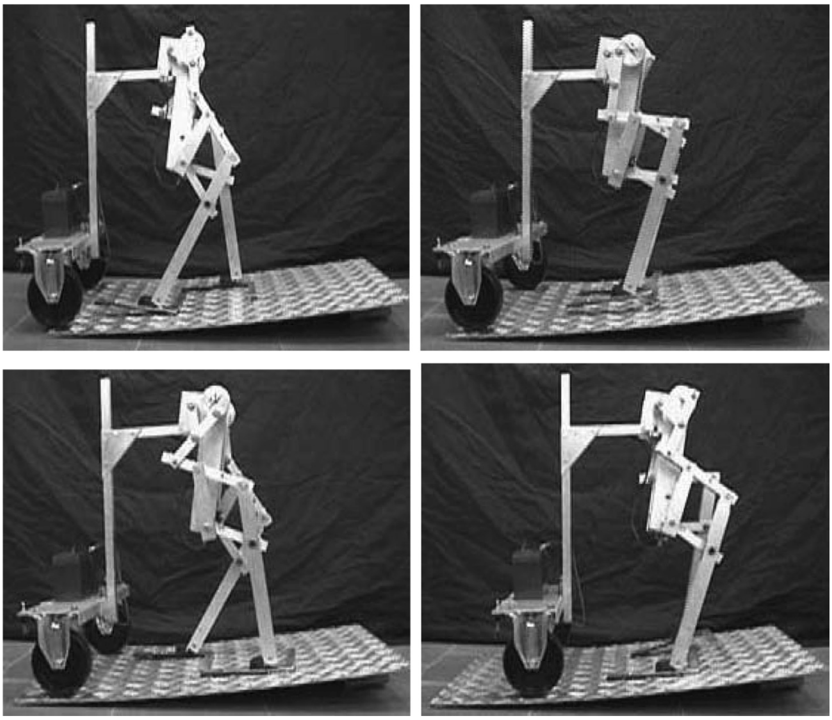


Figure 18 A motion sequence for the rickshaw robot on a surface with a slope at LARM in Cassino.

The prototype has been tested by walking forward and backward on flat terrain. It can climb a slope of 10° and it is experimental verified. Maximum velocity is 3.4 cm/s because of the actuator characteristics.

Batteries have been installed on board and maximum load to carry has been experienced to be equal to 12 kg. This value can be increased by suitably modifying the ankle joint design. The maximum slope can be increased by changing the foot material.

CONCLUSIONS

In this paper a design for a walking robot is presented as based on the design concept of a Chinese rickshaw. The leg is composed of a four-linkage mechanisms for path generation and a pantograph for amplifying the foot-point trajectory. Main features of this design solution can be recognized in simplified control and operation because of one-motor actuation; stability over moderate rough terrain because of the combination of biped and chariot; and low-cost design because of mechanical design of linkages. A prototype has been built and tested to verify the engineering feasibility of the proposed design solution as illustrated with successful results. Future work will concern the design of a steering system for the robot and control strategies for remote control of the system.

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