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ROBOT 2017: Third Iberian Robotics Conference

Volume 1

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Preface

This book contains a selection of papers accepted for presentation and discussion at "Robot 2017: Third Iberian Robotics Conference," held in Seville, Spain, November 22–24, 2017. Robot 2017 is part of a series of conferences that are a joint organization of Sociedad Española para la Investigación y Desarrollo de la Robótica/Spanish Society for Research and Development in Robotics (SEIDROB) and Sociedade Portuguesa de Robótica/Portuguese Society for Robotics (SPR). The conference organization had also the collaboration of several universities and research institutes, including University of Seville, Polytechnic University of Catalonia, University of Zaragoza, University of Aveiro, and University of Lisbon.

Robot 2017 builds upon several successful events, including three biennial workshops (Zaragoza–2007, Barcelona–2009, and Sevilla–2011) and two Iberian Robotics Conferences (Madrid–2013 and Lisbon–2015).

The conference is focused on the robotics scientific and technological activities in the Iberian Peninsula, although open to research and delegates from other countries.

Robot 2017 featured three plenary talks by:

– Oussama Khatib, Director of Stanford Robotics Lab, Stanford University, USA, President of the International Foundation of Robotics Research (IFRR)
– Dario Floreano, Director of the Laboratory of Intelligent Systems, EPFL, Switzerland, Director of the Swiss National Center of Competence in Robotics, Switzerland
– Alin Albu-Schäffer, Head of the Institute of Robotics and Mechatronics at the German Aerospace Center (DLR), Germany.

Robot 2017 featured 27 special sessions, four of them with two slots in the Conference Program, plus 5 sessions coming from the General Track. The conference had an industrial track with four sessions. The main purpose of this track is to present industrial needs and recent achievements in robotic industrial applications looking to promote new collaborations between industry and academia. Six papers of the industrial track have been included in this book.

The Special Sessions were about Aerial Robotics for Inspection, Agricultural Robotics and Field Automation, Autonomous Driving and Driver Assistance Systems, Challenges in Medical Robotics in the Frame of Industry 4.0, Cognitive Architectures, Communication-Aware Robotics, Cooperative and Active Perception for Robotics, Educational Robotics, Legged Locomotion Robots, Machine Learning in Robotics, Marine Robotics, Ontologies and Knowledge Representation for Robotics, Rehabilitation and Assistive Robotics, Robotics and Cyber-Physical Systems for Industry 4.0, Robotic and Unmanned Vehicles for Security, Robot Competitions, Robots Cooperating with Sensor Networks, Robots for Health care, Sensor Technologies oriented to Computer Vision Applications, Simulation in Robotics, Vision and Learning for Robotics, and Visual Perception for Robotics.

Additionally, the four industrial Special Sessions were about Application of Robotics to Manufacturing Processes in the Aeronautic Industry, Application of Robotics to Shipbuilding, Integration of Drones in Low Altitude Aerial Space, and Robotics Solutions for Flexible Manufacturing.

Finally, the sessions in the General Track were about the following topics: Aerial Robotics (double slot), Manipulation, Mobile Robotics, and Mobile Robotics Applications.

The Robot 2017 Call for papers received 201 papers. After a careful review process with at least three independent reviews for each paper, 141 of them have been selected to be included in this book. There are over 500 authors from 21 countries including Australia, Brazil, Colombia, Croatia, Czech Republic, Denmark, Ecuador, Finland, France, Germany, Ireland, Italy, Luxembourg, Macao, Mexico, Poland, Portugal, Spain, United Arab Emirates, UK, and USA.

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 2017 Conference. This acknowledgment goes especially to the members of the Program Committee, Organizers of the Special Sessions, and Reviewers for the hard work required to prepare this volume 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. The work of the Local Organizing Committee was also crucial to produce the Robot 2017 Program and this book.

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 2017

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A Simulation Tool for Visualizing the Assembly Modes and Singularity Locus of 3RPR Planar Parallel Robots

Adrián Peidró([✉]), Óscar Reinoso, José María Marín, Arturo Gil, Luis Payá, and Yerai Berenguer

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Abstract. This paper presents a graphical and intuitive tool for simulating the forward kinematics of planar parallel 3R$\underline{\text{P}}$R robots with arbitrary geometric design. The proposed tool allows the user to visualize the singularity locus of the robot and the evolution of all the solutions to its forward kinematic problem in the complex plane. The user can modify all the geometric design parameters of the robot and instantaneously visualize the effect of these modifications on the singularity locus. As the presented examples illustrate, the proposed tool is especially useful for visualizing the coalescence of different solutions of the forward kinematic problem when approaching higher-order singularities, as well as for visualizing how these special singularities transform when perturbing the different geometric parameters of the robot.

Keywords: Assembly modes · Forward kinematics · Parallel robot · Simulator · Singularity

1 Introduction

Parallel robots are manipulators in which two or more legs, connected in parallel, are used to control the position and/or orientation of a mobile platform. Generally, these robots offer high dynamic characteristics, a high payload-to-weight ratio, and high stiffness. Currently, there exist different simulation tools and packages for studying diverse aspects of parallel robots, such as: work- and configuration-spaces and singularities (*GIM* [14], *CUIK Suite* [15], *SinguLab* [2]), forward kinematics and assembly modes (*Bertini* [1]), dynamics and control (*Matlab/Simulink* [7] and *ADAMS* [5]), and path planning [15].

A central topic in the study of parallel robots is the analysis of parallel singularities, which are the configurations at which it is not possible to control the motion of the mobile platform of the robot by means of its actuators. All parallel singularities are gathered to form the *singularity locus*, whose concrete shape depends on the geometric design of the robot. When modifying the design

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of the robot, the shape and features of the singularity locus vary, which may affect the ability of the robot to reconfigure itself in a controlled manner [16].

PaRoLa (Parallel Robotics Laboratory, http://arvc.umh.es/parola) is a Java-based educational virtual laboratory, developed for simulating and facilitating the comprehension and analysis of diverse kinematic [9] and dynamic [12,13] aspects of parallel robots. One of the main objectives of PaRoLa is to facilitate the graphical analysis of the relationship between the geometric design of the robot and its singularity locus, as mentioned in the previous paragraph. By using PaRoLa, it is possible to vary the different design parameters of a parallel robot and instantaneously visualize how the singularity locus of the robot transforms as a consequence. This feature is very useful for designing parallel robots.

This paper contributes a new graphical and intuitive simulation tool of the virtual laboratory PaRoLa, for simulating the forward kinematics and visualizing the parallel singularities of general 3R<u>P</u>R planar parallel robots. The 3R<u>P</u>R robot is one of the most widely studied parallel robots, since its forward kinematics and singularity locus present the sufficient richness and simplicity to facilitate the study of important problems, such as higher-order singularities [18] and non-singular transitions between different solutions of the forward kinematic problem [19]. The tool presented in this paper is especially useful for graphically studying problems like these, as it will be shown through diverse illustrative examples.

This paper is organized as follows. Section 2 presents the forward kinematics and singularities of the general 3R<u>P</u>R parallel robot. Section 3 describes the tool developed to simulate this robot. Section 4 illustrates the usefulness of the proposed tool through three examples. Finally, Sect. 5 concludes this paper.

2 The 3R<u>P</u>R parallel robot

This section presents the 3R<u>P</u>R planar parallel robot, as well as two aspects of this robot which can be analyzed through the simulation tool presented in this paper, namely: its forward kinematic problem and its parallel singularities. Figure 1 depicts a general 3R<u>P</u>R planar parallel robot. This robot is composed of a fixed platform ACF, a mobile platform BDE, and three actuated legs {AB, CD, EF} of type R<u>P</u>R (Revolute-Prismatic-Revolute), which connect both platforms and control the position and orientation of the mobile platform. The geometry of the fixed platform is defined by parameters $\{c_2, c_3, d_3\}$, whereas the geometry of the mobile platform is defined by $\{l_1, l_3, \beta\}$ (see Fig. 1).

By regulating the lengths $\{\rho_1, \rho_2, \rho_3\}$ of the actuated legs, one can control the position and orientation of the mobile platform in the plane. The position of the mobile platform can be defined by the polar coordinates (ρ_3, θ_3) of joint E, whereas its orientation can be defined by the angle ϕ between edges BE and AC (see Fig. 1). The forward kinematic problem consists in finding the position and orientation of the mobile platform for known lengths $\{\rho_1, \rho_2, \rho_3\}$ (inputs). The unknown angles $\{\theta_3, \phi\}$ (outputs) can be solved from Eqs. (1) and (2):

$$\left\| \begin{bmatrix} c_3 + \rho_3 \cos\theta_3 - l_3 \cos\phi \\ d_3 + \rho_3 \sin\theta_3 - l_3 \sin\phi \end{bmatrix} \right\|^2 - \rho_1^2 = 0 \tag{1}$$

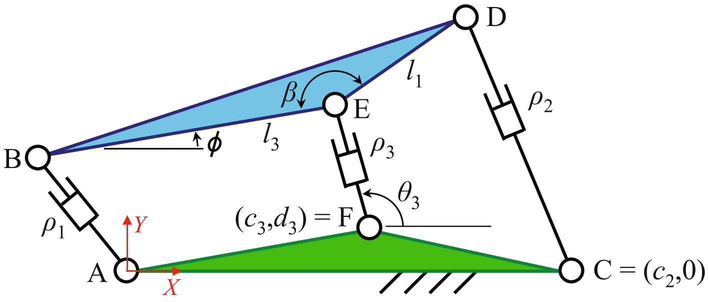


Fig. 1. General 3RPR planar parallel robot, following the notation used in [4].

$$\left\| \begin{bmatrix} c_3 - c_2 + \rho_3 \cos\theta_3 + l_1 \cos(\phi + \pi - \beta) \\ d_3 + \rho_3 \sin\theta_3 + l_1 \sin(\phi + \pi - \beta) \end{bmatrix} \right\|^2 - \rho_2^2 = 0 \tag{2}$$

Equations (1) and (2) express the conditions that the lengths of legs AB and CD must be ρ_1 and ρ_2, respectively. These equations can be solved via elimination [8]: by using Eqs. (1) and (2) to eliminate θ_3, one can arrive at a sextic polynomial equation in $\tan(\phi/2)$, from which 6 solutions for ϕ can be obtained. These solutions will be real or complex depending on $\{c_2, c_3, d_3, l_1, l_3, \beta, \rho_1, \rho_2, \rho_3\}$. For each solution of ϕ (either real or complex), one can use Eqs. (1) and (2) to obtain a unique solution for θ_3 [8]. Thus, the forward kinematics of this robot has 6 different solutions or *assembly modes* $\mathbf{y}^j = [\theta_3^j, \phi^j]^T$ $(j = 1, \ldots, 6)$, where each solution has two components θ_3^j and ϕ^j, which are complex numbers in general:

$$\theta_3^j = \mathrm{Re}(\theta_3^j) + i \cdot \mathrm{Im}(\theta_3^j), \quad \phi^j = \mathrm{Re}(\phi^j) + i \cdot \mathrm{Im}(\phi^j) \quad (i = \text{imaginary unit}) \tag{3}$$

Note that, when any of the two components of a given solution $\mathbf{y}^j$ is complex, this means that the robot cannot be physically assembled in $\mathbf{y}^j$ for the considered geometry and inputs $\{\rho_1, \rho_2, \rho_3\}$, i.e., in this case the solution $\mathbf{y}^j$ is not valid (only real solutions are physically possible configurations for the robot). Nevertheless, although complex solutions have no physical meaning, it is interesting to consider and represent also these solutions, to visualize how they evolve when the configuration of the robot approaches different singular configurations. Unlike other existing tools and packages, the tool presented in Sect. 3 allows the user to graphically visualize the trajectories described by the complex solutions of the forward kinematic problem as the inputs $\{\rho_1, \rho_2, \rho_3\}$ are varied along the joint space. This feature of the proposed tool is especially useful for visualizing how different solutions of the forward kinematic problem coalesce into higher-multiplicity solutions when approaching higher-order kinematic singularities.

2.1 Parallel Singularities of the 3RPR parallel robot

Parallel singularities of the 3RPR robot occur when [8]:

$$\frac{\partial e_1}{\partial \theta_3}\frac{\partial e_2}{\partial \phi} - \frac{\partial e_1}{\partial \phi}\frac{\partial e_2}{\partial \theta_3} = 0 \tag{4}$$

where e_1 and e_2 denote the left-hand sides of Eqs. (1) and (2), respectively. Equation (4) defines the singularity locus of robot 3R$\underline{\text{P}}$R, which generically is a surface in space (ρ_3, θ_3, ϕ), which contains all singular configurations at which it is not possible to control the motion of the mobile platform by means of the linear actuators {AB, CD, EF}. Geometrically, these singular configurations occur when the three lines {AB, CD, EF} are parallel or intersect at the same point. This can be visualized using the tool presented in Sect. 3.

By solving the inverse kinematic problem using Eqs. (1) and (2), it is possible to represent the surface defined by Eq. (4) in the joint space (ρ_1, ρ_2, ρ_3). The planar slices of the surface of singularities in the joint space are singularity curves, which contain *special points* such as cusps, self-intersections, isolated points, and other higher-order singularities [3,16]. These special points are related to the ability of the robot to perform transitions between different solutions of the forward kinematic problem without crossing singularities (*non-singular transitions*), which is useful for enlarging the workspace of the robot [17]. When the joint coordinates approach these singularity curves, at least two different solutions of the forward kinematic problem coalesce.

The shape of the singularity curves depends on the geometric design parameters of the robot: $\{c_2, c_3, d_3, l_1, l_3, \beta\}$. When altering the design of the robot, the shape of the singularity curves changes and, as a consequence, they may acquire or lose special points like those mentioned in the previous paragraph (cusps, isolated points, self-intersections, etc.). Hence, some kinematic characteristics of the robot may be affected when altering the design of the robot (e.g., the robot may lose the ability to perform non-singular transitions if all its cusps disappear). The tool presented in the next section allows the user to visualize how the singularity curves transform when modifying the design of the 3R$\underline{\text{P}}$R robot. In particular, the proposed tool is especially useful for visualizing how the mentioned special points of these curves transform, as we will demonstrate later through some examples.

3 The Developed Tool

This section describes the virtual tool developed for simulating the forward kinematic problem of the 3R$\underline{\text{P}}$R parallel robot and visualizing its singularity locus for any geometric design. The tool has been developed using Easy Java Simulations (http://fem.um.es/Ejs) and can be downloaded from http://arvc.umh.es/parola/3RPR.html (the latest version of Java may be required).

The developed tool is shown in Fig. 2. The tool has two windows (w1) and (w2). Window (w1) has three panels (p1), (p2), and (p3). Panel (p1) represents the 3R$\underline{\text{P}}$R robot, whereas panel (p3) presents sliders and numeric fields for modifying the geometry of the robot or the joint coordinates. Central panel (p2) represents the coordinate planes of the joint space, i.e., the planes (ρ_1, ρ_2), (ρ_2, ρ_3), and (ρ_1, ρ_3). Each plane (ρ_m, ρ_n) represents the singularity locus assuming that the remaining joint coordinate ρ_k is kept constant (i.e., planar slices of

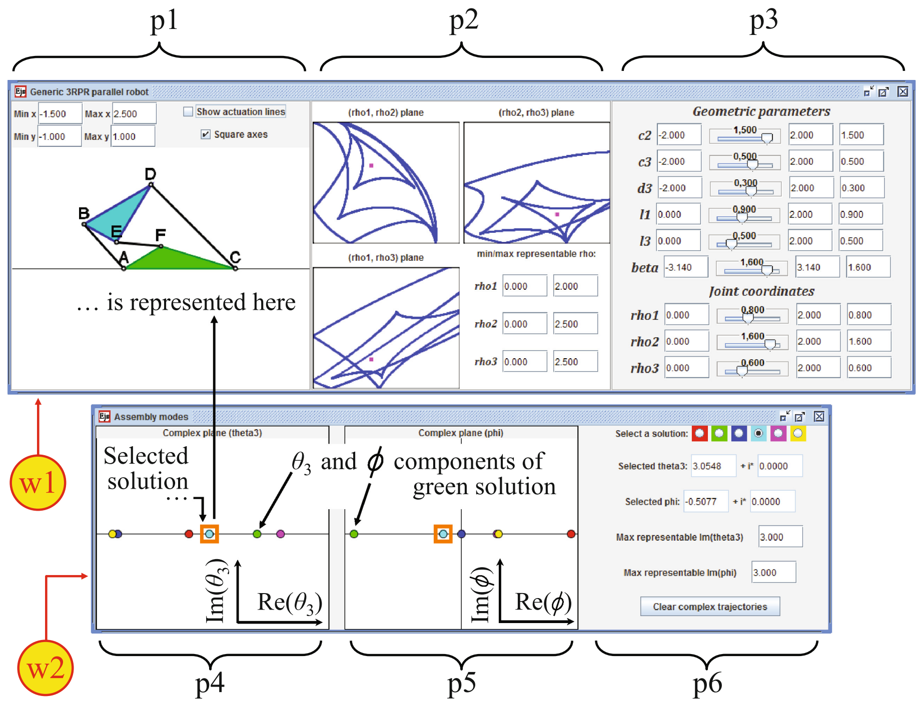


Fig. 2. Tool developed for simulating and studying the kinematics and singularities of 3RPR robots. When placing the mouse pointer on any element of the developed interface (e.g., a button or numerical field), a small message explaining the function of that element pops up below the pointer.

the surface of singularities are represented). Therefore, when ρ_k (or any geometric parameter) is varied in the simulator, the singularity curves shown in plane (ρ_m, ρ_n) transform instantaneously.

The forward kinematics can be simulated by dragging the tiny magenta square available in any of the coordinate planes of panel (p2), or by dragging the sliders of panel (p3). When modifying the joint coordinates through any of these methods, the simulator automatically solves the forward kinematic problem and represents graphically in window (w2) the six solutions to this problem.

Window (w2) also has three panels (p4), (p5), and (p6). Panel (p4) represents the θ_3 component of the six solutions of the forward kinematic problem in the complex plane. Similarly, panel (p5) represents the ϕ component of the six solutions in the complex plane. Note that in both these panels, the solutions wrap around the horizontal real axis (whose length is 2π rad), because the real parts of all solutions are angles [10,12]. In panels (p4) and (p5), each of the six solutions is represented by a different color (red, green, blue, cyan, magenta, and yellow). Finally, panel (p6) allows the user to select which solution should be adopted by the robot in panel (p1). Alternatively, the desired solution can also be selected by directly clicking on the colored points in panels (p4) or (p5) (the currently selected solution is indicated by an orange square enclosing it in these panels). Note that, if a non-real solution is selected, the configuration adopted by the robot in panel (p1) will be incorrect.

4 Illustrative Examples

This section presents three examples that illustrate the usefulness of the proposed tool to visually analyze the forward kinematics and singularities of 3R$\underline{\text{P}}$R parallel robots. Although the presented tool can be used for analyzing any geometric design of the 3R$\underline{\text{P}}$R robot, it is especially useful and interesting for studying non-generic or special designs, for which the singularity curves exhibit higher-order unstable singularities, which disappear when one of the geometric parameters of the robot is perturbed [16]. Next, the presented tool will be used to analyze the forward kinematics and singularities of three designs of the 3R$\underline{\text{P}}$R robot that exhibit higher-order singularities.

4.1 Example 1: Deltoid Singularity

Consider first a 3R$\underline{\text{P}}$R robot with the following geometric design G1: $c_2 = 1.5$, $c_3 = 0.5$, $d_3 = 0$, $l_1 = l_3 = 0.5$, $\beta = \pi$ rad. This design, analyzed in [8], corresponds with a 3R$\underline{\text{P}}$R robot in which both the mobile ($\beta = \pi$) and fixed ($d_3 = 0$) platforms are flat segments instead of triangles, as shown in Fig. 3. This design is interesting for working in vertical planes [4]. For this geometry, and for $\rho_3 = 1$, the singularity locus of the robot in the (ρ_1, ρ_2) plane exhibits an isolated point S1 = $(\rho_1 = 1, \rho_2 = 1.5)$, as indicated in Fig. 4a. This isolated point is a singularity with multiplicity four [10], which means that, when approaching S1 in the (ρ_1, ρ_2) plane, four different solutions of the forward kinematic problem converge to a single real solution whose multiplicity is four. This convergence can be verified using the presented simulator. For example, setting $\rho_2 = 1.5$ in the simulator and using the slider to vary ρ_1 from 1.2 to 1 (describing a horizontal trajectory T1 that approaches S1 in the (ρ_1, ρ_2) plane, as indicated in Fig. 4a), then the solutions of the forward kinematic problem will evolve as depicted in Fig. 3, which shows the evolution of the θ_3 component of the six solutions in the complex plane. As Fig. 3 shows, when approaching the isolated singularity S1 along trajectory T1 (i.e., when $\rho_1 \to 1$), four (two real and two complex) different solutions converge to a single real solution ($\theta_3 = \pi$). This coalescence of four solutions occurs not only for the θ_3 component of these solutions, but also for their ϕ components, which converge to $\phi = 0$ (this can be verified using the proposed simulator). The coalescence of different solutions in only one

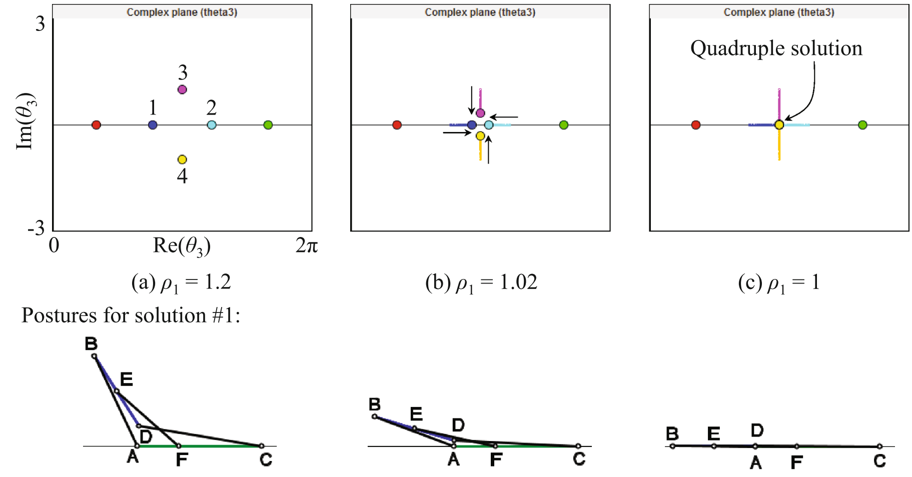


Fig. 3. When approaching the isolated singularity S1 of Fig. 4a, real solutions {1, 2} and complex solutions {3, 4} converge to a real quadruple solution ($\theta_3 = \pi, \phi = 0$). The evolution of the posture of the robot for real solution #1 is represented. As shown in (c), both flat platforms are aligned at the quadruple solution.

component (θ_3 or ϕ) is not a kinematic singularity but a self-intersection of a *reduced configuration space*[1] of the robot [10].

Besides representing the evolution of the solutions to the forward kinematic problem, the proposed tool also allows the user to visualize how the singularity curves transform when altering the geometry of the robot. In particular, we can use the presented tool to visualize how the isolated singularity S1 transforms when perturbing each of the six geometric parameters of the robot. If, departing from the geometry G1, any of the four parameters $\{c_2, c_3, l_1, l_3\}$ is varied using the sliders of the simulator, it can be observed that the isolated singularity S1 moves along the (ρ_1, ρ_2) plane, without changing its shape (it always remains as a point). However, if d_3 or β are perturbed away from their original values ($d_3 = 0$ and $\beta = \pi$) in any direction (such that at least one of the two platforms is no longer a segment but a triangle, see Fig. 4), the isolated singularity S1 always transforms into a deltoid curve (i.e., a closed curve with three cusps) whose size increases with the perturbation, as depicted in Fig. 4. The transformation

[1] *Reduced configuration spaces* are typically used for analyzing non-singular transitions in robots with 2 degrees of freedom, which can be accomplished in the 3R$\underline{\text{P}}$R robot by keeping constant one input (e.g., ρ_3 = constant). In that case, the (complete) *configuration space* is the real solution set $\mathcal{S}$ of Eqs. (1) and (2) in the 4D space $(\rho_1, \rho_2, \theta_3, \phi)$. The projection of $\mathcal{S}$ on a 3D subspace whose axes are the two inputs (ρ_1 and ρ_2) and one output (θ_3 or ϕ) is a reduced configuration space, which is a surface. For example, the self-intersection of this surface in the 3D subspace (ρ_1, ρ_2, ϕ) means that the ϕ components of different solutions coincide, but this is not a kinematic singularity unless the θ_3 components of these very solutions also meet.

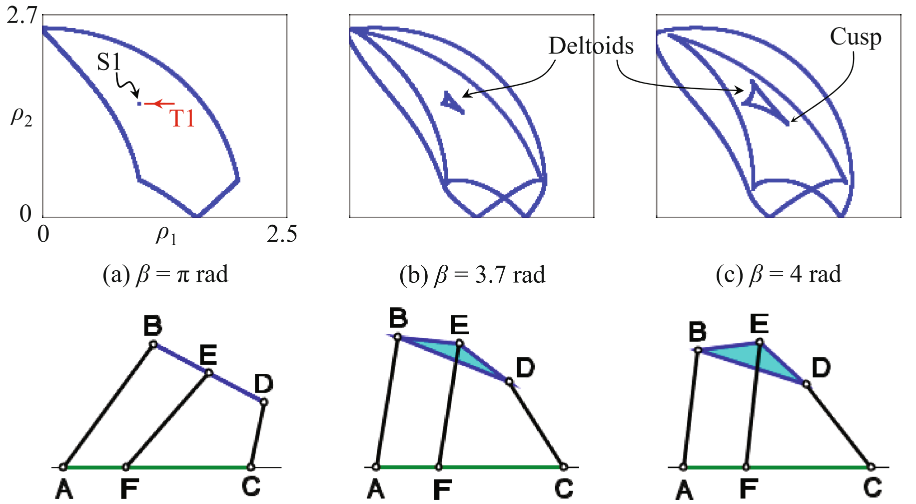


Fig. 4. Transformation of the singularity locus when perturbing geometry G1. When increasing β, the mobile platform is no longer flat and the isolated singularity S1 transforms into a deltoid curve.

of this isolated singularity into a deltoid only depends on d_3 and β [11], which are precisely the only two parameters that determine if the mobile and fixed platforms are flat ($d_3 = 0$, $\beta = \pi$) or triangular ($d_3 \neq 0$, $\beta \neq \pi$).

4.2 Example 2: Lips Singularity

Consider the following geometry G2: $c_2 = 1.4$, $c_3 = 2$, $d_3 = -1.5$, $l_1 = 1.06$, $l_3 = 1.1$, $\beta = 5.65$ rad. Unlike in the previous example, in this case both the fixed and mobile platforms are triangular (see Fig. 6). For a robot with this geometry, and for $\rho_3 \approx 2.8003041$, the singularity locus in the (ρ_1, ρ_2) plane exhibits an isolated singularity at $\text{S2} = (\rho_1 \approx 0.9541219110, \rho_2 \approx 0.3033191642)$ (see Fig. 5b). This isolated singularity is a higher-order singularity of the *lips* type, such that the perturbation of any geometric design parameter of the robot either destroys this isolated singularity or transforms it into a bicuspid closed curve, depending on which geometric parameter is perturbed and on the sign of its perturbation [11,16]. This behavior can be verified using the proposed tool. For example, departing from the geometry G2 and slightly decreasing c_2 using the presented simulator, the isolated point S2 becomes a small bicuspid closed curve (a magnified and rotated view of this curve is shown in Fig. 5a, since this curve is too flat to properly distinguish its shape in this figure). On the contrary, slightly increasing c_2 (departing from the geometry G2) destroys the isolated singularity S2, which disappears from the (ρ_1, ρ_2) plane (Fig. 5c).

To check the behavior of the solutions of the forward kinematic problem at the isolated singularity S2 of Fig. 5b, we can simulate in the proposed tool a

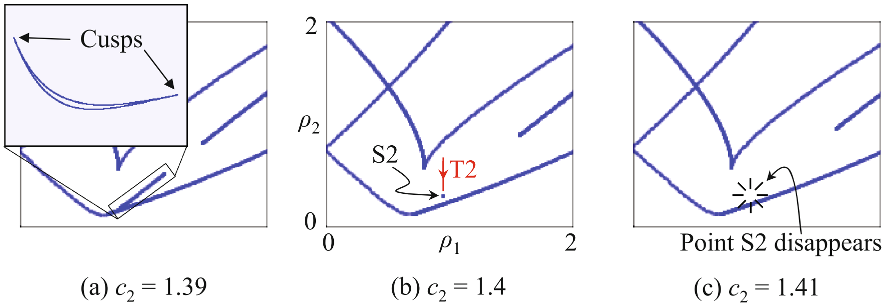


Fig. 5. Transformation of the singularity locus when perturbing geometry G2. The isolated singularity S2 shown in (b) transforms into a closed bicuspid curve when decreasing c_2 (a), whereas it disappears when increasing c_2 (c).

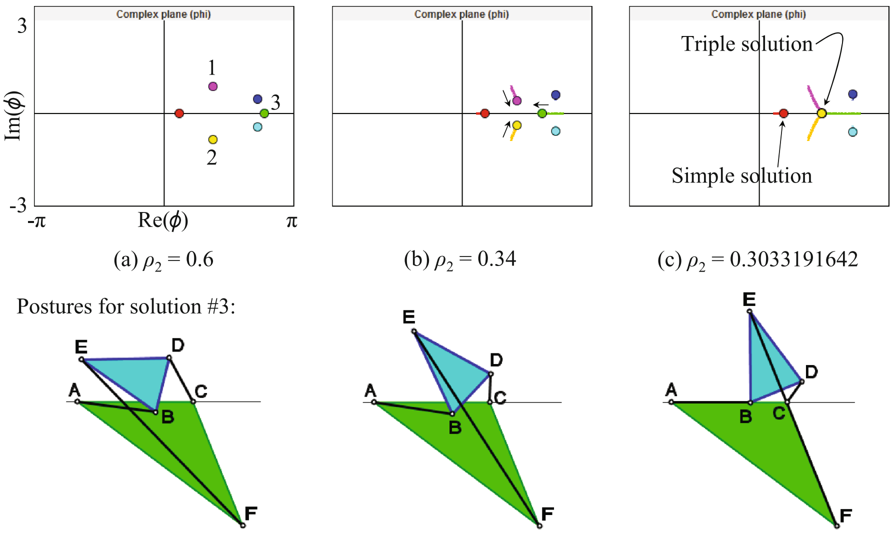


Fig. 6. Coalescence of three solutions when approaching the isolated singularity S2. The convergence of solutions 1 (magenta), 2 (yellow), and 3 (green) occurs in the complex planes of both components θ_3 and ϕ, although this figure only shows the coalescence of the ϕ components. The evolution of the posture of the robot is shown for real solution #3.

trajectory in the (ρ_1, ρ_2) plane that approaches this singularity. For example, setting $\rho_1 = 0.9541219110$ in the simulator and varying ρ_2 from 0.6 to 0.3033191642 using the slider (i.e., describing a vertical trajectory T2 that approaches S2 in the (ρ_1, ρ_2) plane, as shown in Fig. 5b), we can observe the coalescence of three different solutions, as shown in Fig. 6. Therefore, the isolated singularity S2 of Fig. 5b presents a triple solution to the forward kinematic problem (besides a simple solution, also indicated in Fig. 6c). This can be easily understood considering that the isolated point S2 is a (stable) cusp point (at which a triple solution occurs) when visualized in the other two joint planes (ρ_2, ρ_3) and (ρ_1, ρ_3) (this can be easily visualized in the proposed tool).

4.3 Example 3: Swallowtail Singularity

Consider now the following geometry G3, studied in [18]: $c_2 = 1$, $c_3 = 0.203832$, $d_3 = 0.0508422$, $l_1 = 1.839226003$, $l_3 = 0.3876449159$, $\beta = 2.968$ rad. As shown in Fig. 7, this geometry corresponds with a 3R$\underline{\text{P}}$R robot which has *almost* flat platforms, similar to the example of Subsection 4.1 (in which both platforms were *exactly* flat). For this geometry, and for $\rho_3 = 0.891465$, the singularity locus in the (ρ_1, ρ_2) plane exhibits a higher-order singularity at point S3 $= (\rho_1 \approx 0.9500311490225363, \rho_2 \approx 1.6500225946172906)$, indicated in Fig. 8b. This singularity S3 has third degree of shakiness [18], which corresponds to a solution of the forward kinematic problem with multiplicity four [6]. Next, we will verify the occurrence of such a quadruple solution using the simulator presented in this paper. Setting $\rho_2 = 1.6500225946172906$ in the corresponding numeric field of the simulator, and using the slider to vary ρ_1 from 1.2 to 0.9500311490225363, a horizontal trajectory T3 is described in the (ρ_1, ρ_2) plane (see Fig. 8b). The evolution of the six solutions of the forward kinematic problem along trajectory T3 is depicted in Fig. 7, which shows the coalescence of four different solutions (two real and two complex) into a quadruple solution. Although Fig. 7 only shows the coalescence of the θ_3 component of four solutions,

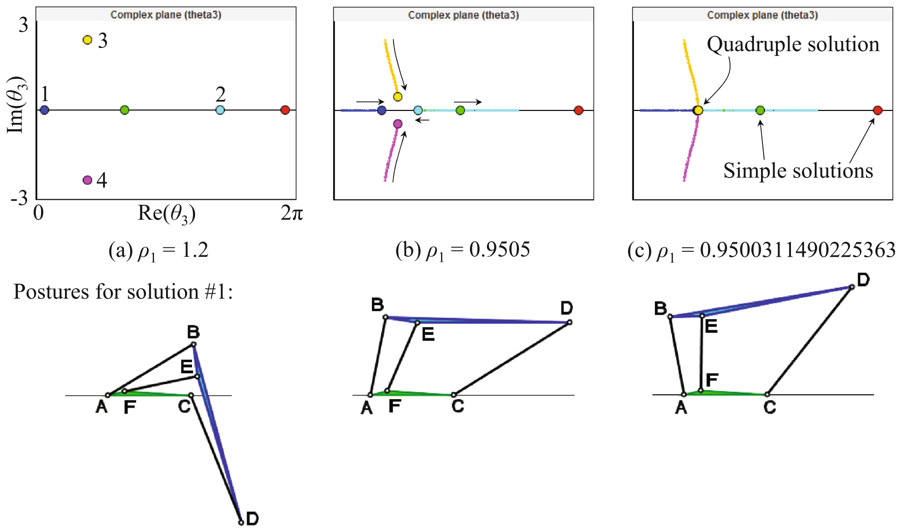
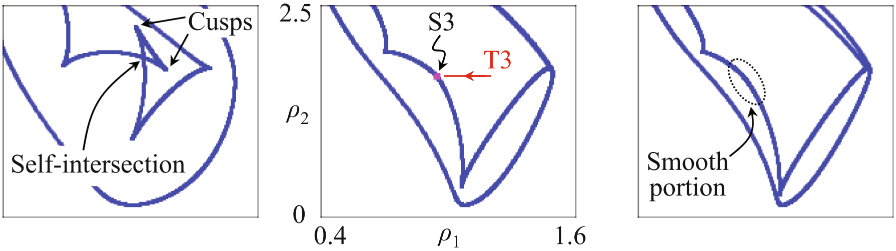


Fig. 7. Coalescence of four solutions (real solutions 1 and 2, and complex solutions 3 and 4) when approaching the singularity S3. The evolution of the posture of the robot for real solution #1 (blue) is represented.



(a) $\beta = 2.3$ rad (b) $\beta = 2.968$ rad (c) $\beta = 3.1$ rad

Fig. 8. Transformation of the singularity locus when perturbing geometry G3.

the ϕ components of these solutions also coalesce (this can be checked using the simulator).

To conclude, we can visualize in the proposed tool how singularity S3 transforms when altering geometry G3. For example, decreasing angle β transforms S3 into a self-intersecting loop with two cusps (see Fig. 8a). On the contrary, increasing β destroys the singularity S3, such that the portion of the singularity curves in the proximity of S3 becomes smooth (see Fig. 8c). This shows that the singularity S3 is of the *swallowtail* type [16].

5 Conclusions and Future Work

This paper has presented a graphic and intuitive simulation tool for studying the forward kinematics of general 3R$\underline{\text{P}}$R planar parallel robots. When varying the joint coordinates of the robot, the tool shows the trajectories described in the complex plane by the different solutions of the forward kinematic problem. Also, the user can freely modify any geometric parameter of the robot and instantaneously visualize how this deforms its singularity locus. Through some examples, we have demonstrated the usefulness of the proposed tool for visualizing the coalescence of different assembly modes when approaching higher-order singularities, as well as for visualizing how these singularities transform when perturbing the geometric design of the robot.

In the future, new features will be added to the presented tool. We will allow the user to load arbitrary 3D joint trajectories in the simulator, so that the forward kinematics can be simulated along any trajectory in the joint space. Also, the dynamics of the robot will be implemented in order to properly simulate singular transitions between different assembly modes, as suggested in [13].

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