Advances in Intelligent Systems and Computing 418

Luís Paulo Reis
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Robot 2015: Second Iberian Robotics Conference

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Preface

This book contains a selection of papers accepted for presentation and discussion at ROBOT 2015: Second Iberian Robotics Conference, held in Lisbon, Portugal, November 19th–21st, 2015. ROBOT 2015 is part of a series of conferences that are a joint organization of SPR – "Sociedade Portuguesa de Robótica/Portuguese Society for Robotics", SEIDROB – Sociedad Española para la Investigación y Desarrollo de la Robótica/Spanish Society for Research and Development in Robotics and CEA-GTRob – Grupo Temático de Robótica/Robotics Thematic Group. The conference organization had also the collaboration of several universities and research institutes, including: University of Minho, University of Porto, University of Lisbon, Polytechnic Institute of Porto, University of Aveiro, University of Zaragoza, University of Malaga, LIACC, INESC-TEC and LARSyS.

Robot 2015 builds upon several successful events, including three biennal workshops (Zaragoza- 2007, Barcelona – 2009 and Sevilla – 2011) and the first Iberian Robotics Conference held in 2013 at Madrid. The conference is focussed on the Robotics scientific and technological activities in the Iberian Peninsula, although open to research and delegates from other countries.

Robot 2015 featured three plenary talks by:

- Manuela Veloso, Herbert A. Simon University Professor at Carnegie Mellon University, USA, on "Symbiotic Autonomous Mobile Service Robots";
- Bill Smart, director of the Personal Robotics Group at Oregon State University, USA on "How the Law Will Think About Robots (and Why You Should Care)"; and
- Jon Agirre Ibarbia, co-ordinator of R&D projects at TECNALIA Research & Innovation, Spain, on "Applications in Flexible Manufacturing with Humans and Robots".

Robot 2015 featured 19 special sessions, plus a main/general robotics track. The special sessions were about: Agricultural Robotics and Field Automation; Autonomous Driving and Driver Assistance Systems; Communication Aware Robotics; Environmental Robotics; Social Robotics: Intelligent and Adaptable AAL

Systems; Future Industrial Robotics Systems; Legged Locomotion Robots; Rehabilitation and Assistive Robotics; Robotic Applications in Art and Architecture; Surgical Robotics; Urban Robotics; Visual Perception for Autonomous Robots; Machine Learning in Robotics; Simulation and Competitions in Robotics; Educational Robotics; Visual Maps in Robotics; Control and Planning in Aerial Robotics, the XVI edition of the Workshop on Physical Agents and a Special Session on Technological Transfer and Innovation.

In total, after a careful review process with at least three independent reviews for each paper, but in some cases 4 or 5 reviews, a total of 118 high quality papers were selected for publication, with a total number of authors over 400, from 21 countries, including: Brazil, China, Costa Rica, Croatia, Czech Republic, Ecuador, France, Germany, Italy, India, Iran, The Netherlands, Poland, Portugal, Serbia, Singapore, Spain, Switzerland, United Kingdom, USA and Viet Nam.

ROBOT 2015 was co-located with the RoCKIn Competition 2015, which took place in the Parque das Nações, Lisboa, between 19 and 23 November, nearby the conference venue. RoCKIn is a Coordination Action funded by the European Commission FP7, and its main goal is to foster robotics research, education and dissemination through robot competitions. Thirteen teams from seven countries, including two teams from Mexico, were qualified and competed in RoCKIn@Home and RoCKIn@Work Challenges. Participants from both events had the opportunity to join in social events and to visit both venues, taking advantage of an extraordinary opportunity to follow presentations and actual robot systems showing recent results in this exciting field.

We would like to thank all Special Sessions' organizers for their hard work on promoting their special session, inviting the Program Committee, organizing the Special Session review process and helping to promote the ROBOT 2015 Conference. This acknowledgment goes especially to Vitor Santos, Angel Sappa, Miguel Oliveira, Danilo Tardioli, Alejandro Mosteo, Luis Riazuelo, João Valente, Antonio Barrientos, Luís Santos, Jorge Dias, Raul Morais Santos, Filipe Santos, Germano Veiga, José Lima, Guillermo Heredia, Anibal Ollero, Manuel Silva, Cristina Santos, Manuel Armada, Vicente Matellán, Miguel Ángel Cazorla, Rodrigo Ventura, Nicolas Garcia-Aracil, Alicia Casals, Elena García, José Pedro Sousa, Marta Malé-Alemany, Paulo Gonçalves, Jose Maria Sabater, Jorge Martins, Pedro Torres, Tamás Haidegger, Alberto Sanfeliu, Juan Andrade, João Sequeira, Anais Garrell, Andry Maykol Pinto, Aníbal Matos, Nuno Cruz, Brígida Mónica Faria, Luis Merino, Nuno Lau, Artur Pereira, Bernardo Cunha, Armando Sousa, Fernando Ribeiro, Eduardo Gallego and Oscar Reinoso Garcia.

We would also like to take this opportunity to thank the rest of the organization members (Carlos Cardeira, Brígida Mónica Faria, Manuel Fernando Silva, Daniel Castro Silva and Pedro Fonseca) for their hard and fine work on the local arrangements, publicity, publication and financial issues. We also express our gratitude to the members of all the Program Committees and additional reviewers, as they were crucial for ensuring the high scientific quality of the event and to all the authors and delegates whose research work and participation made this event a

success. Last, but not the least, we acknowledge and thank our editor, Springer, that was in charge of these proceedings, and in particular to Dr. Thomas Ditzinger.

November 2015

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Monte-Carlo Workspace Calculation of a Serial-Parallel Biped Robot

Adrián Peidró, Arturo Gil, José María Marín, Yerai Berenguer, Luis Payá and Oscar Reinoso

Abstract This paper presents the Monte-Carlo calculation of the work-space of a biped redundant robot for climbing 3D structures. The robot has a hybrid serial-parallel architecture since each leg is composed of two parallel mechanisms connected in series. First, the workspace of the parallel mechanisms is characterized. Then, a Monte-Carlo algorithm is applied to compute the reachable workspace of the biped robot solving only the forward kinematics. This algorithm is modified to compute also the constant-orientation workspace. The algorithms have been implemented in a simulator that can be used to study the variation of the workspace when the geometric parameters of the robot are modified. The simulator is useful for designing the robot, as the examples show.

Keywords Climbing robots · Hybrid robots · Monte-Carlo · Redundant robots · Workspace

1 Introduction

The workspace of a manipulator can be defined as the set of positions and orientations that can be attained by the end-effector, and it plays a crucial role when designing the robot or planning its movements. Methods for determining the workspace can be classified as analytic or numerical. Analytic methods obtain closed-form descriptions of the boundaries of the workspace, they are more efficient but limited to specific classes of manipulators [5, 16]. Numerical methods [4, 11] can be applied to wider classes of robots and are more flexible. Amongst the numerical methods, Monte-Carlo algorithms [1] are specially interesting for complex and redundant robots, such as humanoid robots [9].

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In this paper, we apply a well-known Monte-Carlo algorithm [1] to compute the workspace of a robot designed to climb and explore 3D structures, with the purpose of studying how this workspace is affected by the geometric design parameters of the robot. 3D structures, such as metallic bridges or power transmission lines, require periodic maintenance and inspection tasks that are dangerous for human workers due to risks such as falling from height. To avoid these risks, many climbing robots have been developed to execute these tasks. Climbing robots can have serial [3, 8, 12, 14, 17], parallel [2] or hybrid [7, 15] architecture. Serial architectures have smaller load capacity than parallel robots, but have larger workspaces, which is useful for exploring complex 3D structures. Parallel robots have a limited workspace, but a high load-to-weight ratio that is useful for climbing robots since they must carry their own weight. Finally, hybrid robots have the advantages of both architectures, which makes them very interesting for climbing 3D structures.

The robot studied in this paper is shown in Figure 1a. The robot is biped and hybrid, since each leg is composed of two serially connected parallel mechanisms. Its legs are specially designed to facilitate the execution of the typical movements that are necessary to explore 3D structures, such as movements along beams or columns, or transitions between planes with different spatial orientation. Also, the robot is redundant, because it has 10 degrees of freedom between its feet. Due to the complexity of this robot, it is difficult to obtain an analytic description of its workspace, hence we decided to use a simple Monte-Carlo method.

This paper is organized as follows. Section 2 briefly describes the architecture of the robot and analyzes the workspace of the parallel mechanisms of the legs. In Section 3, the solution to forward kinematics is used with a Monte-Carlo method to compute the workspace of the robot. Then, Section 4 presents a simulation tool developed to study the relation between the design parameters of the robot and its workspace. Finally, the conclusions are exposed in Section 5.

2 Robot Architecture and Workspace of the Parallel Mechanisms

Figure 1a shows the studied robot. It has two legs $\{A, B\}$ connected to a hip H through revolute joints (angles θ_A and θ_B). Each leg j is composed of a core link C_j and two platforms P_{1j} and P_{2j}. Each platform is connected to C_j through a passive slider and two linear actuators in parallel, constituting the parallel mechanism of Figure 1b. Thus, each leg is composed of two parallel mechanisms of this type connected in series. The robot has 10 degrees of freedom: eight linear actuators in the legs and two revolute joints in the hip. The reference frames E_A and E_B of Figure 1a are attached to the platforms P_{1A} and P_{1B}, which are the feet. The reference frames H_A and H_B are fixed to the hip. All these reference frames have their origins in the middle plane of the legs, as shown in Figure 1a.

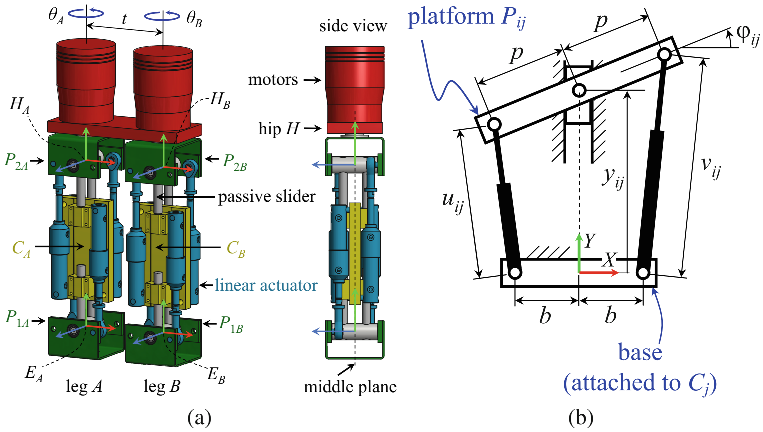

Fig. 1 (a) CAD model of the studied climbing robot. The X, Y, and Z axes of the reference frames are indicated with red, green, and blue colors, respectively. (b) 2-DOF parallel mechanism of the legs of the robot.

Next, we will analyze the workspace of the parallel mechanisms. Figure 1b shows the i-th parallel mechanism of the leg j ($i \in \{1, 2\}$, $j \in \{A, B\}$), which has a platform P_{ij} connected to the core link C_j through a passive slider and two linear actuators of lengths u_{ij} and v_{ij}. The forward kinematics of this mechanism consists in computing $\left\{y_{ij}, \varphi_{ij}\right\}$ in terms of $\left\{u_{ij}, v_{ij}\right\}$, and this problem was solved in [10]. The inverse problem can be easily solved analyzing Figure 1b:

$$u_{ij} = \sqrt{(p \cos \varphi_{ij} - b)^2 + (y_{ij} - p \sin \varphi_{ij})^2} \tag{1}$$

$$v_{ij} = \sqrt{(p \cos \varphi_{ij} - b)^2 + (y_{ij} + p \sin \varphi_{ij})^2} \tag{2}$$

In practice, the linear actuators have a minimum length $\rho_0 > 0$ and a stroke $\Delta\rho > 0$, which means that $u_{ij}, v_{ij} \in [\rho_0, \rho_0 + \Delta\rho]$. Thus, the workspace can be defined as the set of pairs (y_{ij}, φ_{ij}) for which the right-hand side of both Eqs. (1) and (2) is in $[\rho_0, \rho_0 + \Delta\rho]$. For example, Figure 2 shows the workspace for $b = p = 4$, $\rho_0 = 19.5$, and $\Delta\rho = 5$ (all in cm). This workspace is composed of four regions R_i enclosed by the curves where u_{ij} or v_{ij} equal ρ_0 or $\rho_0 + \Delta\rho$. The configuration of the mechanism is different in each region, as shown in Figure 2. Only the configurations of R_1 are valid, since the configurations of the other regions require mechanical interferences: y_{ij} cannot be negative (regions R_3 and R_4), and the linear actuators cannot interfere with the passive slider (regions R_2 and R_4). Thus, for this example the workspace is defined as follows:

$$WS = \left\{(\varphi_{ij}, y_{ij}) \in \mathbb{R}^2 : \varphi_{min} \leq \varphi_{ij} \leq \varphi_{max}, \underline{y_{ij}}(\varphi_{ij}) \leq y_{ij} \leq \overline{y_{ij}}(\varphi_{ij})\right\} \tag{3}$$

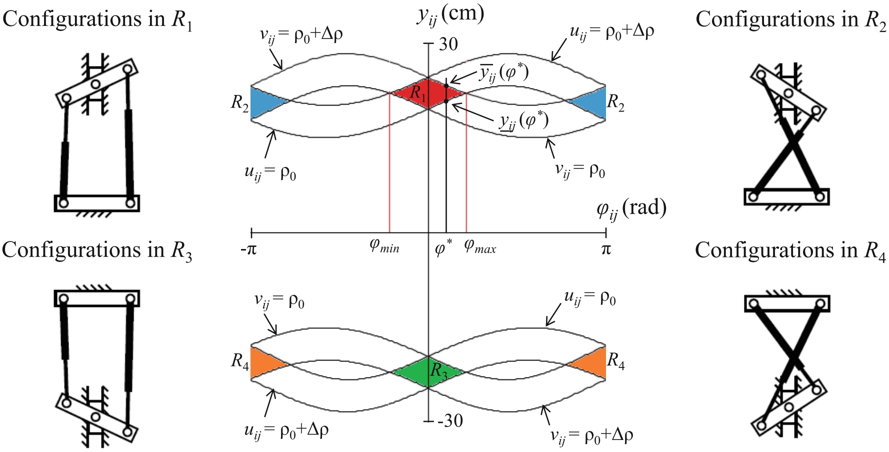

Fig. 2 Workspace of a parallel mechanism with $b = p = 4$, $\rho_0 = 19.5$, $\Delta\rho = 5$ (cm)

where $\underline{y_{ij}}(\varphi^*)$ and $\overline{y_{ij}}(\varphi^*)$ are the lower and upper bounds of the variable y_{ij} for $\varphi_{ij} = \varphi^*$, respectively (see Figure 2). In the following, we will assume that the workspace of the parallel mechanisms has the form of Eq. (3), which defines a more general set. Although this type of workspace has been derived from a particular geometry, the workspace of the parallel mechanisms will be similar to the region R_1 of Figure 2 if b, p, and $\Delta\rho$ are similar and small compared to ρ_0.

3 Monte-Carlo Workspace Calculation

In this section, we will use the equations of forward kinematics with a Monte-Carlo method to compute the workspace. The workspace considered here is the set of points that can be attained by one foot of the robot (free foot) when the other foot is fixed. Since the robot is symmetric, we can consider, without loss of generality, foot A as the fixed foot and foot B as the free one.

3.1 Forward Kinematics

Next, we will compute the position and orientation of the foot B relative to the foot A in terms of the rotations of the hip (angles θ_A and θ_B) and the rotations φ_{ij} and translations y_{ij} of the parallel mechanisms ($i \in \{1, 2\}$, $j \in \{A, B\}$). First, we will obtain the relative position and orientation between the hip and the foot of a generic leg j. According to Figure 3, the position and orientation of the hip relative to the

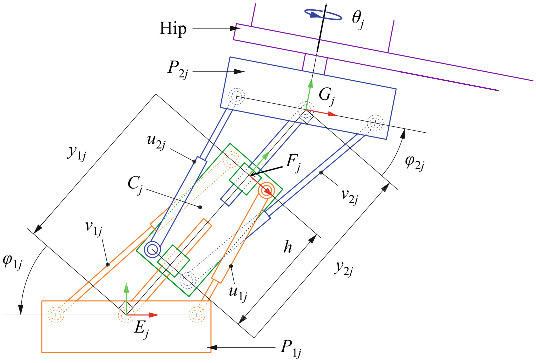

Fig. 3 Kinematics of the generic leg $j \in \{A, B\}$.

foot of the leg j can be obtained multiplying the following matrices, which relate the reference frames E_j, F_j, G_j, and H_j:

$$
{}^{E_j}\mathbf{T}_{H_j} = {}^{E_j}\mathbf{T}_{F_j}\,{}^{F_j}\mathbf{T}_{G_j}\,{}^{G_j}\mathbf{T}_{H_j} = \begin{bmatrix} c_{\varphi_{1j}} & s_{\varphi_{1j}} & 0 & y_{1j}s_{\varphi_{1j}} \\ -s_{\varphi_{1j}} & c_{\varphi_{1j}} & 0 & y_{1j}c_{\varphi_{1j}} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \times
$$

$$
\begin{bmatrix} c_{\varphi_{2j}} & -s_{\varphi_{2j}} & 0 & 0 \\ s_{\varphi_{2j}} & c_{\varphi_{2j}} & 0 & y_{2j}-h \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_{\theta_j} & 0 & s_{\theta_j} & 0 \\ 0 & 1 & 0 & 0 \\ -s_{\theta_j} & 0 & c_{\theta_j} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_{\theta_j}c_{\Phi_j} & s_{\Phi_j} & s_{\theta_j}c_{\Phi_j} & y_j s_{\varphi_{1j}} \\ -c_{\theta_j}s_{\Phi_j} & c_{\Phi_j} & -s_{\theta_j}s_{\Phi_j} & y_j c_{\varphi_{1j}} \\ -s_{\theta_j} & 0 & c_{\theta_j} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)
$$

where $\Phi_j = \varphi_{1j} - \varphi_{2j}$, $y_j = y_{1j} + y_{2j} - h$, and h is the size of the core link of the leg j. The symbols s_x and c_x denote respectively $\sin(x)$ and $\cos(x)$, and θ_j is the angle that the frame G_j must be rotated about its Y axis to align that frame with the frame H_j of the hip (shown in Figure 1a). Particularizing the previous matrix for the two legs of the robot ($j = A$ and $j = B$), we obtain the position and orientation of the foot B with respect to the foot A as follows:

$$
{}^{E_A}\mathbf{T}_{E_B} = {}^{E_A}\mathbf{T}_{H_A}\,{}^{H_A}\mathbf{T}_{H_B}\,{}^{H_B}\mathbf{T}_{E_B} = {}^{E_A}\mathbf{T}_{H_A} \begin{bmatrix} \mathbf{I} & [t, 0, 0]^T \\ \mathbf{0}_{1\times 3} & 1 \end{bmatrix} \left({}^{E_B}\mathbf{T}_{H_B}\right)^{-1} \quad (5)
$$

where $\mathbf{I}$ is the 3×3 identity matrix, $\mathbf{0}_{1\times 3} = [0, 0, 0]$, and ${}^{H_A}\mathbf{T}_{H_B}$ encodes the position and orientation of the frame H_B relative to the frame H_A (see Figure 1a). Performing the products of Eq. (5), the matrix that encodes the position and orientation of the frame E_B relative to the frame E_A can be written as follows:

$$
{}^{E_A}\mathbf{T}_{E_B} = \begin{bmatrix} {}^{E_A}\mathbf{R}_{E_B} & \left[p_x \;\; p_y \;\; p_z\right]^T \\ \mathbf{0}_{1\times 3} & 1 \end{bmatrix} \quad (6)
$$

The position vector of the previous matrix has the following expression:

$$\begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = y_A \begin{bmatrix} s_{\varphi_{1A}} \\ c_{\varphi_{1A}} \\ 0 \end{bmatrix} + y_B \begin{bmatrix} -c_{\Theta} c_{\Phi_A} s_{\varphi_{2B}} - s_{\Phi_A} c_{\varphi_{2B}} \\ c_{\Theta} s_{\Phi_A} s_{\varphi_{2B}} - c_{\Phi_A} c_{\varphi_{2B}} \\ s_{\Theta} s_{\varphi_{2B}} \end{bmatrix} + t \begin{bmatrix} c_{\theta_A} c_{\Phi_A} \\ -c_{\theta_A} s_{\Phi_A} \\ -s_{\theta_A} \end{bmatrix} \tag{7}$$

where $\Theta = \theta_A - \theta_B$. The rotation submatrix of ${}^{E_A}\mathbf{T}_{E_B}$ has the following form:

$${}^{E_A}\mathbf{R}_{E_B} = \begin{bmatrix} s_{\Phi_A} s_{\Phi_B} + c_{\Theta} c_{\Phi_A} c_{\Phi_B} & s_{\Phi_A} c_{\Phi_B} - c_{\Theta} c_{\Phi_A} s_{\Phi_B} & s_{\Theta} c_{\Phi_A} \\ c_{\Phi_A} s_{\Phi_B} - c_{\Theta} s_{\Phi_A} c_{\Phi_B} & c_{\Phi_A} c_{\Phi_B} + c_{\Theta} s_{\Phi_A} s_{\Phi_B} & -s_{\Theta} s_{\Phi_A} \\ -s_{\Theta} c_{\Phi_B} & s_{\Theta} s_{\Phi_B} & c_{\Theta} \end{bmatrix} \tag{8}$$

Next, Eqs. (7) and (8) will be used to compute the following workspaces:

- Reachable workspace: the set of points $\mathbf{P} = [p_x, p_y, p_z]^T$ that can be reached by the free foot with at least one orientation
- Constant-orientation workspace: the set of points $\mathbf{P} = [p_x, p_y, p_z]^T$ that can be reached by the free foot with a specific orientation

3.2 Computation of the Reachable Workspace

Once the solution to forward kinematics of the complete biped robot is available, the reachable workspace can be easily generated using a Monte-Carlo method [1]. This approach consists in varying randomly the following variables in their ranges: $\{\varphi_{1A}, \varphi_{2A}, \varphi_{1B}, \varphi_{2B}, y_A, y_B, \theta_A, \theta_B\}$, generating a point $\mathbf{P} = [p_x, p_y, p_z]^T$ for each value of these variables. The generated points form a 3D cloud point in space that constitutes a discrete approximation of the workspace.

To apply this method, we must find the variation ranges of the previous variables, for each leg j. It will be assumed that $\theta_j \in [-\pi, \pi]$ (the legs can perform complete revolutions about the axes of the hip). The angles φ_{ij} must belong to the workspace of the parallel mechanisms of the legs. It will be assumed that such workspaces are of the type studied in Section 2, which implies that $\varphi_{min} \leq \varphi_{ij} \leq \varphi_{max}$. Finally, the valid ranges for y_j can be found as follows: given $\varphi_{ij} \in [\varphi_{min}, \varphi_{max}]$ ($i \in \{1, 2\}$), then according to Eq. (3), y_{ij} must satisfy:

$$\underline{y_{ij}}(\varphi_{ij}) \leq y_{ij} \leq \overline{y_{ij}}(\varphi_{ij}) \tag{9}$$

Since $y_j = y_{1j} + y_{2j} - h$, then the variables y_j must verify:

$$\underline{y_{1j}}(\varphi_{1j}) + \underline{y_{2j}}(\varphi_{2j}) - h \leq y_j \leq \overline{y_{1j}}(\varphi_{1j}) + \overline{y_{2j}}(\varphi_{2j}) - h \tag{10}$$

Once the variation ranges of all the variables are known, the Monte-Carlo algorithm to compute the reachable workspace can be summarized in Algorithm 1. In this algorithm, N_r is the number of sampled random points.

Algorithm 1. Monte-Carlo calculation of the reachable workspace

1: $WS = \emptyset \rightarrow$ The reachable workspace is initialized as an empty set.
2: **for** $k = 1$ to N_r **do**
3:    Randomly sample θ_A and θ_B in $[-\pi, \pi]$
4:    Randomly sample $\varphi_{1A}, \varphi_{2A}, \varphi_{1B}$, and φ_{2B} in $[\varphi_{min}, \varphi_{max}]$
5:    Compute the lower and upper limits for y_j $(j \in \{A, B\})$:
6:       $\underline{y_j} = \underline{y_{1j}}(\varphi_{1j}) + \underline{y_{2j}}(\varphi_{2j}) - h$
7:       $\overline{y_j} = \overline{y_{1j}}(\varphi_{1j}) + \overline{y_{2j}}(\varphi_{2j}) - h$
8:    Randomly sample y_j in $[\underline{y_j}, \overline{y_j}]$ $(j \in \{A, B\})$
9:    Compute the position $\mathbf{P} = [p_x, p_y, p_z]^T$ of the free foot using Eq. (7)
10:    Add the point $\mathbf{P}$ to WS
11: **end for**

To sample the variables θ_A and θ_B in line 3 of Algorithm 1, a uniform distribution can be used. However, the variables y_j and φ_{ij} (whose limits define the limits of the workspace) should be sampled using a beta distribution with parameters $\alpha, \beta \in (0, 1)$. Using this non-uniform distribution for these variables favors the generation of random points close to the boundaries of the workspace, which results in a better definition of these boundaries [6].

3.3 Computation of the Constant-Orientation Workspace

The constant-orientation workspace is the set of points of the space that can be reached with a desired orientation, which can be specified as:

$$^{E_A}\mathbf{R}_{E_B} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix} \tag{11}$$

where r_{ij} are known quantities. Algorithm 1 can still be used to generate random points in the constant-orientation workspace. However, unlike in Algorithm 1, not all the angles $\{\varphi_{ij}, \theta_j\}$ can be sampled independently now: these angles must satisfy certain relations to guarantee that the generated random points have the desired orientation. Two cases are distinguished:

Case 1: $r_{33}^2 \neq 1$. Equating the element (3,3) of matrices (8) and (11) permits computing the angle Θ as follows:

$$c_\Theta = r_{33} \longrightarrow s_\Theta = \sigma\sqrt{1 - r_{33}^2} \longrightarrow \Theta = \theta_A - \theta_B = \text{atan2}(s_\Theta, c_\Theta) \tag{12}$$

where $\sigma \in \{-1, 1\}$. Once s_Θ is known, Equating the elements (1,3), (2,3), (3,1) and (3,2) of Eqs. (8) and (11) allows for the calculation of Φ_A and Φ_B:

$$c_{\Phi_A} = r_{13}/s_\Theta, \quad s_{\Phi_A} = -r_{23}/s_\Theta \longrightarrow \Phi_A = \varphi_{1A} - \varphi_{2A} = \text{atan2}(s_{\Phi_A}, c_{\Phi_A}) \tag{13}$$

$$c_{\Phi_B} = -r_{31}/s_\Theta, \quad s_{\Phi_B} = r_{32}/s_\Theta \longrightarrow \Phi_B = \varphi_{1B} - \varphi_{2B} = \text{atan2}(s_{\Phi_B}, c_{\Phi_B}) \tag{14}$$

Note that Eqs. (12), (13), and (14) fix the differences $\theta_A - \theta_B$, $\varphi_{1A} - \varphi_{2A}$, and $\varphi_{1B} - \varphi_{2B}$, respectively. Thus, we cannot give random values to the six angles $\{\varphi_{1A}, \varphi_{2A}, \varphi_{1B}, \varphi_{2B}, \theta_A, \theta_B\}$ simultaneously. Instead, we can give values to the angles $\{\theta_B, \varphi_{2A}, \varphi_{2B}\}$ and compute the other three angles using the previous equations to guarantee that the generated points have the desired orientation. Note that, after calculating $\{\varphi_{1A}, \varphi_{1B}\}$, these angles may not be in $[\varphi_{min}, \varphi_{max}]$, in which case the point must be discarded since it does not satisfy the joint limits.

Case 2: $r_{33}^2 = 1$. In this case, Θ can be calculated from Eq. (12), but Φ_A and Φ_B cannot be computed from Eqs. (13) and (14) since $s_\Theta = 0$. To compute these angles, we substitute $c_\Theta = r_{33}$ into the elements (1,2) and (2,2) of Eq. (8) and equate these elements to r_{12} and r_{22}:

$$\begin{bmatrix} r_{12} \\ r_{22} \end{bmatrix} = \begin{bmatrix} s_{\Phi_A} c_{\Phi_B} - r_{33} c_{\Phi_A} s_{\Phi_B} \\ c_{\Phi_A} c_{\Phi_B} + r_{33} s_{\Phi_A} s_{\Phi_B} \end{bmatrix} = \begin{bmatrix} \sin(\Phi_A - r_{33}\Phi_B) \\ \cos(\Phi_A - r_{33}\Phi_B) \end{bmatrix} \tag{15}$$

where the last equality is true because $r_{33} = 1$ or $r_{33} = -1$. In this case, Algorithm 1 can also be used with the following modification: $\{\varphi_{1B}, \varphi_{2B}, \varphi_{2A}\}$ are randomly sampled, whereas φ_{1A} is computed as $\varphi_{1A} = \varphi_{2A} + r_{33}\Phi_B + \text{atan2}(r_{12}, r_{22})$, discarding the point if $\varphi_{1A} \notin [\varphi_{min}, \varphi_{max}]$.

Finally, the previous methods compute discrete approximations of the solid workspace. However, for practical purposes (e.g., for visualization) it is sufficient to know the surfaces that delimit these solids. The boundaries of the computed workspaces can be extracted using the algorithm described in [1], which defines a 3D grid composed of N_g boxes in each dimension. The boxes that contain workspace points are marked with "1", whereas the remaining boxes are marked with "0". Then, the workspace boundary is composed of the boxes that are marked with "1" and have at least one neighboring box marked with "0".

4 Simulation Tool and Examples

This section presents a simulation tool developed in Java to study the workspace of this robot. The tool can be downloaded from http://arvc.umh.es/parola/climber.html and may require the latest version of Java.

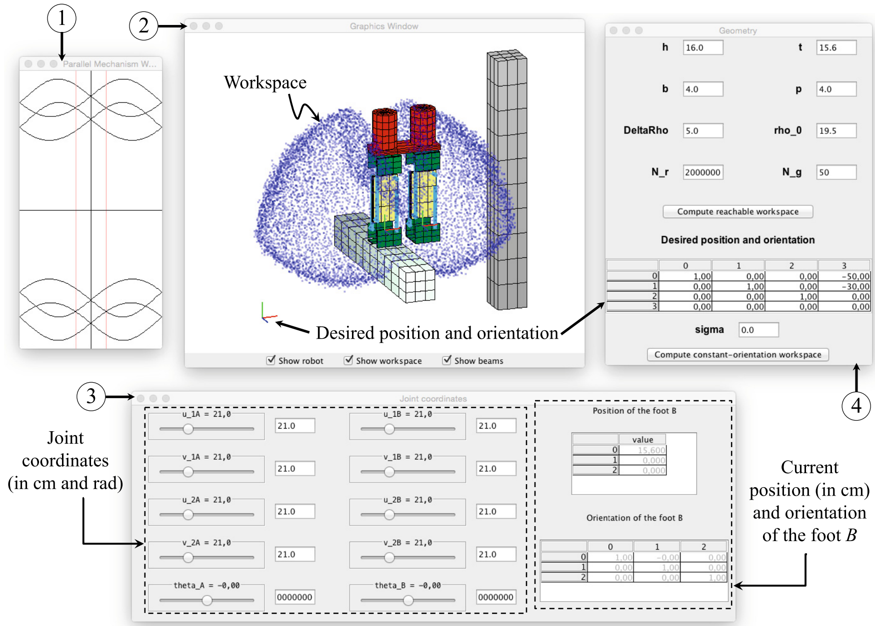

Fig. 4 Simulator developed to study the workspace of the biped robot.

The tool, which has four windows, is shown in Figure 4. Window 1 shows the workspace of the parallel mechanisms, as defined in Section 2, so that the user can see if this workspace has the form of Eq. (3). Window 2 shows the biped robot in a virtual environment composed of two beams, along with the workspace calculated using the previous Monte-Carlo method. In the simulator, the foot A is fixed to the horizontal beam, and the foot B is free. Window 3 has some sliders and numeric fields to modify the value of the joint coordinates. When a joint coordinate is modified, the forward kinematics is solved and the posture of the robot in Window 2 is modified accordingly. Window 3 also shows the current position and orientation of the foot B (vector $[p_x, p_y, p_z]^T$ and matrix ${}^{E_A}\mathbf{R}_{E_B}$). Finally, Window 4 can be used to design the robot: in it, the six design parameters $\{h, b, t, p, \Delta\rho, \rho_0\}$ (in cm) can be modified to study how the shape and size of the workspace varies with these parameters.

Next, we will analyze some examples that show how this tool can be used to design the robot. In the following examples, the shown workspaces have been obtained using $N_r = 2 \cdot 10^6$ random points and $N_g = 50$.

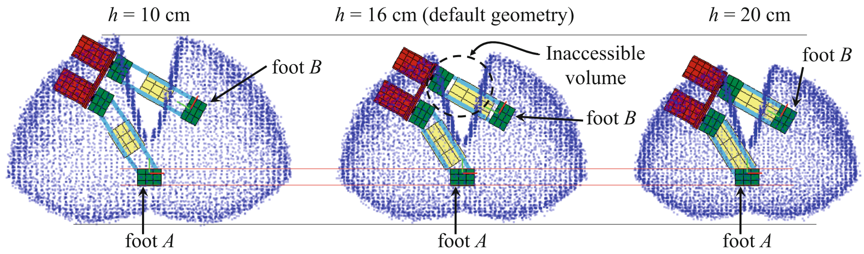

Fig. 5 Variation of the reachable workspace when h is modified.

4.1 Example 1: Sensitivity of the Reachable Workspace with Respect to the Design Parameters

In this example, we will study the changes in the shape and size of the reachable workspace when perturbing the design parameters from their default values: $\rho_0 = 19.5$, $\Delta\rho = 5$, $b = p = 4$, $t = 15.6$, $h = 16$ (all in cm). The reachable workspace for this geometry is shown in Figure 5 (center), which shows that the points above the fixed foot A cannot be reached by the foot B. Next, we will vary the design parameters (one at a time, keeping the rest at their default values) to obtain a larger workspace in which the region above the foot A is accessible.

Figure 5 shows that increasing h reduces the size of the reachable workspace, leaving its shape practically unaffected. If the parameters t and ρ_0 are respectively varied in the intervals [10, 20] cm and [15, 25] cm in the simulator, it can be checked that the size of the workspace increases with these parameters, but its shape hardly varies with them. Also, it can be checked that varying b in (0, 10] cm hardly affects the shape or size of the reachable workspace. Thus, varying these four parameters generates workspaces where the points above the foot A are still inaccessible. However, varying the parameter p modifies noticeably the shape of the workspace, as shown in

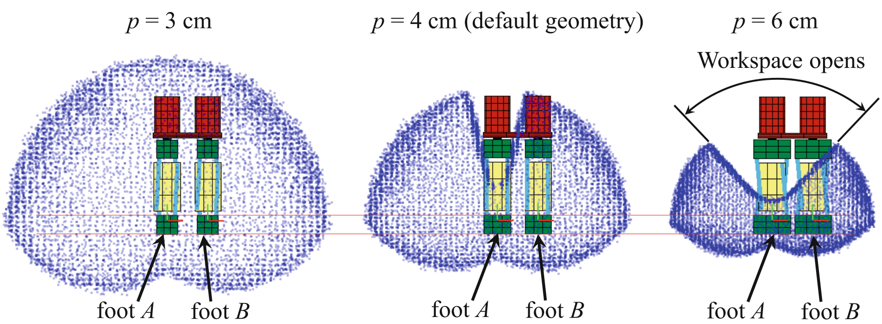

Fig. 6 Variation of the reachable workspace when p is modified.

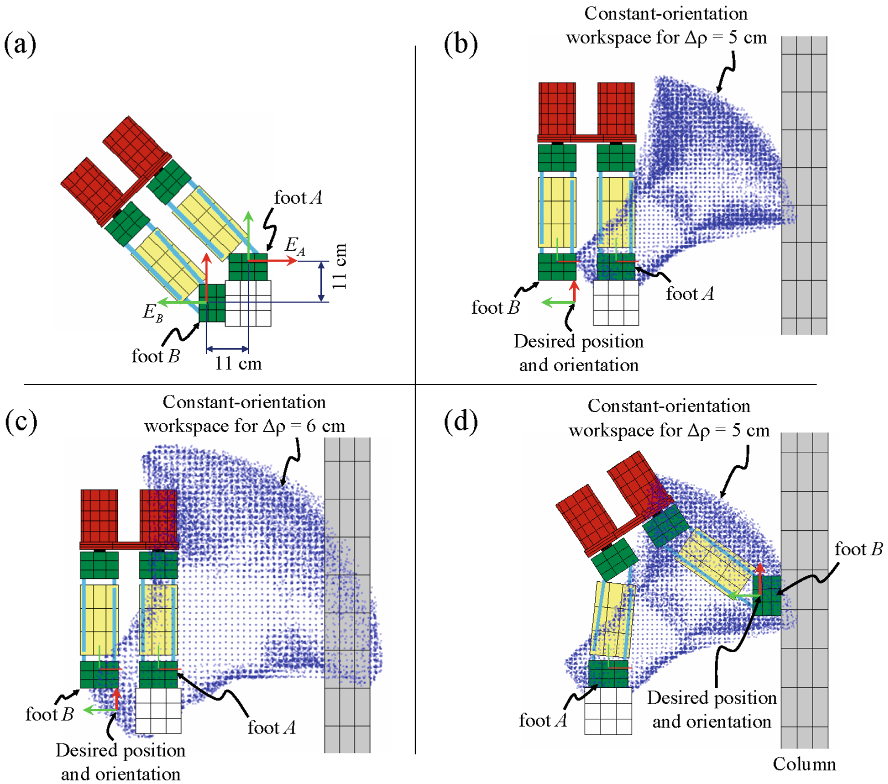

Fig. 7 (a) Desired position and orientation to change between different faces of a beam. For $\Delta\rho = 5$ cm (b), the constant-orientation workspace for the desired orientation does not contain the desired point, but it contains the point for $\Delta\rho = 6$ cm (c). (d) Performing transitions between different beams using the default geometry.

Figure 6. This figure shows that the reachable workspace opens as p increases. Thus, it is convenient to reduce p as shown in Figure 6 in order to eliminate the inaccessible region above the foot A. It can be checked that varying $\Delta\rho$ in [3, 6] cm produces a similar effect in the opposite direction: the workspace opens as $\Delta\rho$ decreases.

4.2 *Example 2: Transition Between Different Faces of a Beam*

In this example, we assume that all the design parameters are fixed at their default values except $\Delta\rho$, whose value must be chosen so as to permit the robot to perform a transition between different faces of a beam, as shown in Figure 7a. According to this figure, the desired position and orientation for the foot B relative to the fixed foot A are given by the following matrices:

$$^{E_A}\mathbf{R}_{E_B} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad \begin{bmatrix} p_x \\ p_y \\ p_z \end{bmatrix} = \begin{bmatrix} -11 \\ -11 \\ 0 \end{bmatrix} \text{ cm} \tag{16}$$

Introducing these matrices in the simulator, and using $\Delta\rho = 5$ cm (default stroke) yields the constant-orientation workspace of Figure 7b. Note that, for the default stroke, the desired point cannot be attained with the desired orientation because it lies outside the computed constant-orientation workspace. However, if the workspace is recalculated for $\Delta\rho = 6$ cm, we obtain the workspace of Figure 7c, which contains the desired point. Thus, choosing a linear actuator with a stroke of 6 cm would permit the robot to change between different faces of the beam in this example.

Note that the orientation defined in Eq. (16) is also necessary to attach the foot B to the column, as indicated in Figure 7d. As shown in this figure, the constant-orientation workspace for $\Delta\rho = 5$ cm contains points that are near the surface of the column. Thus, it is possible to attach the foot B to the column using the default geometry.

5 Conclusions and Future Work

This paper has presented a Monte-Carlo workspace analysis of a serial-parallel climbing robot. First, the workspace of the parallel mechanisms has been calculated to use it in the calculation of the workspace of the complete robot. Then, the solution to forward kinematics has been used together with a Monte-Carlo method to compute the reachable and constant-orientation workspaces of the robot. These calculations have been implemented in a simulator, which has been used to manually and visually study the sensitivity of the shape and size of the workspace with respect to the design parameters. In the future, an algorithm to automatically perform the sensitivity analysis and optimization of the design of the robot will be devised, similar to [13]. Also, we will compute other types of workspace (such as the orientation workspace) and study the singularities.

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