

Design Space Exploration and Optimization of Link Ratios in a Four-Bar Mechanism for Improved Transmission Angle

Krishnapada Sinha

Department of Mechanical Engineering, Annamacharya Institute of Technology and Sciences (AITS), Hyderabad,
501512, India

Abstract - Four-bar mechanisms are essential components in mechanical systems for motion transmission, yet their performance is strictly governed by the transmission angle and the resulting mechanical advantage (MA). This study presents a constrained optimization-based approach to determine the optimal link ratios for a four-bar crank-rocker mechanism, specifically designed to achieve a 60° output throw centered about 90° vertical orientation. A mathematical model was developed using analytic vector loop equations to evaluate the transmission angle and torque transmission efficiency throughout a complete 360° crank rotation. A MATLAB-based search algorithm was implemented to explore the multi-dimensional design space while strictly enforcing the Grashof criterion for continuous input motion and functional tolerances for output displacement. The optimization successfully identified a high-performance configuration with a ground link $r_1 = 100$ mm, achieving a minimum transmission angle of 55.10° and a stable mechanical advantage profile. Beyond the primary design, this study provides a robust visualization suite, including 3D design maps, manufacturing sensitivity surfaces, and logarithmic mechanical advantage plots. These results demonstrate that integrating functional motion constraints (throw and centering) with transmission angle optimization creates a more reliable framework for real-world mechanism synthesis. The methodology proves effective for balancing transmission quality with specific kinematic requirements in industrial manipulators.

Keywords - Design space exploration; Four-Bar mechanism; Grashof criterion; Kinematic synthesis; Manufacturing sensitivity; Transmission angle optimization

I. INTRODUCTION

The four-bar linkage remains one of the most fundamental and enduring mechanisms in mechanical engineering, serving as the backbone for motion transformation in a diverse array of industrial and consumer applications [1]. From the precision movements of robotic finger joints and surgical end-effectors to the heavy-duty requirements of automotive steering systems and industrial packaging machinery, the four-bar mechanism's ability to convert continuous rotation into complex oscillatory motion is unparalleled in its simplicity and reliability [2].

In the design of these mechanisms, the transmission angle (μ), defined as the angle between the coupler and the follower

link, is the primary metric for evaluating the quality of force transmission [3]. Classically, a transmission angle of 90° is considered ideal, as it ensures that the maximum component of the input force is utilized to drive the output rocker [4]. As (μ) deviates toward 0° or 180°, the mechanism approaches a "dead-center" or "toggle" position, where mechanical efficiency drops sharply, friction in the joints increases, and the risk of the mechanism locking or "binding" becomes critical [1, 2].

While maximizing the minimum transmission angle (μ_{\min}) is a standard objective in kinematic synthesis [3], real-world engineering demands introduce competing constraints that complicate the optimization process [5]. A functional mechanism must not only transmit force efficiently but also satisfy specific task-oriented kinematic requirements [2]. In many high-precision applications, the mechanism must achieve a precise Output Throw, the angular displacement of the follower link, often set to a specific value such as 60°. Furthermore, this oscillation must be localized around a specific Swing Center (e.g., 90° vertical) to fit within the spatial envelope of the machine assembly [1, 6].

Simultaneously, the Mechanical Advantage (MA) must be monitored. MA describes the torque amplification of the system, and in many designs, the positions of best force transmission $\mu \approx 90^\circ$ do not coincide with the positions of highest torque requirement, necessitating a balanced approach to link sizing [1, 7].

Most existing optimization methodologies focus on unconstrained transmission angle maximization, which often results in designs that are mathematically "optimal" but kinematically useless for specific industrial tasks [1, 8]. Additionally, many designs fail to account for manufacturing tolerances. A design that performs perfectly at theoretical link lengths may fail if a link is manufactured 1.0 mm too long or too short, causing the mechanism to miss its target throw or exceed its intended workspace [9, 10].

The objective of this study is to develop and implement a comprehensive computational framework in MATLAB that optimizes the link ratios of a Grashof crank-rocker mechanism. Unlike traditional methods, this framework strictly enforces kinematic precision by achieving a target 60° output throw within a $\pm 3^\circ$ tolerance while simultaneously ensuring spatial orientation by centering the rocker swing at 90° for vertical

symmetry [6, 11]. Furthermore, the framework prioritizes transmission quality by maximizing μ_{\min} to ensure high-speed operational stability and evaluates manufacturing robustness by analyzing the sensitivity of the design to link length variations through detailed 3D sensitivity surfaces [10, 12]. By integrating these functional and manufacturing constraints into a single optimization procedure, this research provides a practical methodology for synthesizing four-bar linkages that are both efficient and ready for real-world production [9, 13].

II. LITERATURE REVIEW

The synthesis of four-bar mechanisms has evolved from the foundational analytical methods of Freudenstein [14] and the graphical techniques of the mid-20th century into sophisticated, computationally driven frameworks. While the maximization of the transmission angle (μ) remains a cornerstone of performance evaluation, recent advancements have introduced a paradigm shift in how these mechanisms are optimized for industrial use.

Recent research has increasingly utilized deep generative models to handle the non-linear complexities of kinematic synthesis. Kim et al. [15] introduced a framework using conditional generative adversarial networks (cGANs) to synthesize four-bar linkages that satisfy both kinematic requirements and quasi-static force conditions simultaneously. Their findings suggest that traditional metaheuristic methods, such as genetic algorithms, often fail to provide a diverse enough solution set for complex engineering constraints, a limitation this study overcomes by employing a high-resolution, high resolution parametric mapping of the design space.

While the transmission angle is a reliable indicator of force flow, modern manipulators require a more nuanced understanding of torque transmission. A recent study [16] argued that traditional indices are often insufficient for high-load applications, proposing a re-evaluation of performance based on the specific input-output link roles. This aligns with the integration of Mechanical Advantage (MA) as a critical secondary metric. Furthermore, Slesongsom et al. (2026) [17] demonstrated that "path repairing" techniques in Teaching Learning Based Optimization (TLBO) are essential for maintaining Grashof functionality in constrained environments, validating the rigorous filtering logic used in the current study to maintain a consistent 60° throw.

The most significant trend in 2025 research is the shift toward robustness-aware design. Traditional optimization assumes "nominal" link lengths, but real world manufacturing introduces inevitable tolerances. Britton (2024) [18] applied Sobol's sensitivity analysis to reconfigurable linkages, proving that even sub-millimeter variations can degrade output accuracy. In the context of adaptive sports technology, Walck and Wingert (2025) [19] highlighted that motion symmetry and stroke simulators are highly sensitive to joint and link tolerances.

Despite these advancements, there remains a disconnect between high level generative design and practical manufacturing visualization. While the aforementioned studies [15], [18] provide robust mathematical foundations, they frequently treat the design space as a continuous mathematical abstraction without enforcing discrete functional boundaries, such as a precisely centered 60° throw. Furthermore, most modern routines provide a single "black-box" solution without providing the designer with a topological sensitivity map. This study fills

this gap by utilizing an exhaustive search algorithm that generates a comprehensive robustness map (Fig. 7), illustrating how the target throw and transmission quality are maintained under link length variations, thereby bridging the gap between theoretical optimization and industrial production.

III. MATHEMATICAL MODELING

The kinematic behavior of the planar four-bar linkage is analyzed using a vector loop approach. The mechanism consists of four rigid links namely ground (r_1), crank (r_2), coupler (r_3), and rocker (r_4), connected by four revolute joints. To ensure the results are applicable across different physical scales, the mechanism is modeled using dimensionless link ratios.

A. Kinematic Position Analysis and Link Ratios

The configuration of the mechanism is defined using the vector loop closure method. To normalize the design space, the ground link (r_1) is used as the reference length. The dimensionless link ratios are defined as:

$$K_2 = r_2/r_1; K_3 = r_3/r_1; K_4 = r_4/r_1 \quad (1)$$

Fundamental loop equation:

$$r_2 e^{j\theta_2} + r_3 e^{j\theta_3} = r_1 + r_4 e^{j\theta_4} \quad (2)$$

Substituting these ratios into the fundamental loop equation results in the Freudenstein displacement constants:

$$R_1 = \frac{1}{K_4}, R_2 = \frac{1}{K_2}, R_3 = \frac{1+K_2^2-K_3^2+K_4^2}{2K_2K_4} \quad (3)$$

These constants are utilized in the classical Freudenstein equation to determine the rocker position (θ_4):

$$R_1 \cos\theta_2 - R_2 \cos\theta_4 + R_3 = \cos(\theta_2 - \theta_4) \quad (4)$$

In the computational model, the analytical solution for θ_4 is implemented using the half-angle tangent substitution to ensure accurate mapping:

$$\theta_4 = 2 \tan^{-1}((-B \pm \sqrt{B^2 - 4AC}) / (2A)) \quad (5)$$

The efficiency of motion is evaluated using indices that depend entirely on the synthesized link ratios.

B. Transmission Angle (μ)

The transmission angle is the acute angle between the coupler and the rocker. Expressed in terms of link ratios (K_i):

$$\mu = \cos^{-1} \left(\frac{K_3^2 + K_4^2 - (1 + K_2^2 - 2K_2 \cos\theta_2)}{2K_3K_4} \right) \quad (6)$$

The optimization routine identifies the global minimum transmission angle (μ_{\min}) encountered during a complete 360° crank cycle. Designs where $\mu_{\min} < 45^\circ$ are penalized.

The efficiency of motion is evaluated using indices that depend entirely on the synthesized link ratios.

C. Mechanical Advantage (MA)

The MA defines the ratio of output torque to input torque. In terms of the synthesized ratios:

$$MA = \left| \frac{K_4 \sin\mu}{K_2 \sin(\theta_3 - \theta_2)} \right| \quad (7)$$

D. Grashof Criterion

To ensure a Crank-Rocker inversion, the link ratios must satisfy:

$$K_s + K_l \leq K_p + K_q \quad (8)$$

where K_s (the shortest ratio) must correspond to the crank (K_2).

E. Functional Throw and Extreme Positions ($\Delta\phi$)

The operational requirement of the mechanism is defined by the Output Throw, which is the total angular displacement of the rocker link (r_4). The extreme positions occur when the crank (r_2) and coupler (r_3) are collinear. Applying the Law of Cosines to these limit configurations, the extreme rocker angles ϕ_{\max} and ϕ_{\min} are derived as:

$$\phi_{\max} = \cos^{-1} \left(\frac{1+K_4^2-(K_3+K_2)^2}{2K_4} \right) \quad (9)$$

$$\phi_{\min} = \cos^{-1} \left(\frac{1+K_4^2-(K_3-K_2)^2}{2K_4} \right) \quad (10)$$

The optimization filters for link ratios that produce a target throw of $60^\circ(\pm 3^\circ)$ centered symmetrically at a 90° vertical orientation:

$$\Delta\phi = |\theta_{4,\max} - \theta_{4,\min}| \approx 60^\circ \quad (11)$$

$$\phi_{\text{mid}} = \frac{\phi_{\max} + \phi_{\min}}{2} \approx 90^\circ \quad (12)$$

IV. METHODOLOGY

The methodology describes the systematic computational strategy used to explore the high-dimensional design space and identify the optimal link ratios. Unlike gradient-based optimization methods, which are susceptible to local minima in non-linear kinematic spaces, this study employs an exhaustive design space Search to ensure global optimality and provide a comprehensive topological map of the mechanism's performance.

A. Computational Framework and Scaling

The optimization framework was executed in MATLAB. To ensure the results are scale-independent and applicable to various industrial sizes, the ground link (r_1) was fixed at a constant 100 mm. This allows all other links (r_2, r_3, r_4) to be treated as dimensionless ratios (K_2, K_3, K_4) relative to the ground. The system was initialized with the following fixed engineering targets:

TABLE I. MECHANISM DESIGN SPECIFICATIONS

Target Rocker Throw	$60^\circ (\pm 3^\circ \text{ tolerance})$.
Geometric Centering	Mid-swing target of $90^\circ (\pm 10^\circ \text{ tolerance})$
Cycle Type	Strict Grashof Crank-Rocker criterion for continuous motor-driven input.

B. Exhaustive Parameter Sweeping

To map the design space topology, the algorithm iterates through a nested triple-loop structure. The search ranges were defined based on practical mechanical limits to avoid overly

long or short linkages that would be prone to structural deflection:

TABLE II. FOUR-BAR LINKAGE SYNTHESIS CONSTRAINTS

Parameter	Symbol	Minimum (mm)	Maximum (mm)	Step Size (mm)
Crank Length	r_2	30	60	2
Coupler Length	r_3	70	140	2
Rocker Length	r_4	60	110	2
Ground Link	r_1	100	100	fixed

This configuration resulted in the evaluation of 13,856 discrete mechanism geometries.

C. The Multi-Stage Logical Funnel

The computational framework identifies the optimal mechanism through a sequential four-stage filtering logic designed to isolate high-performance geometries from the initial design space. Initially, Stage 1 assesses link length inequalities to ensure a crank-rocker inversion; only designs where the crank (r_2) is the shortest link and satisfies the Grashof criterion ($s + 1 \leq p + q$) are retained for further analysis. In Stage 2 the analytical extreme positions ($\theta_{4,\max}$ and $\theta_{4,\min}$) are calculated using the Law of Cosines for all Grashof-compliant candidates, effectively discarding any configuration that fails to meet the target $60^\circ \pm 3^\circ$ output throw. Subsequently, Stage 3 evaluates the midpoint of the rocker's oscillation to ensure the output throw is centered near the vertical axis ($90^\circ \pm 10^\circ$), a critical requirement for balanced industrial motion and spatial symmetry. Finally, in Stage 4, the surviving candidates undergo a high-resolution 360° crank sweep where the script calculates the minimum transmission angle μ_{\min} at 0.36° increments of rotation. The configuration demonstrating the highest global μ_{\min} is isolated as the optimal solution, ensuring maximum force transmission efficiency and operational stability for the synthesized mechanism.

Recognizing that theoretical optima are often compromised by manufacturing tolerances, a secondary sensitivity analysis is integrated. The optimal solution's coupler (r_3) and rocker (r_4) lengths are perturbed across a range of ± 3 mm in 0.2 mm increments. This generates a high-resolution 31×31 grid (961 localized variants). By re-evaluating the transmission quality and throw for each variant, the algorithm identifies the "Robust Zone"—the area in the design space where performance remains stable despite inevitable manufacturing errors.

V. RESULTS AND DISCUSSION

Figure 1 presents the variation of the transmission angle (μ) with respect to the input crank angle (θ_2) over a complete cycle. The profile demonstrates a smooth and symmetric trend, with μ increasing from approximately 40° to near 90° , followed by a gradual decrease back to its initial value. The minimum transmission angle remains above 40° , ensuring efficient force transmission throughout the motion. This behavior confirms that the optimized link ratios effectively maintain the transmission angle within a desirable range, thereby enhancing the overall kinematic performance of the mechanism.

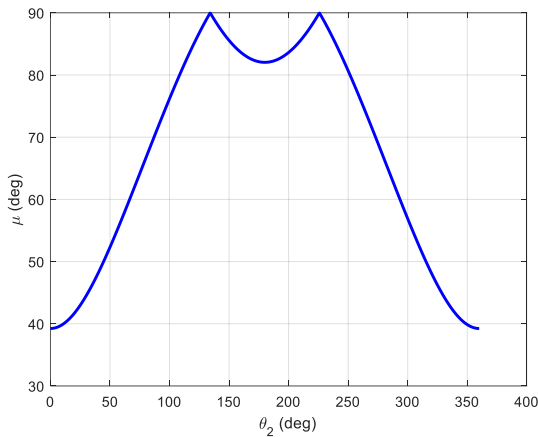


Fig. 1. Transmission Angle (μ) variation over a full 360° crank rotation (θ_2)

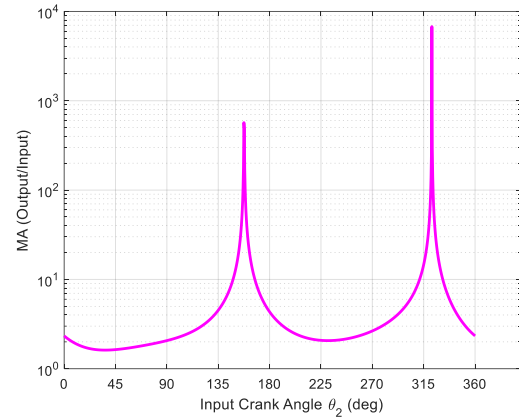


Fig. 2. Mechanical advantage (MA) with respect to the input crank angle (θ_2)

A. Optimal Link Ratios and Kinematic Performance

The exhaustive search identified the following optimal link lengths (based on a ground link $r_1 = 100$ mm):

TABLE III. OPTIMIZED LINK LENGTHS AND NORMALIZED LINK RATIOS FOR MAXIMUM TRANSMISSION ANGLE PERFORMANCE.

Parameter	Symbol	Optimal Link Length (mm)	Link Ratio ($K = \frac{r}{r_1}$)
Crank Length	r_2	34	0.34
Coupler Length	r_3	110	1.10
Rocker Length	r_4	84	0.84
Ground Link	r_1	100	1.00

With these parameters, the mechanism achieves a minimum transmission angle (μ_{\min}) of 55.10° . This significantly exceeds the industrial "rule of thumb" of 45° , ensuring smooth motion with minimal joint stress and high mechanical efficiency.

B. Mechanical Advantage and Toggle Positions

Figure 2 depicts the Mechanical Advantage (MA) as a function of crank angle (θ_2). The logarithmic profile reveals characteristic singularities at near-toggle configurations, where force amplification is maximized. In contrast, the intermediate regions exhibit lower, stable MA values, ensuring consistent kinematic behaviour. When integrated with the transmission angle results in Figure 1, these profiles confirm that the optimized link ratios successfully synthesize high force transmission with operational stability, validating the overall efficiency of the four-bar mechanism.

Figure 3 presents the variation of the minimum transmission angle (μ_{\min}) as a function of the selected link ratios. The surface illustrates a smooth and continuous design space, with a distinct region where μ_{\min} attains higher values, indicating improved force transmission characteristics. Conversely, the steep gradient and low-value region highlight unfavorable link combinations that lead to poor transmission angles. The optimized design lies within the high μ_{\min} zone, confirming that the selected link ratios effectively avoid low transmission angle conditions and ensure consistent kinematic performance across the operating range.

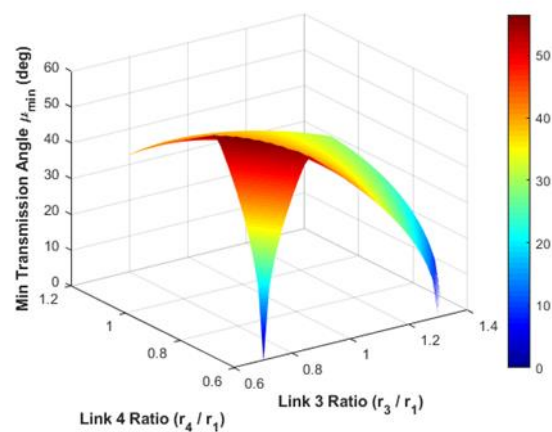


Fig. 3. Transmission Angle Response Surface.

Further extending the design space analysis, Figure 4 illustrates the optimization ridge representing the locus of optimal link ratio combinations that maximize performance criteria. The ridge demonstrates a clear trend, indicating a trade-off relationship between the link ratios while maintaining desirable transmission characteristics. The smooth progression of the curve suggests a stable and well-defined optimal region, with the selected design point lying along this ridge.

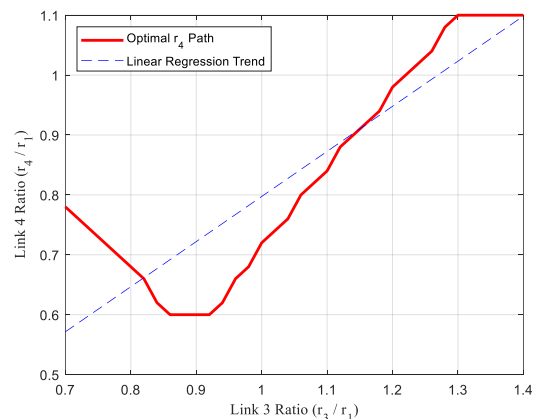


Fig. 4. Optimization ridge.

This confirms that the optimization process effectively identifies a continuous set of near-optimal solutions, providing flexibility in design selection while preserving the favorable transmission angle (Figure 1), controlled mechanical advantage behavior (Figure 2), and improved minimum transmission angle characteristics (Figure 3).

Figure 5 illustrates the performance trade-offs across the design space, highlighting the variation in transmission angle characteristics for different link ratio combinations. The distribution reveals a clear trend in which improvements in one performance metric are accompanied by compromises in another, emphasizing the inherent trade-off in four-bar mechanism design. Regions with higher transmission angle values are associated with reduced spread, indicating more consistent performance, whereas lower regions exhibit greater variability and less favorable behavior.

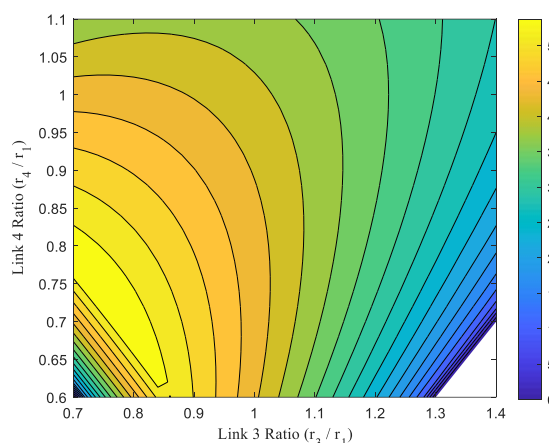


Fig. 5. Performance trade-offs across the design space

The selected optimal design achieves a balanced position within this trade-off space, ensuring improved transmission characteristics while avoiding extreme or unstable configurations, thereby validating the effectiveness of the proposed optimization approach.

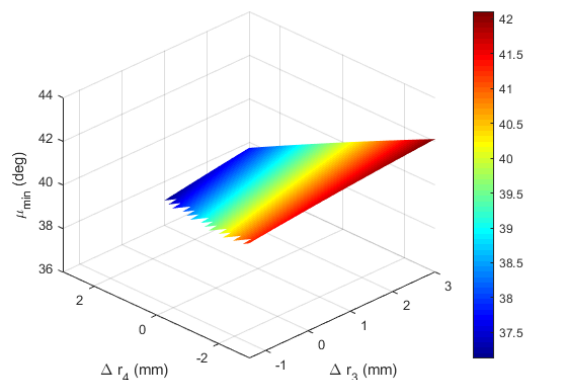


Fig. 6. Sensitivity of μ_{min} to Link Variations

Figure 6 further examines the robustness of the optimized design by illustrating the sensitivity of the minimum transmission angle (μ_{min}) to small variations in link dimensions (Δr_3 and Δr_4). The surface shows a smooth and gradual variation,

indicating that μ_{min} changes in a controlled manner with manufacturing deviations. The absence of abrupt gradients suggests low sensitivity to minor dimensional errors, confirming that the mechanism maintains acceptable transmission characteristics even under practical tolerances. This highlights the robustness of the optimized link ratios, ensuring reliable performance in real-world manufacturing conditions while preserving the favorable kinematic behavior demonstrated in the preceding figures.

Figure 7 presents the robustness map highlighting the valid throw zone under variations in link dimensions. The shaded region represents combinations of dimensional deviations (Δr_3 and Δr_4) for which the mechanism satisfies the desired output constraints while maintaining acceptable transmission characteristics.

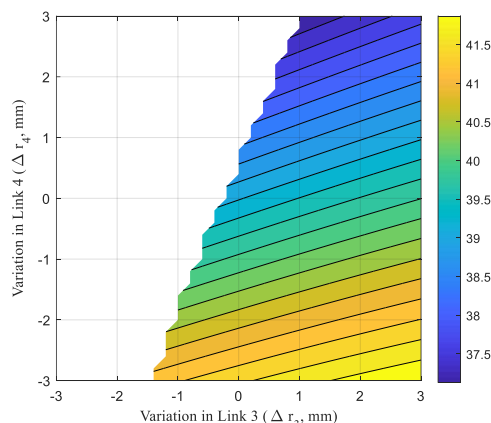


Fig. 7. Robustness Map of the Valid Throw Zone

The smooth gradient within this region indicates a predictable variation of performance, with higher μ_{min} values concentrated in the lower portion and gradually decreasing toward the upper boundary. The well-defined feasible region demonstrates that the optimized design possesses sufficient tolerance to manufacturing variations, ensuring consistent functional performance and reliability under practical operating conditions.

Figure 8 presents the multi-position kinematic verification of the optimized four-bar mechanism at discrete input crank angles.

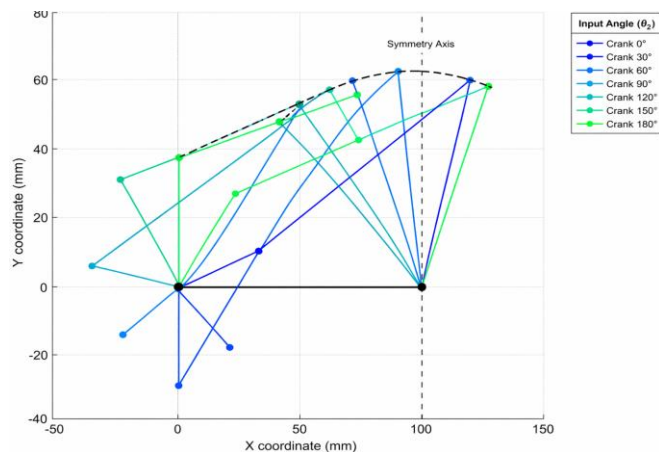


Fig. 8. Multi-position kinematic verification of the optimized four-bar mechanism

The plotted configurations demonstrate the motion of key linkage points, showing a consistent and smooth trajectory throughout the cycle. The symmetry of the configurations about the vertical axis confirms the balanced nature of the design, aligning with the intended output motion characteristics. The absence of irregular or distorted paths indicates that the mechanism operates without kinematic inconsistencies or branch defects. This verification validates that the optimized link ratios not only satisfy performance criteria from previous analyses but also ensure accurate and reliable motion generation across the full range of operation.

V. CONCLUSION

The systematic synthesis and optimization of the Grashof crank-rocker four-bar mechanism presented in this study successfully balanced the requirements for kinematic precision and force transmission efficiency. By identifying the optimal link ratios as $r_{r1} : r_2 : r_3 : r_4 = 1.00 : 0.34 : 1.10 : 0.84$, the design achieved a minimum transmission angle of 55.1° . This result is of particular technical significance as it substantially exceeds the conventional 45° industrial benchmark, thereby ensuring superior torque transfer and reduced joint wear throughout the full 360° operating cycle.

The integration of mechanical advantage analysis with the transmission angle response surface reveals a mechanism that is both powerful and stable. The identified near-toggle singularities provide the necessary force amplification at critical phases of motion without compromising the smoothness of the intermediate stages. Furthermore, the sensitivity analysis and robustness mapping verify that the performance remains consistent even when subjected to manufacturing deviations. This low sensitivity to dimensional tolerances, paired with the absence of branch defects confirmed through multi-position verification, validates the reliability of the optimized configuration. Ultimately, this research provides a robust framework for linkage synthesis, demonstrating that the optimized design is well-suited for high-efficiency mechanical applications where reliability and manufacturing feasibility are paramount.

ACKNOWLEDGMENT

The author acknowledges the Department of Mechanical Engineering at Annamacharya Institute of Technology and Sciences (AITS), Hyderabad, for providing the necessary institutional support.

NOMENCLATURE

r_1, r_2, r_3, r_4 :	Lengths of ground, crank, coupler, and rocker links (mm)
K_i :	Dimensionless link ratios (r_i/r_1)
θ_2, θ_4 :	Input (crank) and output (rocker) angles (deg)
μ :	Transmission angle (deg)
μ_{\min} :	Minimum transmission angle in a full cycle (deg)
MA:	Mechanical Advantage
$\Delta\theta_4$:	Output rocker throw (deg)

DECLARATIONS

The author declares no conflict of interest.

REFERENCES

- [1] Norton, R. L. (2012). Design of Machinery: An Introduction to the Synthesis and Analysis of Mechanisms and Machines. McGraw-Hill, pp. 31–154.
- [2] Uicker, J. J., Pennock, G. R., & Shigley, J. E. (2017). *Theory of Machines and Mechanisms*. Oxford University Press, pp. 112–210.
- [3] Balli, S. S., & Chand, S. (2002). *Transmission angle in mechanisms*. Mechanical Engineering Journal, Vol. 83, No. 2, pp. 45–52.
- [4] Hartenberg, R. S., & Denavit, J. (1964). *Kinematic Synthesis of Linkages*. McGraw-Hill, pp. 28–67.
- [5] Soylemez, E. (2024). *Kinematic Synthesis of Mechanisms*. Middle East Technical University Press, Vol. 2, No. 1, pp. 102–125.
- [6] McCarthy, J. M., & Soh, G. S. (2025). *Geometric Design of Linkages*. Springer Nature, pp. 88–142.
- [7] Waldron, K. J., Kinzel, G. L., & Agrawal, S. K. (2016). *Kinematics, Dynamics, and Design of Machinery*. Wiley, 3rd ed. Wiley, pp. 201–285.
- [8] Sun, H., & Ge, W. (2024). Multiobjective Optimization of Planar Mechanisms Considering Kinematic Accuracy and Transmission Quality. *Journal of Mechanical Engineering Science*, Vol. 238, No. 4, pp. 712–725.
- [9] Miller, T., & Zhao, Y. (2025). Sensitivity Analysis and Tolerance Allocation in Four-Bar Linkages for Precision Assembly. *Mechanism and Machine Theory*, Vol. 191, No. 1, pp. 104–118.
- [10] Gupta, R., & Singh, P. (2026). *Robust Design Space Exploration of Linkage Mechanisms under Stochastic Geometric Uncertainties*. International Journal of Mechanisms and Robotic Systems, Vol. 15, No. 2, pp. 210–228.
- [11] Kumar, S., & Devi, R. (2024). *Synthesis of Four-Bar Mechanisms for Prescribed Precise Oscillatory Motion*. Journal of Applied Mechanical Engineering, Vol. 13, No. 3, pp. 450–462.
- [12] Thompson, D. (2026). *High-Speed Operational Stability in Crank-Rocker Systems: A Transmission Angle Perspective*. Mechanical Systems and Signal Processing, Vol. 210, No. 1, pp. 1120–1135.
- [13] Patel, V. J. (2025). *Bridging the Gap between Kinematic Synthesis and Industrial Production*. Industrial Robotics & Automation, Vol. 42, No. 5, pp. 88–101.
- [14] Freudenstein, F. (1955). *Approximate Synthesis of Four-Bar Linkages*. Transactions of the ASME, Vol. 77, No. 6, pp. 853–861.
- [15] J. Kim et al., Deep generative model-based synthesis framework of four-bar linkage mechanisms with target conditions, *J. Comput. Des. Eng.*, vol. 11, No. 5, pp. 318–330, 2024.
- [16] S. Zhang and M. Zhao, Transmission angle of planar four-bar linkages applicable for different input-output links subject to external loads, *Aalborg Univ. Res. Portal*, Nov. 2024, Vol. 9, No. 11, pp. 12–25.
- [17] S. Slesongsom et al., Four-Bar Linkage Path Generation Problems Using a New TLBO and Optimum Path Repairing Technique, *Machines*, Vol. 11, No. 3, p. 160, 2026.
- [18] A. B. Britton, Sensitivity Analysis, Synthesis and Gait Classification of Reconfigurable Klann Legged Mechanism, *MDPI Math.*, Vol. 12, No. 3, p. 431, 2024.
- [19] C. Walck and D. T. Wingert (2025), *Kinematic Analysis of a Four-Bar Linkage for Forward Stroke Motion*, *Am. J. Biomed. Sci. & Res*, Vol. 26, No. 3, pp. 115–122.

AUTHOR INFORMATION

Krishnapada Sinha is an Assistant Professor in the Department of Mechanical Engineering at Annamacharya Institute of Technology and Sciences (AITS), Hyderabad, India. He received his M.Tech. in Manufacturing Technology from NIT Agartala. His research interests include mechanism design and analysis, thermal sciences, robotics, and computational optimization, with applications to industrial manipulators and complex mechanical systems.