Mechanical Design of a Novel Biped Climbing and Walking Robot

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Abstract. The present paper deals with the mechanical design of a novel biped climbing and walking robot, which is provided of a 2 (3-RPS) leg mechanism with 6 d.o.f.s. and which makes use of suction-cups for climbing on flat and rigid vertical surfaces. The serial-parallel kinematic structure of each leg mechanism, along with the climbing and walking motions of the proposed biped robot, are analyzed.

1 Introduction

In the last years, the mechatronic design of a low-cost biped robot was carried out in Cassino and several prototypes of the EP-WAR (Electro-Pneumatic-Walking-Robot) were designed, built and tested since 1995, as reported in (Figliolini and Ceccarelli, 1997; 1999; 2004). In particular, the last prototype, named EP-WAR3, was provided of a binary pneumatic actuation in order to be controlled in on/off environment by a PLC (Programmable-Logic-Controller) and good performances were obtained to walk along a straight line, turn right and left, climb and descend stairs. The equilibrium of the EP-WAR prototypes was obtained by means of two suction-cups, which were installed on the underside of each foot. Later, the attention was focused on the gait analysis and mechanical design of six-legged walking robots, as shown in (Figliolini and Rea, 2007; Figliolini et al., 2009). Currently, the mechatronic design of a novel biped climbing and walking robot is in progress at the University of Cassino. Several prototypes of walking and climbing robots were designed, built and tested around the world, but only some of these have inspired the current research project. In fact, the most significant and pertinent prototypes are described in (Nishi, 1992; Hirose and Kawabe, 1998; Bahr et al., 1996; Minor and Mukherjee, 2003; Balaguer et al., 2005). In particular, referring to (Nishi, 1992; Hirose and Kawabe, 1998), a biped robot capable of moving on wall surfaces with irregular shapes and the quadruped robot NINJA, were developed in Japan at the Miyazaki University and Tokyo Institute of Technology, respectively. Similarly, a quadruped climbing robot for the aircraft maintenance, named ROSTAM, was developed at Wichita State University (U.S.A.), before to design a new light-weight biped robot, as reported in (Bahr et al., 1996). Two biped designs for miniature climbing robots were proposed in (Minor

and Mukherjee, 2003), as based on under-actuated kinematic structures. Finally, an interesting overview on the main features of non-conventional climbing robots mobility on complex 3D environments is reported in (Balaguer et al., 2005).
Therefore, at moment, our attention has been focused on the overall mechanical design of a novel biped climbing and walking robot, which is provided of a 2 (3-RPS) leg mechanism with 6 d.o.f.s. and which makes use of suction-cups for climbing on flat and rigid vertical surfaces. The type and dimensional synthesis of the serial-parallel kinematic structure of each leg mechanism, along with the climbing and walking motion analysis, are presented in this paper by referring to (Kim and Tsai, 2003; Mattiazzo et al., 2005; Lukanin, 2005; Di Gregorio and Parenti-Castelli, 2006) and as first step of the current research project.

2 The 2 (3-RPS) Leg Mechanism

The idea of the proposed 2 (3-RPS) leg mechanism comes from the design specifications, which are aimed to obtain wide workspace and good mobility, high rotation and stiffness, along with a good integration of the linear actuators in the overall kinematic structure. In particular, the foot is represented by the second moving platform of the serial-parallel kinematic structure, which can be rotated up to 90° with respect to the robot body, as required to climb vertical walls by starting from an horizontal walking. Referring to Fig.1, the proposed leg mechanism shows 6 d.o.f.s since composed by two modules of 3-RPS (Revolute-Prismatic-Spherical) parallel mechanisms, which are connected in series from the robot body to the foot. Each 3-RPS parallel mechanism shows 3 d.o.f.s of the moving platform with respect to the reference platform, *i.e.* one translation along the normal (*Z*-axis) to the reference platform and two rotations across the *X* and *Y* axes of the *O X Y Z* fixed frame. In particular, referring to the kinematic sketch of Fig. 1a, each 3-RPS parallel mechanism is composed by a moving platform, which is connected to the fixed platform through 3-RPS legs.

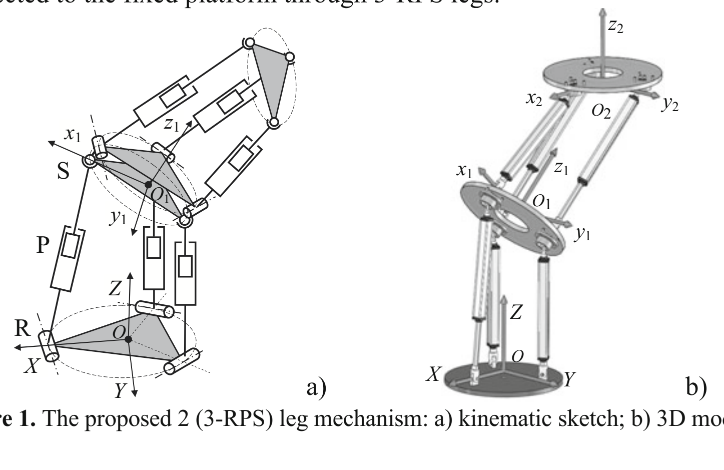

Figure 1. The proposed 2 (3-RPS) leg mechanism: a) kinematic sketch; b) 3D model.

Each of these legs is composed by a prismatic pair P, which is connected to the moving platform through a spherical joint S and to the fixed platform through a revolute joint R. These R and S joints are installed on the fixed and moving platforms at 120° among them in the order to allow only the radial rotation of each RPS leg. Figure 1b shows a 3-D view of the proposed leg mechanism, where the foot is parallel to the platform of the robot body.
Therefore, the proposed 2 (3-RPS) leg mechanism has been assembled in order to have the equilateral triangle among the three spherical joints S of the upper 3-RPS parallel mechanism in opposite position with respect to the antagonist leg mechanism. In particular, Figs. 2a and 2b show the leg mechanism configurations to perform the long and short steps, with step sizes p_1 and p_2, respectively. Figure 2c shows the starting configuration to climb a vertical wall, before to in stroke completely the left leg to perform the next climbing step, as shown in Fig. 2d.

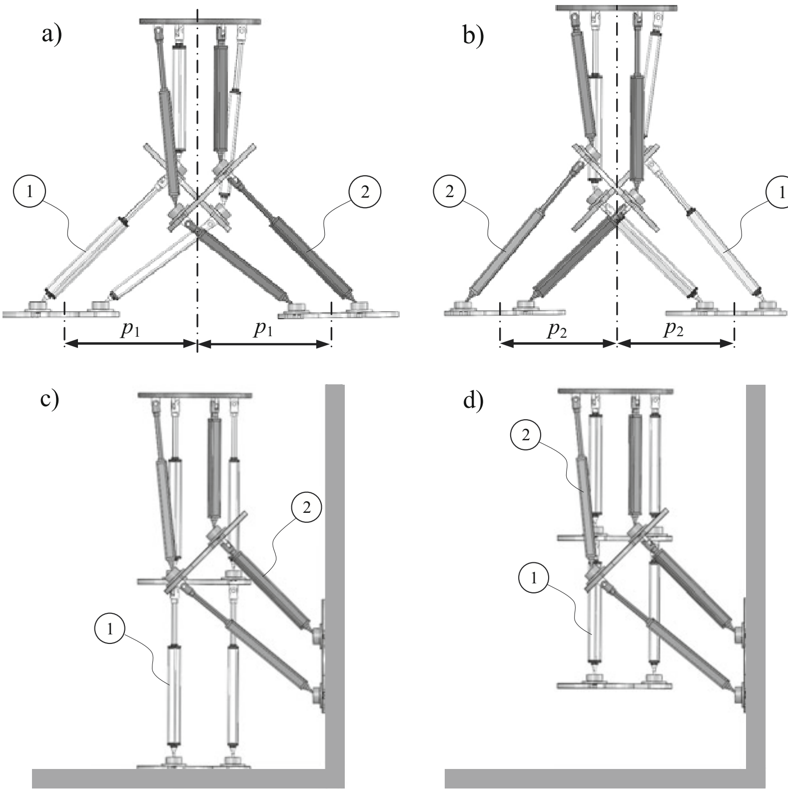

Figure 2. Starting configurations of both 2 (3-RPS) leg mechanisms (left and right legs are indicated with 1 and 2, respectively): a) long step with step size p_1; b) short step with step size p_2; c) vertical wall climbing; d) first configuration on the vertical wall.

3 The 3-RPS Parallel Mechanism: Kinematic Synthesis

The kinematic synthesis of one-module of the proposed 2 (3-RPS) leg mechanism has been formulated by referring to the kinematic sketches of Fig. 3, where Figs. 3a and 3b show the top and front views of one 3-RPS parallel mechanism for the maximum clockwise and counter-clockwise rotations, β_M and γ_M, respectively, of the moving platform (link *AB*).
Figure 3a shows the case for which the linear actuator that is represented through the link *CB*, moves outstroke to perform the maximum clockwise rotation β_M of the link *AB*. Similarly, Fig. 3b shows the case for which the two linear actuators that are represented through the link *DA*, move outstroke to perform the maximum counter-clockwise rotation γ_M of the link *AB*. The proposed algorithm has been formulated as function of the following design parameters, the side size *L* of the equilateral triangle made by the three R joints and the lenght l_0 of the fully instroke RPS leg, while α is equal to 60°. The input data are *L*, l_0 and α = 60°, while the main design specification is β_M= 45°. Thus, referring to Fig. 3a, one has

$$d = L\cos(\alpha/2) \ , \tag{1}$$

$$x_{B'} = d(1-\cos\beta_M) \quad \text{and} \quad y_{B'} = d\sin\beta_M \ , \tag{2}$$

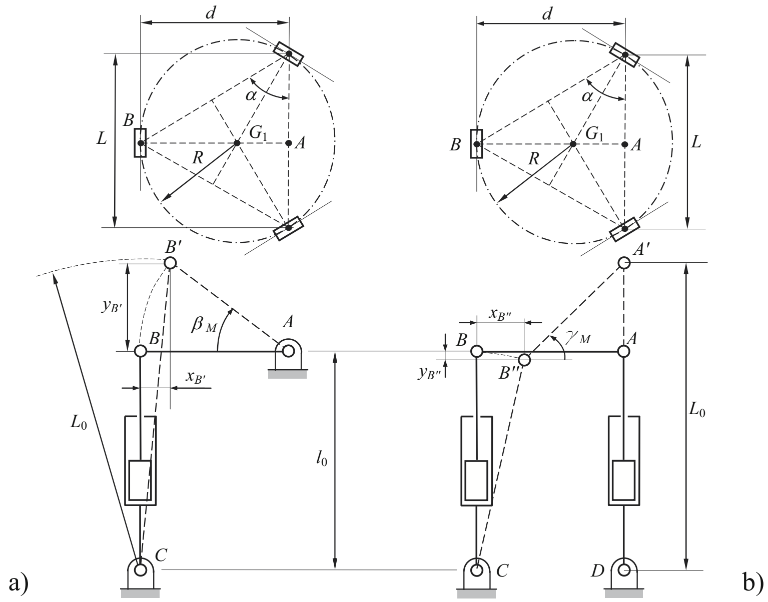

Figure 3. Kinematic sketches of one-module for two configurations: a) max clockwise rotation through β_M of *AB*; b) max counter-clockwise rotation through γ_M of *AB*.

which give

$$L_0 = \sqrt{x_{B'}^{\,2} + \left(l_0 + y_{B'}\right)^2} \qquad \text{and} \qquad s = L_0 - l_0\,, \tag{3}$$

where s is the stroke of the linear actuator of link CB. Likewise, referring to Fig. 3b, one has

$$x_{B''} = d\left(1 - \cos\gamma_M\right) \qquad \text{and} \qquad y_{B''} = l_0 - L_0 + d\sin\gamma_M\,, \tag{4}$$

which give

$$l_0 = \sqrt{\left(l_0 - y_{B''}\right)^2 + x_{B''}^2}\,. \tag{5}$$

Thus, substituting the Eqs. (4) in Eq. (5) and developing, it yields

$$2L_0\sin\gamma_M + 2d^2\cos\gamma_M + l_0^2 - L_0^2 - 2d^2 = 0 \tag{6}$$

that for

$$\sin\gamma_M = \frac{2t}{1+t^2} \qquad \text{and} \qquad \cos\gamma_M = \frac{1-t^2}{1+t^2}\,, \tag{7}$$

gives the following second order algebraic equation

$$\left(L_0^2 - l_0^2 + 4d^2\right)t^2 - 4L_0 d t + L_0^2 - l_0^2 = 0\,. \tag{8}$$

Both solutions of Eq. (8) are given by

$$\gamma_{M_{1,2}} = 2\tan^{-1} t_{1,2} \quad \text{for} \quad t_{1,2} = \frac{2L_0 d \pm \sqrt{2l_0^2 L_0^2 - l_0^4 - L_0^4 + 4d^2 l_0^2}}{L_0^2 - l_0^2 + 4d^2}\,. \tag{9}$$

Thus, for L = 300 mm, l_0 = 545 mm, α = 60° and β_M = 45°, this algorithm gives : d = 259,81 mm, d_0 = 183,71 mm, L_0 = 732,67 mm, s = 187,67 mm and γ_M = 48,58°. Two configurations of a prototype with pnuematic actuation is shown in Fig. 4.

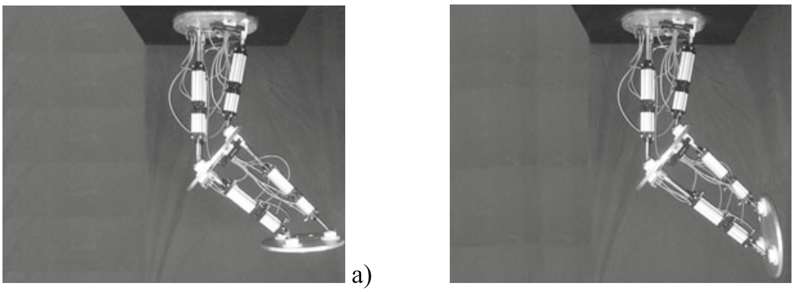

Figure 4. Two configurations of a built prototype: a) fully ahead to perform a short step, as leg 1 of Fig.2b; b) fully ahead to perform a vertical wall climbing, as leg 2 of Figs.2c and 2d.

4 The 3-RPS Parallel Mechanism: Workspace Analysis

The workspace analysis for the 3-RPS parallel mechanism has been carried out by using a numerical procedure for the Forward Kinematics (FK), as proposed in (Lukanin, 2005) and then extended in (Figliolini et al., 2009). In particular, the Newton-Kantorovich Method has been applied in order to obtain a numerical solution for the FK and workspace analysis of the 3-RPS parallel mechanism. Referring to Fig. 5, a set of geometrical constraints can be expressed as $|A_1 B_1| = |B_1 C_1| = |C_1 A_1| = \sqrt{3}\, R$ or in the Cartesian form as

$$\begin{cases} \left(X_{B1}-X_{A1}\right)^2+\left(Y_{B1}-Y_{A1}\right)^2+\left(Z_{B1}-Z_{A1}\right)^2=3R^2 \\ \left(X_{C1}-X_{B1}\right)^2+\left(Y_{C1}-Y_{B1}\right)^2+\left(Z_{C1}-Z_{B1}\right)^2=3R^2 \\ \left(X_{A1}-X_{C1}\right)^2+\left(Y_{A1}-Y_{C1}\right)^2+\left(Z_{A1}-Z_{C1}\right)^2=3R^2 \end{cases}, \tag{10}$$

where the Cartesian coordinates of the points A_1, B_1 and C_1 are given by

$$\begin{cases} X_{A1}=R-l_1\cos\alpha \\ Y_{A1}=0 \\ Z_{A1}=l_1\sin\alpha \end{cases}, \begin{cases} X_{B1}=-1/2\left(R-l_2\cos\beta\right) \\ Y_{B1}=-\sqrt{3}/2\left(R-l_2\cos\beta\right) \\ Z_{B1}=l_2\sin\beta \end{cases}, \begin{cases} X_{C1}=-1/2\left(R-l_3\cos\gamma\right) \\ Y_{C1}=\sqrt{3}/2\left(R-l_3\cos\gamma\right) \\ Z_{C1}=l_3\sin\gamma \end{cases}. \tag{11}$$

Thus, substituting these Cartesian coordinates into Eqs. (10), a system of three non-linear equations is obtained in the unknown α, β and γ for the input parameters l_1, l_2 and l_3, which can be expressed in compact form as

$$f_i\left(\alpha,\beta,\gamma\right)=0 \qquad \text{for} \qquad i=1,2,3. \tag{11}$$

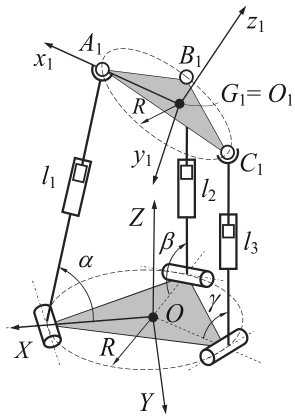

Figure 5. Kinematic sketch of the 3-RPS parallel mechanism.

This system of three non-linear equations has been solved numerically by using the Newton-Kantorovich Method, which is based on the linearization of each equation through the Taylor Series. In particular, a system of three linear equations has been obtained and solved by applying the common Cramer's determinant method, where the 3 x 3 matrix of the coefficients is given by the Jacobi matrix, which elements are obtained as partial derivatives of the functions f_i for $i = 1$, 2 and 3 of the Eqs. (11) with respect to α, β and γ.
This algorithm for the FK analysis of the 3-RPS parallel mechanism has been implemented in a MatLab code and the workspace of point G_1 of the moving platform has been obtained by varying the lengths l_1, l_2 and l_3 within the range of values to perform the maximum stroke s of Eq. (3). In fact, this stroke can give the maximum rotation $\beta_M = 45°$ (G_{1m} moves up to G_{A1}, G_{B1} or G_{C1}) or the maximum translation s (G_{1m} moves up to G_{1M}) of the moving platform, when only one (l_1, l_2 or l_3) or all three (l_1, l_2 and l_3) linear actuators are moved at end outstroke, respectively, as shown in the axonometric projections of Fig. 6.

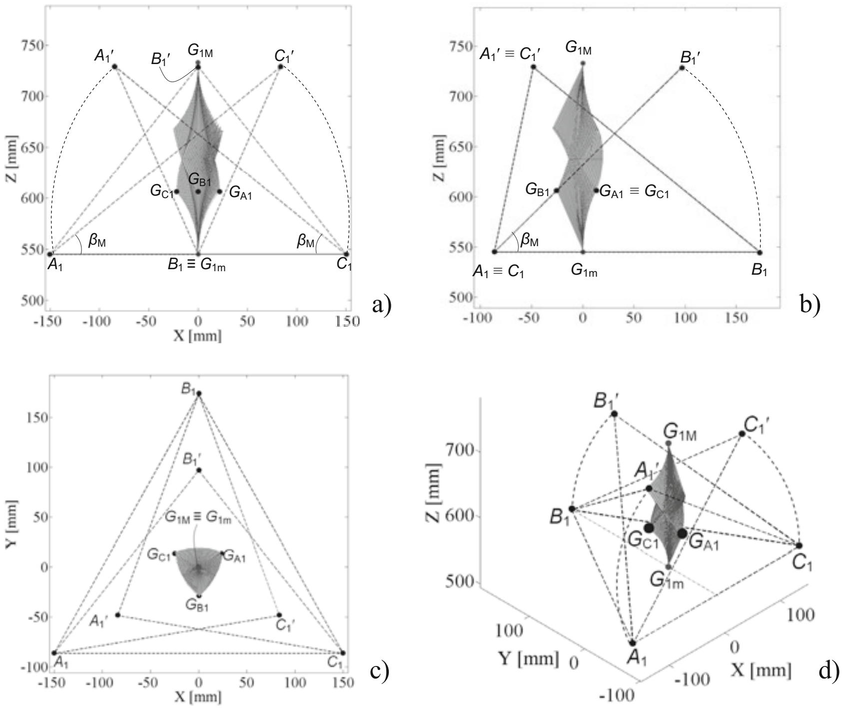

Figure 6. Workspace of the 3-RPS parallel mechanism: a) $X\,Z$ front view; b) $Y\,Z$ lateral view; c) $X\,Y$ top view; d) $X\,Y\,Z$ axonometric view.

Conclusions

The mechanical design of a novel biped climbing and walking robot with a 2 (3-RPS) leg mechanism has been described. In particular, the type synthesis of the leg mechanism along with the analysis of the climbing and walking motions, the dimensional synthesis and the workspace analysis of the 3-RPS parallel mechanism, have been carried out. Moreover, a first prototype of the 2 (3-RPS) leg mechanism with pneumatic actuation has been built and shown in the paper. The dimensional synthesis and the workspace analysis of the whole leg mechanism is in progress to formulate a general algorithm for the required walking and climbing performances.

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