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MATLAB TOOLBOX FOR THE STUDY OF FOUR-BAR MECHANISMS

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Matlab toolbox for the study of four-bar mechanisms

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ABSTRACT Four-bar mechanisms are key components of mechanical engineering used in various industrial and technical applications. These mechanical systems, also known as quadricycles, are made up of four linkages that are connected in a closed form. Four-bar mechanisms provide a broad range of motion and adaptability in designing machines and devices by varying the lengths and angles of these connections. The generated toolbox may be utilized to assist in developing four-bar mechanisms in educational and research settings. The toolbox includes a simple and intuitive interface that allows users to learn about the mechanism's trajectories, dimensions, locations, velocities, and accelerations. The toolbox can analyze three mechanisms: double rocker, crank, and crank-rocker. The interface produces both numerical and graphical outputs. In addition, a prototype has been added to the toolbox that interacts serially with Matlab, allowing the software's computations to be compared to real-world values of the mechanism. Finally, if the user makes an error in selecting the mechanism or data entry, the toolbox provides assistance and ideas to correct the issue.

Index terms: Toolbox for four-bar mechanisms; GUI for four-bar mechanisms; mechanism design; M4B; Matlab Toolbox.

1. INTRODUCTION. Application engineering is critical in the development of any technology. Most moving machinery uses four-bar linkage arrangements. Four-bar links are widely used in machine design, industry, research, and everyday applications (Mishra, 2021). Their straightforward mechanical nature makes them ideal for path creation. For example, any change in the length of the bars or the driving angle will significantly impact the final output's location, speed, and direction. These

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mechanisms can attain faster velocities, create more significant force rates utilizing a single degree of freedom, and follow predetermined trajectories more accurately than open-kinematic chain manipulators.

Furthermore, the four-bar linkage mechanism is used in a wide range of industrial applications, including rigid-body guiding, reciprocating compressors, rotary engines, scotch yokes, rope climbing robots, and robot end-effect grippers (Gao et al., 2021; Hussain et al., 2021; Kulkarni et al., 2025; Libu George & Bharanidaran, 2022; Shao et al., 2024). Such systems are undoubtedly used to create various motion patterns other than actuator motion (Hernández et al., 2021; Peón-Escalante et al., 2023). These mechanisms are used in biomedical engineering to provide high-precision motion (for example, microsurgery applications) (Fortunić et al., 2023; Li et al., 2022; Zarrabi Ekbatani et al., 2024). Many design issues might arise due to such systems; for example, the precision of a robot arm's end-point location is significantly reduced because of the cumulative inaccuracy from each revolute joint of the robot. Furthermore, low mechanical stiffness will reduce the accuracy of motion tracking (Cervantes-Culebro et al., 2021).

The four-bar mechanism's mathematical model is widely recognized. Nonetheless, the angular velocity of the driving bar (i.e., the crank) is supposed to be constant. However, this is nearly impossible in practice due to the rotating unbalanced system's variable inertia. As a result of the continuous variations in inertia throughout the rotation of the stiff links comprising the mechanism, the angular speed of the crank in the four-bar mechanism exhibits a regularly changing behavior (Sardashti et al., 2022). This fluctuating behavior results in highly nonlinear, time-variant, and complex dynamics of the four-bar system, making real-world control of such dynamics a difficult task (Flota-Bañuelos et al., 2021).
Due to their highly non-linear dynamics, it is hard to design suitable control strategies that appropriately govern their behavior (Nguyen-Van et al., 2022). In practice, these linked mechanisms are commonly employed to execute function, trajectory, and motion creation tasks, often considering the position's kinematic state. This technique has been used in several real-world applications (Kang et al., 2022; Matekar Sanjay B.and Fulambarkar, 2021). Other ways for modeling four-bar mechanisms have been presented, such as (Ramesh & Plecnik, 2024), in which a parallelogram closed-loop mechanism was put into an open-loop robot structure to simplify the overall system's dynamics model. By using a basic control algorithm, high motion tracking performance was achieved.

It is vital to note that the requisite speed and acceleration are only fulfilled at the specified design points and not during the whole operating cycle of the drive connection. Higher-order kinematic synthesis considers velocities and/or accelerations in the design issue and calculates the mechanism's design parameters that fulfill the intended job's criteria. Furthermore, in the process of dimensional synthesis, the features of the output movement of the mechanisms are often developed with a constant input speed in mind (Baskar Aravind and Plecnik, 2021; Ramesh & Plecnik, n.d.; Wang et al., 2022). However, suppose the output speed requirements change while the mechanism operates. In that case, the mechanism's dimensions must be rebuilt given

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that the features of a mechanism's output movement are dependent on its input movement. (Hur et al., 2024; José A. Montoya R. Peón-Escalante & Peñuñuri, 2024; Shi et al., 2025), suggested an alternative way to achieve this goal without affecting the dimensions of the current mechanism, which is by introducing an auxiliary mechanism.

(Baskar et al., 2023; Nguyen Vu Linhand Kuo, 2022; Wu et al., 2021; Zhang et al., 2021) Developed the constraint equations of four-bar connections for motion generation, function generation, and path generation. Freudenstein was the father of modern kinematics, and his contributions made kinematic synthesis of mechanisms possible through digital computation. Grashof's law is also an example of how the law has been successfully used to improve manufacturing processes (Ekambaram, 2021). A dynamic modeling and controller design for a flexible four-bar system were investigated by (Qiu et al., 2023). The design process can satisfy the movement characteristics specified for a trajectory that corresponds to a complete cycle of the input link when an individual motor and mechanism are treated as a single system that is properly controlled (Basaran, 2025; Nie et al., 2024).

The analysis, design, optimization, and simulation of mechanism systems have all benefited from dynamic modeling. Scholars worldwide have studied the dynamic response, performance evaluation, and optimization of mechanical systems using dynamic models. In this work, a toolbox for Matlab is presented in which the calculations for obtaining trajectories, link measurements, and fracture point previews are synthesized through simulation and graphical representation. A prototype was created and linked to the toolbox to verify the simulated results. For the analytical development, the Euclidean distance was used to define simple rotation functions and represent the trajectories. It is important to note that the Euclidean distance, which measures the straight-line distance between two points in a multidimensional space, differs from the Manhattan distance, which calculates the sum of the absolute differences of their coordinates along each dimension. While the Euclidean distance is more suitable for representing direct paths, the Manhattan distance is often used in grid-based systems or scenarios where movement is restricted to orthogonal directions (Torres-Moreno et al., 2022). Finally, the graphical interface of the toolbox developed for four-bar mechanisms allows the user to choose between the different types of mechanisms and analysis to be performed according to his preference.

The following parts of this paper are organized as follows: Section 2 details the mathematical modeling employed in the toolbox for four-bar mechanisms. Section 3 presents the main results of the study and discusses their significance. Finally, the conclusions of the study are presented in Section 4.

2. METHODOLOGY Using the PRISMA technique presented in Figure 1, which comprises a set of items for selecting and analyzing the articles to be studied, the research started with a systematic review. The following standards for inclusion and exclusion were applied: Scientific publications published

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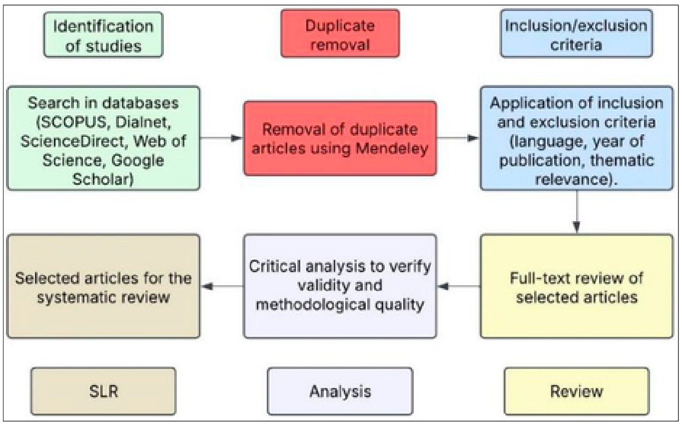
during the previous five years were considered. Additionally, articles published in both English and Spanish were taken into consideration. Lastly, studies examining the mechanics of four bars in any research were considered. The terms "Four-bar mechanisms," "Applications for four-bar mechanisms," and "App for four-bar mechanisms" were used in the systematic search that was conducted using the databases of SCOPUS, Dialnet, ScienceDirect, Web of Science, and Google Scholar. The Boolean AND method was applied, restricting the search to the title, abstract, and keywords to enhance the search bias. From the chosen publications, a database was assembled, accounting for the author, year, title, keywords, connection to the research, and outcomes; duplicate papers were removed by exporting this database to the Mendeley program. Ultimately, a thorough critical examination of the papers was conducted to verify the validity and methodological caliber of the chosen research.

Figure 1

PRISMA methodology flow diagram.



Nota. Diagram developed by the authors.

2.1. Spiral development model To create the four-bar mechanism toolbox, the spiral evolutionary

development model was

employed to ensure that the toolbox reaches the necessary maturity through a sequence of evolutionary deliveries enabled by each repetition cycle (Delgado Olivera & Díaz Alonso, 2021). The spiral model schematic that was employed is shown in Figure 2. This method has been successfully employed in several works, such as those carried out by (Simisterra-Quiñonez et al., 2021; Yépez Ponce et al., 2023).

2.2. Dynamics of the four-bar mechanism Figure 3 shows a schematic of the four-bar linkage

mechanism presented in this article. A

servomotor powers the mechanism's initial link (a). The motion will be restricted to rotations between 0 and 180 degrees when using a servomotor.

Figure 2

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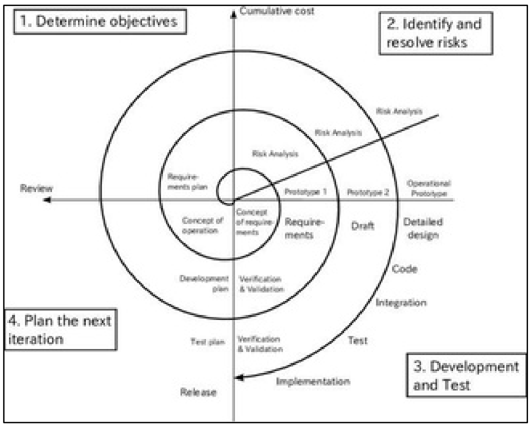
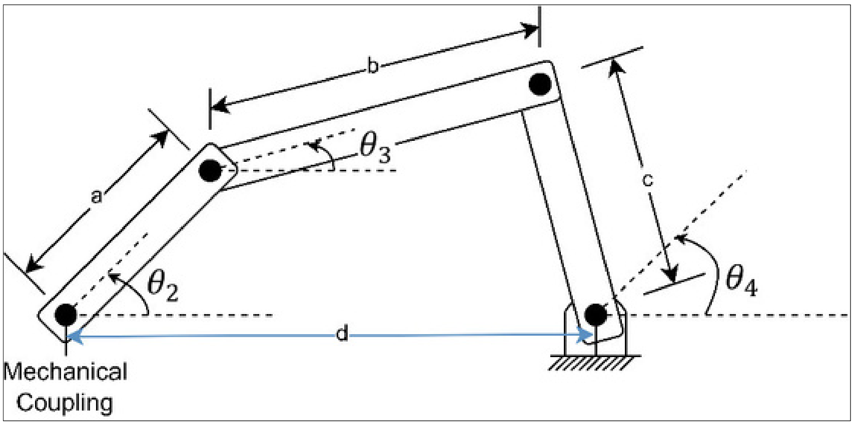
Evolutionary development model (spiral).



Nota. The graph represents the Spiral development cycle model that was employed and was taken from *Saillard (2015), p. 21.*

Figure 3

Schematic of the four-bar mechanism.



Nota. In the graph, the dimensions of the links are represented by lowercase letters, and the rotations by theta angles.

Equations 1 and 2 form the system of nonlinear equations that allow us to determine the direction that each of the bars will have with respect to the x-axis and y-axis at all times respectively.

$$ff1 = aa\cdot cccccc\theta\theta 2 + bb\cdot cccccc\theta\theta 3 - cc\cdot cccccc\theta\theta 4 - dd\cdot cccccc\theta\theta 1 \quad (1)$$

$$ff2 = aa\cdot ccssss\theta\theta 2 + bb\cdot ccssss\theta\theta 3 - cc\cdot ccssss\theta\theta 4 - dd\cdot ccssss\theta\theta 1 \quad (2)$$

In 3, is presented the equations 1 and 2 in matrix form, this is used to determine the fracture zones of the mechanism.

$$BB = [aa\cdot cccccc\theta\theta 2 + bb\cdot cccccc\theta\theta 3 - cc\cdot cccccc\theta\theta 4 - dd\cdot cccccc\theta\theta 1 \quad aa\cdot ccssss\theta\theta 2 + bb\cdot ccssss\theta\theta 3 - cc\cdot ccssss\theta\theta 4 - dd\cdot ccssss\theta\theta 1] \quad (3)$$

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2.3. Freudenstein equations It is an analytical method for calculating a four-bar mechanism's

displacement or position,
velocities, and accelerations. It is one of the most widely used methods by engineers because it can be programmed with a computer (Felipe, 2024). The Freundestein equations, shown in equations 4 and 5, are fundamental to this approach and provide a systematic way to analyze the kinematics of four-bar mechanisms. These equations are specifically applied to the mechanism illustrated in Figure 3, demonstrating their practical utility in real-world engineering problems.

$$\frac{d}{a}\cdot\cos\theta_4 - \frac{d}{c}\cdot\cos\theta_2 + \frac{a^2-b^2+c^2+d^2}{2\cdot a\cdot c} = \cos(\theta_2-\theta_4) \qquad (٤)$$

$$\frac{d}{a}\cdot\cos\theta_3 + \frac{d}{b}\cdot\cos\theta_2 + \frac{c^2-a^2-b^2-d^2}{2\cdot a\cdot b} = \cos(\theta_2-\theta_3) \qquad (٥)$$

2.4. Jacobian Matrix

The Jacobian matrix is a technique for linearizing a system of nonlinear equations at a given point so that the properties of the linear system can be applied to solve and analyze these systems conveniently (Ramos Corredor et al., 2022). The Jacobian matrix allows for analyzing the performance, configuration design, planning, and control of parallel mechanisms (Cervantes-Figueroa, 2022). In this work, the Jacobian matrix is used to relate the positions, velocities, and accelerations of the different parts of the four-bar mechanism as a function of the input data. These results will be presented using tables and graphs within the interface. It also allows the mechanism to be sized and the lengths of the bars or links to be extended.
The Jacobian matrix (see equation 6) is formed by the partial derivatives of equations 1 and 2 as

a function of the dependent variables (θ_3, θ_4).

$$J = \begin{bmatrix} -b\cdot\sin\theta_3 & c\cdot\sin\theta_4 \\ b\cdot\cos\theta_3 & -c\cdot\cos\theta_4 \end{bmatrix} \qquad (٦)$$

2.5. Grashof's Law In the field of mechanism kinematics, Grashof's law establishes fundamental

criteria for analyzing
the behavior of four-bar mechanisms. Therefore, (Quintero Riaza & Mejía Calderón, 2021), this law enables the determination of the type of motion a mechanism can execute, classifying it according to the relative lengths of its links. By considering these lengths, various movements can be predicted, such as:

- If the shorter bar is fixed as the other bars finish spins, double-turn, or crank.
- Back and forth, if the fixed bar and the short bar are next to each other.
- Double rocker, if the fixed bar is on the other side of the shorter bar.

In the toolbox interface, these three cases can be simulated.

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3. RESULTS The Matlab toolbox developed for four-bar mechanisms allows users to quickly and intuitively obtain motion parameters based on the selected mechanism type. The toolbox, along with the mechanism design in SolidWorks, is available in a shared repository (https://www.dropbox.com/scl/fo/zqq0qlfic6o1uq2ywf543/AJBNb1oTjVaRIBu52UcliYk?rlkey=6bqqt8c2ofax2pcblhd73badu&st=kjpzg858&dl=0) that includes all necessary files for simulation and design. The toolbox code is fully customizable, enabling users to adapt it to their specific requirements. By running the M4B command in Matlab, a window opens with default values, facilitating the design and simulation of four-bar mechanisms. This combination of simplicity and flexibility makes the toolbox a powerful tool for engineering analysis and education.

3.1. Toolbox Functionality

The toolbox allows users to select among three mechanism types: double rocker, double crank, and crank-rocker (see Figure 4). Once the mechanism type is selected, users can initiate the simulation to visualize the trajectory of moving parts (see Figure 5). Additionally, the toolbox generates a table with the values of involved variables, such as positions, velocities, and accelerations, facilitating controller optimization and mechanism dimensioning (see Figure 6). These features enable users to analyze the mechanism's behavior within specific simulation intervals by adjusting start and end angles for precise results.

Figure 4

Selection of the type of mechanism.

Nota. In the drop-down menu, you can select one of the three mechanisms mentioned in item 2.5.

3.2. Error Detection and Guidance The toolbox generates plots showing the evolution of angular displacement, angular velocity, and angular acceleration as a function of the input angle (see Figure 7). These plots provide a detailed visual analysis of the mechanism's motion, which is crucial for validating designs and optimizing parameters. Furthermore, the toolbox detects errors in input parameters, such as incorrect

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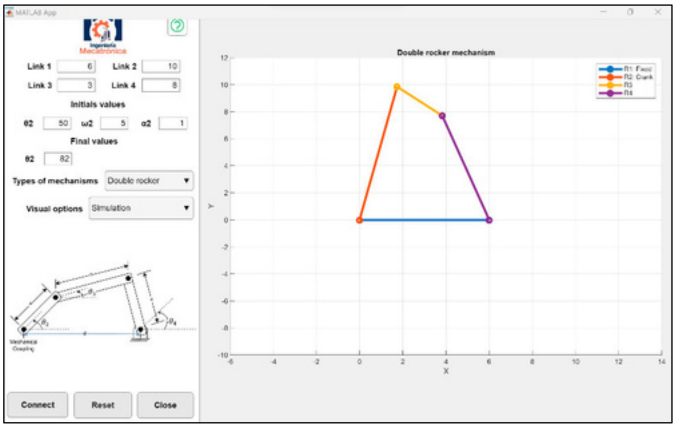
angles or dimensions, and notifies the user if the mechanism is "fractured" (see Figure 8). In case of errors, the toolbox offers a help function that suggests corrections and recommends the most suitable mechanism type.

Figure 5

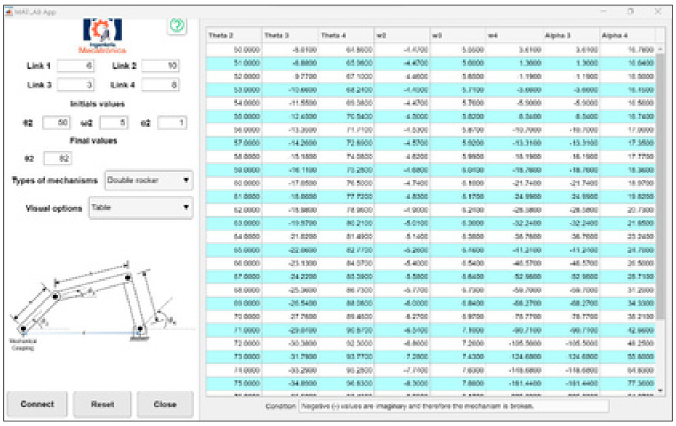
Simulation of the mechanism trajectory.



Nota. In the graph, you can see the mechanism generated from the user data entered.

Figure 6

Table of variables.



Nota. In the graph, you can see how the mechanism's positions, velocities, and accelerations are stored in a table in the simulation interval given by the user.

3.3. Experimental Validation To validate the analytical results, a physical prototype of the four-

bar mechanism was developed,

and its SolidWorks files are available in the repository for 3D printing and assembly. The prototype includes a servomotor to control bar positions and potentiometers at the joints to measure actual positions (see Figure 9). Simulated and measured values are compared in the toolbox interface, allowing users to verify the accuracy of the simulations. This experimental validation confirms that the simulated data aligns with real-world results.

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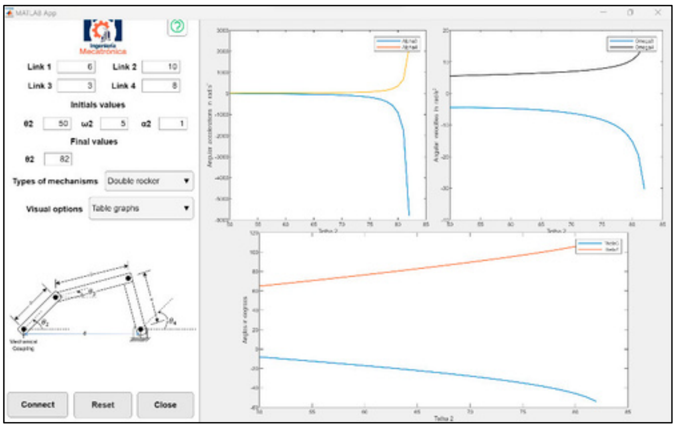
Figure 7

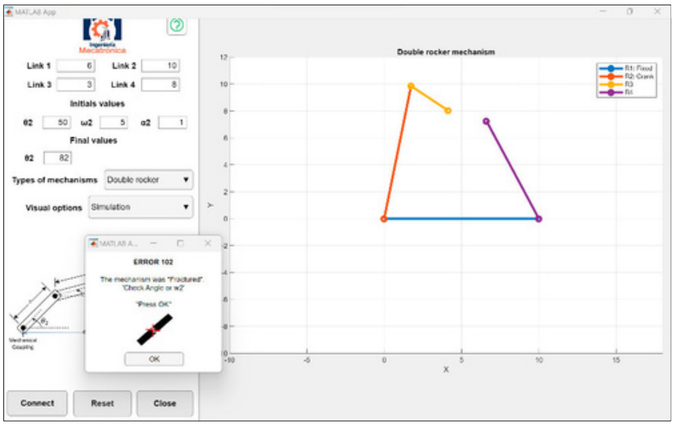
Mechanism simulation plots.



Nota. The graph shows the evolution of angular displacement, angular velocity, and angular acceleration as a function of the input angle, providing a detailed visual analysis of the mechanism's movement.

Figure 8

Fractures in four-bar mechanisms.

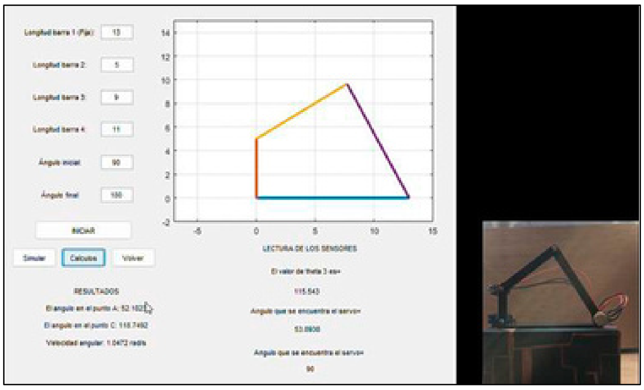


Nota. Error message generated by the tool in Matlab indicating that the mechanism is "fractured". The message suggests checking the input angle ($\theta\theta 2$) to correct the mechanism configuration before continuing the simulation.

In the lower part of Figure 9, both the calculated values and those measured by the sensors in the real system are presented. For ease of interpretation, these data are more clearly detailed in Table 1. In addition, a validation of the values obtained was performed by calculating the root mean square error (RMSE). This indicator allows the accuracy of the model to be evaluated by comparing the calculated values with the measured ones. A low RMSE indicates high precision, while a high value suggests a greater discrepancy between the data.

Figure 9

Digital and real four-bar mechanisms.



Nota. The lower left part of the graph shows the simulated values and the lower middle part shows the values measured by the sensors.

Table 1

Data Obtained: Calculated Values vs. Measured Values.

N° of Data	Calculated Values	Measured Values
1	115.500	115.290
2	115.521	115.731
3	115.542	115.332
4	115.563	115.353
5	115.583	115.373
6	115.604	115.814
7	115.625	115.415
8	115.646	115.436
9	115.667	115.457
10	115.688	115.898
11	115.708	115.498
12	115.729	115.519
13	115.750	115.540
14	115.771	115.561
15	115.792	116.002
16	115.813	115.603
17	115.833	116.043
18	115.854	116.064
19	115.875	116.085
20	115.896	115.686
21	115.917	116.127
22	115.938	115.728
23	115.958	116.168

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24	115.979	116.189
25	116.000	116.210

Nota. The values presented correspond to 25 measurements for the angle θ_3.

The RMSE value obtained for these data was 0.21°. This error represents the average deviation between the calculated values and the measured values in the 25 measurements performed. Despite the small difference, it is important to consider this margin of error in the analysis of the results. Maintaining a low RMSE indicates that the measurements are aligned with the expected values, which provides confidence in the accuracy of the system. These data correspond to measurements of the angle θ_3, fundamental for the evaluation of the system behavior.

3.4. Contributions and Future Perspectives

The developed toolbox simplifies the design and simulation of four-bar mechanisms while providing advanced tools for optimization and error analysis. It generates detailed plots and variable tables, making it a valuable resource for both research and teaching. The toolbox's current capabilities include error detection, comprehensive output data, and real-device connectivity, which enhance its practicality for real-world applications. These features have already demonstrated their utility in fields such as robotics, automotive systems, and industrial automation, where four-bar mechanisms are widely used. The toolbox's adaptability and integration with modern control systems highlight its potential for advancing kinematic analysis and mechanism design.

4. DISCUSSION

A paid software for kinematic analysis of four-bar systems is presented by FOURBAR Student Edition, developed by Robert L. Norton; in contrast to the produced version, this application does not display the angles θ_3 and θ_4 as output data. Furthermore, the designed interface enables the crank to rotate fully in the simulation, whereas FOURBAR only visualizes half of the crank's

(Salcedo, 2020), developed a didactic material based on GeoGebra aimed at the visualization and understanding of the kinematic analysis of a four-bar mechanism, which offers the student the possibility of manipulating the input conditions that configure such mechanism to appreciate then the corresponding effect on the behavior of the dependent variables involved; however, unlike the developed tool, it is not possible to obtain the tables of results, the selection of the type of mechanism to be developed and the application of Grashof's laws.

(Gonzáles Miranda et al., 2023) developed an APP for Android devices that generates graphs of predetermined four-bar mechanisms. In the graph, the lengths and orientations of the links can be edited by touching the revolute joints with the fingers, and the classification of the mechanism drawn in real time yields the links' value and angles' value. Unlike the developed application, no error alerts are issued, and it cannot be connected to a real device.

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(Zapata-Loria et al., 2019) developed a mobile application that uniquely calculates the positions of four-bar plane mechanisms.

Finally, in (López Solbes, 2013), a similar application developed in Matlab is presented with the main difference that in this application, no tables are generated, and it is not connected to a real mechanism.

5. CONCLUSIONS

Parameter optimization, such as link lengths, can considerably increase the performance of these mechanisms, allowing for a higher range of motion and precision in various industrial applications. Furthermore, computational simulation is essential in providing a platform for evaluating mechanisms' dynamic and kinematic behavior before manufacture, saving time and resources. Four-bar mechanisms have also been shown to be broadly helpful in robotics, industrial automation, and medical devices, demonstrating their flexibility. However, issues in control and energy efficiency in complex systems continue, providing potential for future study in this sector.

The toolbox developed in the educational field is very beneficial since it helps to understand the behavior of this type of mechanism simply and intuitively. Meanwhile, in the research field, it would save time in designing an application with this type of mechanism because the trajectory would be known beforehand and if there were any restrictions.

Finally, the need to address specific challenges related to the complexity of dynamics, precise control, and integration with electronic systems has been identified.

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