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A DESIGN OF SIX-BAR LINKAGE FOR TRAJECTORY REPLICATION

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Abstract: *This paper presents a novel copying mechanism for the replication of trajectories. Inspired by the pantograph and incorporating design elements of the Peaucellier–Lipkin linkage, this mechanism represents a distinctive approach and shows how a desired trajectory can be transformed into a more convenient one using a six-bar linkage. By bridging the output trajectory of this mechanism (the desired trajectory) with the input trajectory (a more convenient trajectory), a larger radius of action can be achieved with a simplified linkage structure. This mechanism can be used in many industries where trajectory manipulation is critical for improved user experience and operational efficiency*

Key words: *Copying mechanism, Trajectory replication, Pantograph-inspired design, Peaucellier-Lipkin linkage elements, Six-bar linkage.*

1. INTRODUCTION

The theory of mechanisms and machines provides a deep understanding of the fundamental principles that govern the movement and operation of mechanical systems. To understand the intricacies of these systems, one must engage in the analysis and synthesis of planar mechanisms. Among the most commonly studied planar mechanisms are the simpler four-membered mechanisms, which are described in detail in the articles [1, 2, 3 and 4]. In contrast, the six-bar mechanism, which consists of six links and the associated joints, is more complex compared to the four-link linkage. This complexity is reflected in additional degrees of freedom, which offer a wider range of possible movements. This increased flexibility makes six-bar linkages particularly valuable for various technical and mechanical applications where specific kinematic properties play a central role. Consequently, the study and application of six-bar mechanisms contribute significantly to broadening our understanding of mechanical systems and enhancing their capabilities in various practical contexts. Some applications of six-bar mechanisms include:

- Prosthetic (the design of certain prosthetic limbs may incorporate six-bar linkages to mimic more natural and fluid movements [5])
- Mechanical Linkages (six-bar mechanisms can be employed in various mechanical linkages where specific motion trajectories need to be achieved, such as in machinery and manufacturing equipment [6])
- Robotics (six-bar linkages can be utilized in the design of robotic arms and manipulators, providing a balance between flexibility and controlled motion [7])
- Gait Generation in Walking Robots (in the field of robotics, six-bar mechanisms can contribute to the development of walking robots by providing a mechanism for generating natural and stable gaits [8])
- Shaper machines (to maintain the velocity of the mechanism’s slider constant within a specified range of the rotational motion of the input link [9])
- Agricultural Equipment (six-bar linkages can be utilized in the design of agricultural machinery for the spacing between plants by changing the anchor points of link 5 without any adjustment of the angular speed of the input cranks [10])
- And many more usage in different fields of mechanical engineering.

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The primary aim of this paper is to elucidate the synthesis process of a six-bar linkage mechanism, demonstrating its capability to generate a novel curve that optimally approximates a predefined desired trajectory. This optimization is gauged in terms of minimal deviations concerning shape, position, and various metrics. To comprehensively understand the design and functioning of this mechanism, it is imperative to conduct a thorough analysis of its origins. Therefore, the paper initiates with an exploration of the Peaucellier–Lipkin linkage and the Pantograph, two planar linkage mechanisms that bear significant resemblance to the proposed six-bar linkage.

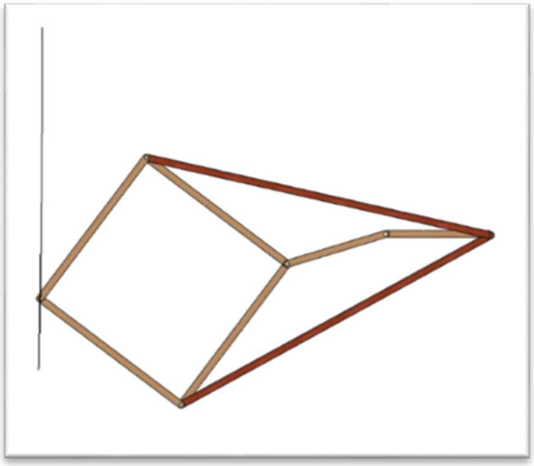

Fig. 1. Peaucellier–Lipkin linkage

The Peaucellier–Lipkin linkage (Fig. 1) is a captivating planar mechanical linkage independently invented by Charles-Nicolas Peaucellier and Yom Tov Lipman Lipkin in 1864. This linkage holds significance for its ability to convert rotary motion into an approximate straight-line motion [11]. What makes it remarkable is its demonstration of achieving straight-line motion using simple, planar elements. Comprising six bars and eight joints, the Peaucellier–Lipkin linkage is arranged in a manner that enables the end-effector (a point on one of the bars) to move in a perfect straight line when one of the input cranks rotates.

A standout feature of this linkage is its unique capability to convert rotary motion into approximate linear motion, a task not easily accomplished in the realm of mechanical linkages. The mechanism is often visualized as a series of interconnected rhombi and is commonly known as the "rhombic drive" or the "Peaucellier cell." Its operation relies on the inversion of parallelogram and rhombus configurations, leading to the straight-line motion of the coupler. In the context of locomotion, paper [12] details how six nontraditional legs collaborate to provide movement to a walking machine. These legs are based on the one-degree-of-freedom Peaucellier–Lipkin mechanism, showcasing the adaptability and versatility of the linkage in contributing to innovative solutions in walking robotics.

The pantograph, illustrated in Figure 2, constitutes a mechanical linkage characterized by a configuration of rigid rods interconnected through articulate joints. This arrangement facilitates the replication of the movement of one or more rods by the remaining components. Primarily designed for the purpose of copying or scaling movements from a singular point to another, the pantograph emerges as an invaluable tool in scenarios demanding meticulous duplication of motion. Its applications are notably prevalent in drafting, engraving, and diverse industrial processes, as expounded upon in [13 and 14].

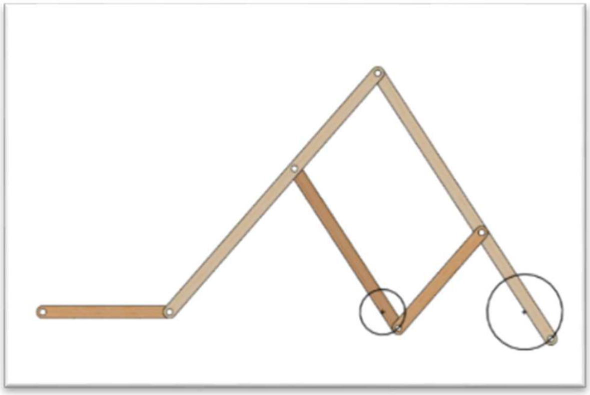

Fig. 2. Pantograph

The most usual form of a pantograph consists of four linked bars arranged in a parallelogram shape. Two of these bars are fixed, and the other two can move. As one pair of bars moves, the linkage system ensures that the other pair moves in a corresponding manner. The result is a scaled or duplicated motion between the two ends of the pantograph. Pantographs have been historically employed in drafting and artistic applications, where they enable the enlargement or reduction of drawings with reliable accuracy. By moving a stylus over a master drawing, the connected pen or tool at the other end of the pantograph reproduces the same motions, creating an enlarged or reduced copy of the original image. In addition to drafting and artistic uses, pantographs find applications in various industrial processes, such as the replication of patterns in manufacturing or the control of robotic systems. The mechanism's ability to accurately replicate movements make it valuable in scenarios where precision and consistency are essential A classic pantograph is commonly a four-bar linkage, but there could be custom-designed mechanisms with six bars that serve specific purposes, although they may not be termed as "pantographs" in the traditional sense.

With combination of number and displacement of members of Peaucellier–Lipkin linkage and abilities of Pantograph mechanism novel mechanism can be obtained as it is shown of Fig. 3. In Fig. 3 is shown one of the variants of this mechanism which will be elaborated in this paper.

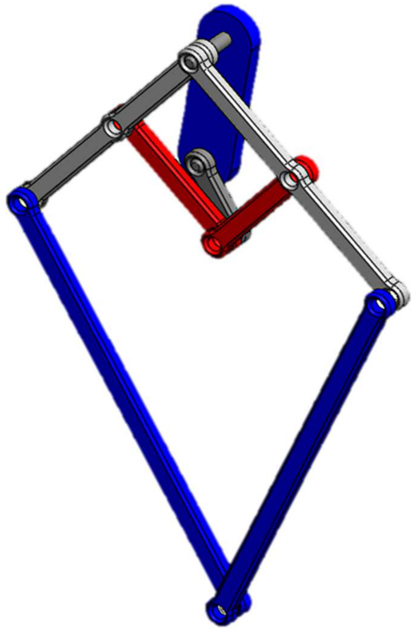

Fig. 3. Novel mechanism as a result of merging Peaucellier–Lipkin linkage and Panthograph

2. INFORMATION

On Fig.4 it is shown a six-bar mechanism as a type of planar mechanical linkage consisting of six rigid bars connected by six revolute joints. Main body of this mechanism are bars BC', BC'', AD', AD'', C'E and C''E. Point B is fixed and point A represents an input point where input trajectory is placed. On Fig. 3 and Fig 4 it is shown that input trajectory is a circle that was obtained from crank OA. Point O is also fixed and around it gives rotation to bar OA.

Through testing of the six-bar linkage mechanism, it was observed that it behaves like a typical pantograph for certain lengths of its links, performing pantographic copying of the input trajectory. This is achieved when BC' = BC'' = C'E = C''E and BD'= BD'' = AD'= AD''. In this case, when an input trajectory in point A is circle, as it can be seen on Fig. 4, the output trajectory will be also circle scaled by some factor. By varying the lengths of the mechanism's links, the shape and dimensions of the output path change concerning the input, allowing diverse output trajectories to be obtained from a single input curve.

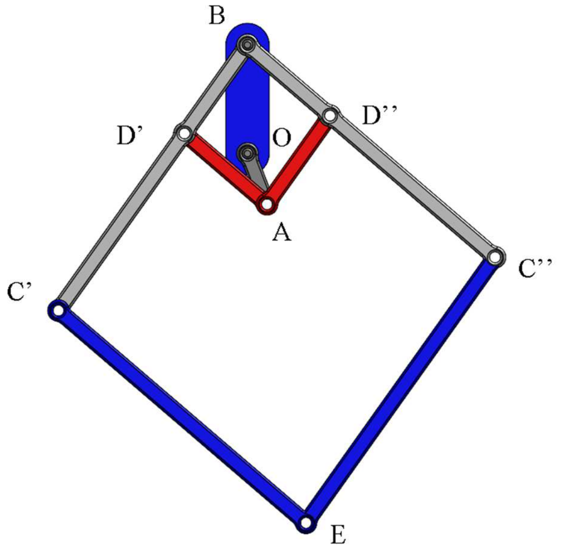

Fig. 4. Mechanism with given linkage

On Fig. 5, Fig. 6 and Fig. 7 is shown how variations of output path can be created. As said, input trajectory is circle, given by OA bar. This will be for proposed length of bars BC' = BC'' = C'E = C''E=2 and BD'= BD'' = AD'= AD''= 1. Fig. 5 shows a case when AD' and AD'' are varied as 0.75, 0.9, 1, 1.05 and 1.1 and their trajectories can be seen. When BC' and BC'' are varied in such manner that their length is 0.9, 1, 1.1 and 1.2 their trajectories are shown on Fig. 6. Finally, last variation of member's length is shown on Fig. 7 when EC' and EC'' have lengths 1, 1.25, 1.5, 1.75, 2, 2.25 and 2.5.

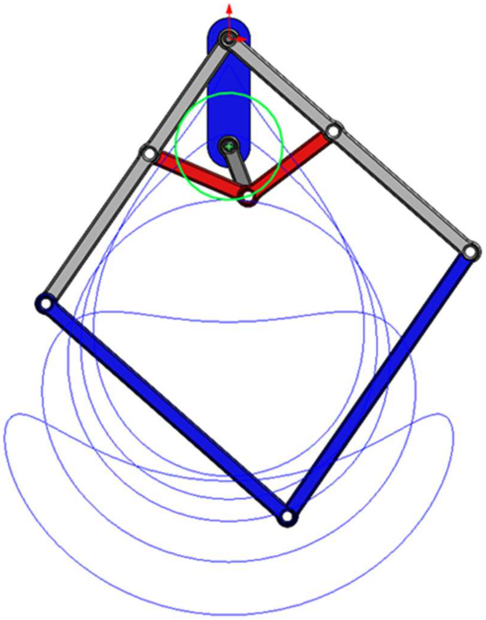

Fig. 5. Trajectories of mechanism when length of members AD' and AD''are varied

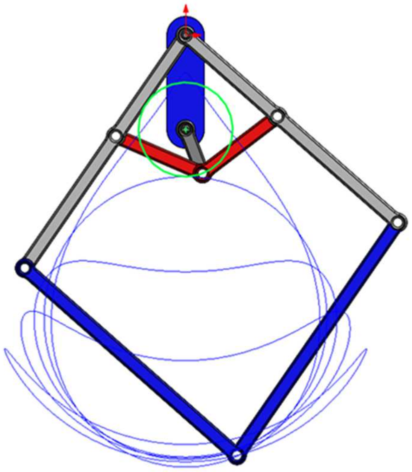

Fig. 6. Trajectories of mechanism when length of members BC' and BC''are varied

The synthesis of a linkage mechanism for a specified trajectory in engineering involves several key steps. Firstly, the demanded trajectory must be clearly defined, whether it's a straight line, curve, or a more intricate path. For this type of mechanism it is important to highlight that this demanded trajectory must be Jordans curve. A Jordan curve, named after the French mathematician Camille Jordan, is a simple, closed curve in the plane that does not cross itself. In other words, it forms a continuous loop without any self-intersections. The Jordan Curve Theorem, proposed by Jordan in the late 19th century, provides a formal statement about such curves that they are both simple (non-self-intersecting) and closed (forms a loop). [15 and 16].

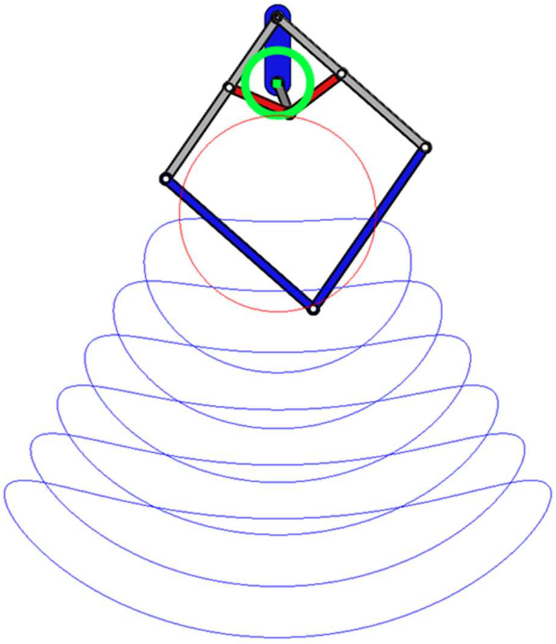

Fig. 7. Trajectories of mechanism when length of members EC' and EC''are varied

Once demanded trajectory is defined kinematic equations are then formulated to describe the relationship between joint angles and link positions for the selected mechanism. The inversion and analysis of these equations, often employing methods like numerical optimization or CAD simulations, help determine the necessary joint angles or link lengths for the desired trajectory. Fig. 5, Fig. 6 and Fig 7. are showing that there are a lot of trajectories that can be obtained for having one basic type of trajectory such as is a circle for input trajectory.

An iterative optimization process is employed to refine design parameters, adjusting link lengths and joint positions to minimize the disparity between the synthesized and demanded trajectories. Additionally, constraints such as avoiding singularities, maintaining closure conditions, and accounting for physical limitations are considered throughout the synthesis process [17]. Overall, this systematic approach is crucial for achieving precise motion in engineering applications, particularly in robotics, automation, and mechanical systems.

The synthesis of the six-bar linkage mechanism is based on two types of complementary kinematic problems. The first type is the direct problem, where the synthesized path is defined based on the input trajectory. The second, the so-called inverse problem, involves synthesizing the input path based on the demanded curve. This work methodologically combines the resolution of both mentioned problems into a single, unique iterative method, representing a key scientific contribution of this paper.

Achieving this synthesis goal is realized through a specially designed system of iterative procedures will be a scope of future works. In the synthesis process of the mechanism, the desired trajectory, acquired through empirical data acquisition, is approximated by a synthetic closed curve, providing an optimal approximation of the desired trajectory. As it was said by varying the geometric characteristics of the six-bar pantograph mechanism as the starting mechanism, a series of new six-bar mechanisms are generated that are no longer working as pantographs. Using these new mechanisms, the inverse mapping of the desired trajectory is transferred to a set of input line curves. Within this set of input line curves, the one that deviates least either from a circle or another suitable line curve generated by a simple and known planar mechanism is found.

The criterion for minimal deviation can be adopted for determination of the input curve, either the mentioned circle or another suitable trajectory that is result of the geometric parameters of the planar mechanism that generates it are determined iteratively. This completes the first phase in the synthesis process, moving on to the iterative optimization stage. To assess the deviation between the output trajectory of a linkage mechanism and the demanded trajectory, it can be done by various methods, both qualitative and quantitative. First type of this assessment can be called as Visual Inspection. This will include to plot the output trajectory and the demanded trajectory on the same graph using a CAD tool or graphing software. Visually inspect the alignment, shape, and overall similarity between the two trajectories. Similar to this plots of the output and demanded trajectories can be overlaid on the same graph.

Second type of assess the deviation is Quantitative Metrics. In this procedure it can be defined quantitative metrics to measure the deviation, such as the Root Mean Square Error (RMSE), Mean Absolute Error (MAE), or Maximum Deviation. These metrics provide numerical values that quantify the overall or point-wise differences between the two trajectories.

The Root Mean Square Error (RMSE) functions as a statistical metric for quantifying the disparities that arise from the predictions made by a model or system when compared to the observed values. This metric is particularly useful for evaluating the precision of a model's predictions or assessing the discrepancy between the output and the required trajectory in a linkage mechanism. The calculation and interpretation of RMSE are as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(output_i - demanded_i)^2}{n}} \quad (1)$$

The Mean Absolute Error (MAE) is a different statistical measure that is used to quantify the average size of errors between predicted and actual values. Similar to RMSE (Root Mean Square Error), MAE is commonly used in various fields such as engineering, statistics, and machine learning to assess the accuracy of models or systems. In the context of a linkage mechanism, MAE can be utilized to assess the average deviation between the output trajectory and the desired trajectory. MAE is calculated and interpreted in the following manner:

$$MAE = \sqrt{\frac{\sum_{i=1}^{n}|output_i - demanded_i|}{n}} \quad (2)$$

For evaluating results and deviation of trajectories of planar mechanism MAE can be used alongside RMSE to gain a comprehensive understanding of how well the output trajectory aligns with the demanded trajectory.

These metrics collectively offer insights into the accuracy and precision of the mechanism's motion replication.

One of the primary functions of linkage mechanisms are generate specific trajectories depend of given task. The lengths of the linkage members play a crucial role in determining the shape and characteristics of these trajectories. Most of the time, changing the lengths of mechanisms members will not suit the needs for optimum mechanism design. As presented here circle as input trajectory can provide a limited number of output trajectories that may not fit demanded trajectory. In that case, it is needed to introduce a combination of mechanisms to gain demanded trajectory. One such example can be seen on Fig. 8, where a four bar mechanism is used as input for six bar mechanism. This four bar mechanism has input from its crank and generates its own output trajectory. This output trajectory is used as input trajectory for six bar mechanism and with right adjustment of mechanisms length members it can produce a whole new set of output trajectories. These output trajectories will be compared with demanded trajectory and by using RMSE, MAE or both will then design of mechanism be completed. When designing a complex mechanism such is this one, the analysis of each of the planar mechanisms individually is needed in order to avoid any problems that can occur during mechanisms work (self-locking, impossible positions, inferable angles…).

Synthesis of one four bar mechanism is complex task by itself but design of complex mechanism is proving even more difficult. For this type of problem six bar mechanism can be used in two cases. First one, as a mere fine tuning for any other input mechanism by changing a length of its members. Other case is when it is needed a certain distance between input drive and output trajectories. This is usually needed in certain thermic process where for example electric motor that drives a mechanism is must be put an away from heat. In this case, mechanism can be designed to create this needed distance and thus keeps motor away. Beside thermic process there are other usages for this complex mechanisms, in particular this six bar mechanism.

One such problem is constructing a mechanism that simulates a human walk.

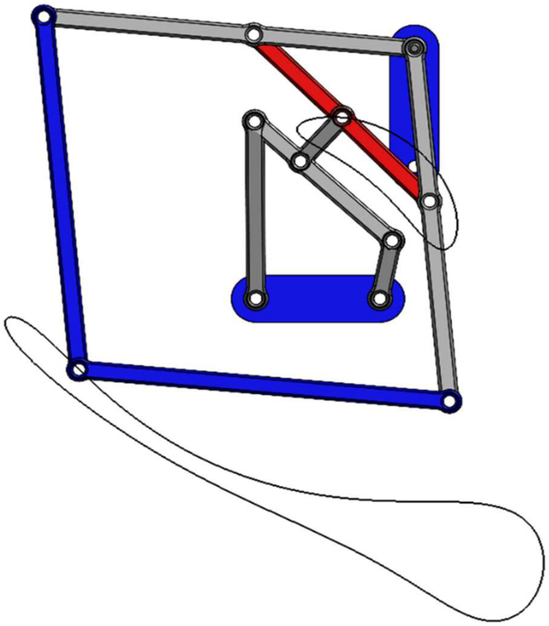

Fig. 8. Six bar mechanism with input mechanism

3. SIMULATION OF LEG MECHANSIM

One interesting example of usage of six bar mechanism is in bipedal walking mechanism. Linkage walking mechanisms are mechanical systems that can convert rotary motion into linear motion, and simulate the movement of animals or humans. Human walk is considered as one of greatest challenges in theory of mechanisms and machines and it is still an interesting topic [18 and 19]. In paper [20] it is given an example of leg mechanism with ability for balancing itself with different mechanism [21]. These papers are continuation of research started with from research paper [22] where one DOF mechanism is shown. Also in this paper, a necessary input is given, and that is a demanded trajectory as shown on Fig. 9.

Paper [22] has described how Center of Mass (CoM) is moving along a sinusoidal path with both vertical and horizontal components. This motion is crucial for efficient walking, as it reduces the energy needed to lift and propel the body forward. It represents one of crucial curve for researchers that are developing bipedal robots in order to closely mimic human gait

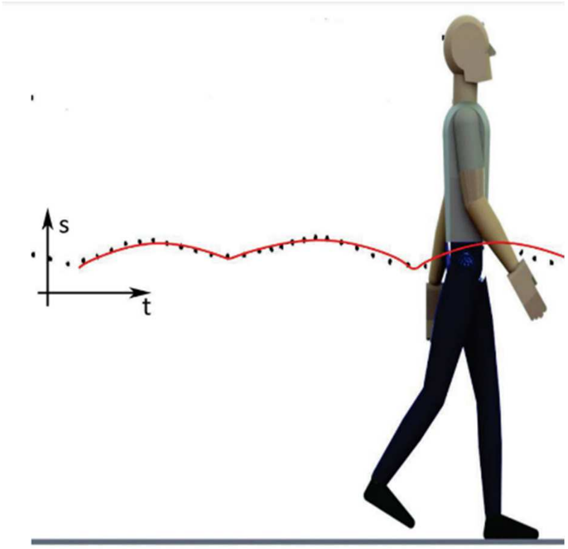

Fig. 9. The mechanical walker trajectory (red curve) and the positions of the walking man's center of mass (black dots) [22]

Demanded trajectory is shown on Fig. 9 as red line. This line is the center of mass (CoM), which is a critical factor in the design and construction of bipedal robot mechanisms. The location and control of the center of mass play a significant role in ensuring the stability and dynamic balance of a bipedal robot, much like in humans [23, 24 and 25]. Replicating human-like motion in bipedal robots often involves mimicking the natural sway and adjustments of the human CoM.

In order to successfully replicate a human walking a mechanism is designed as shown on Fig 10, 11 and 12. Aldo this walking mechanisms with one degree of freedom is relatively simple systems but it can find its application in specific scenarios where basic walking or oscillatory motions are sufficient. One such case is very basic rehabilitation in medical centers. There are many faults with 1-DOF walking mechanisms and that is why they are considered obsolete

In order to use six bar mechanism as walking mechanism first, input trajectory must be determined. Simples input mechanism is to just to add rotation movement as just to add a crank. By changing several factors such as length of input crank and combination of different length of mechanism members it is achieved a movement shown on Fig 13.

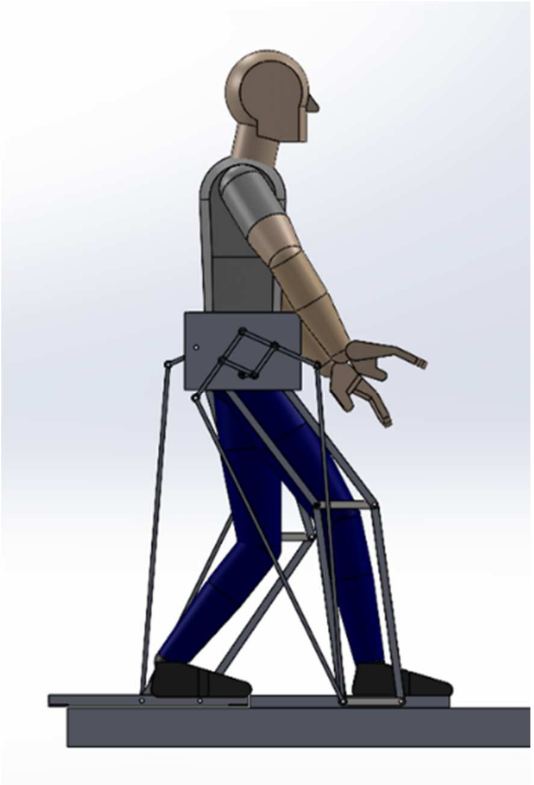

Fig. 10. Side view of leg mechanism with proposed six bar mechanism

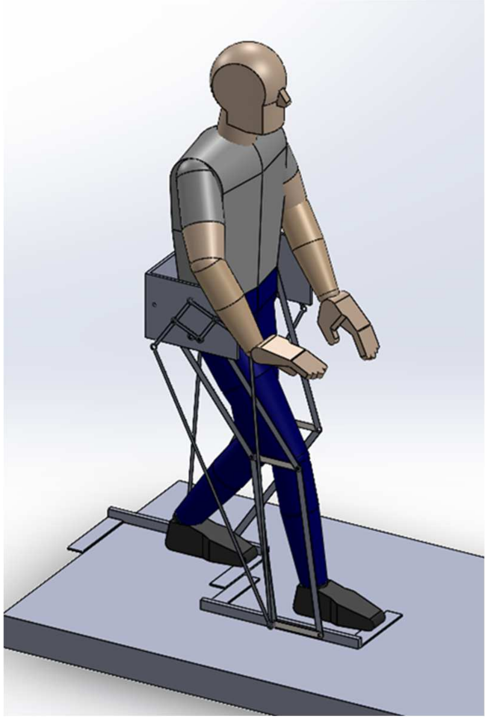

Fig. 11. Isometric view of leg mechanism with proposed six bar mechanism

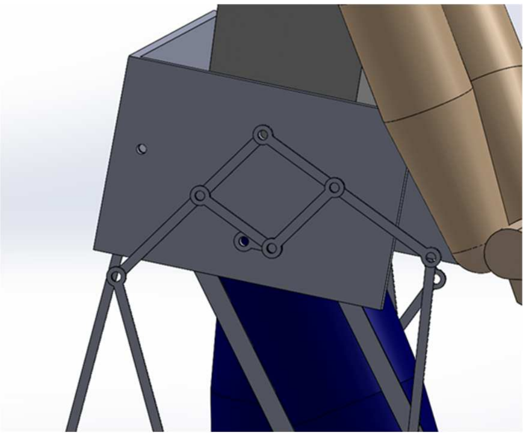

Fig. 12. Close detail of proposed six bar mechanism

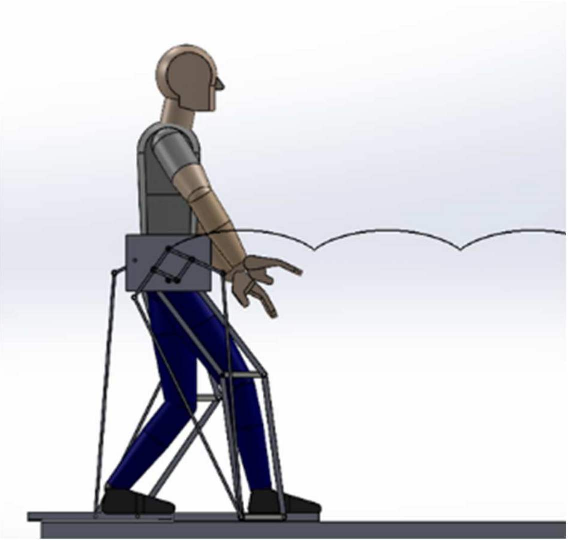

Fig. 13. Trajectory of walking man's CoM when man is on six bar mechanism walker

The synthesis of linkage mechanisms for demanded trajectories requires a combination of theoretical understanding, mathematical modeling, and practical experimentation. It often involves a balance between achieving the desired motion characteristics and addressing engineering constraints and limitations. Advanced tools such as optimization algorithms and simulation software play a significant role in the synthesis process.

4. CONCLUSION

The exploration of six-bar linkage mechanisms, inspired by the characteristics of pantographs, has provided a new approach to trajectory copying. The ability to manipulate the lengths of the mechanism's links as a mean to gain a variety of different output trajectories from a single input curve, showcasing the adaptability and potential for customized motion patterns. The synthesis of these mechanisms addresses both direct and inverse kinematic problems, culminating in an iterative methodology that marks a pivotal scientific contribution. By focusing on the geometric characteristics of the mechanism's links, this research contributes to the understanding and categorization of output curves, offering insights into the optimization of trajectories synthesis.

The proposed innovative linkage mechanism for trajectory replicating introduces a user-friendly framework, streamlining the translation of complex movement patterns into accessible formats. With promising applications in industries where trajectory manipulation enhances user experience and operational efficiency, these planar mechanisms present a novel paradigm for addressing complex motion challenges. The iterative optimization process, integrating empirical data acquisition and synthetic closed curves, exemplifies a novel and effective approach to trajectory synthesis. As researchers navigate the ever-evolving landscape of robotics, the findings from this study may add for further research in planar mechanisms. They offer a glimpse into the potential for diverse applications and advancements in trajectory copying technology. The synthesized mechanisms, as discovered, provide a promising avenue for the development of robotic systems capable of generating optimal approximations of desired trajectories.

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Un design al unui mecanism cu șase bare pentru replicarea traiectoriei

Această lucrare prezintă un nou mecanism de copiere pentru replicarea traiectoriilor. Inspirat de pantograf și încorporând elemente de design ale legăturii Peaucellier-Lipkin, acest mecanism reprezintă o abordare distinctivă și arată cum o traiectorie dorită poate fi transformată într-una mai convenabilă folosind o legătură cu șase bare. Prin unirea traiectoriei de ieșire a acestui mecanism (traiectoria dorită) cu traiectoria de intrare (o traiectorie mai convenabilă), se poate obține o rază de acțiune mai mare cu o structură de legătură simplificată. Acest mecanism poate fi utilizat în multe industrii în care manipularea traiectoriei este critică pentru o experiență îmbunătățită a utilizatorului și eficiență operațională. Cuvinte cheie: mecanism de copiere, replicare traiectorie, design inspirat de pantograf, elemente de legătură Peaucellier-Lipkin, legătură cu șase bare**.**

Cuvinte cheie: *Mecanism de copiere, replicare traiectorie, design inspirat de pantograf, elemente de legătură Peaucellier-Lipkin, legătură cu șase bare.*

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