



Optimizing Rotary Joint Structures: A Hybrid Approach Combining FEM, Neuro-Fuzzy, And Water Cycle-Moth Flame Algorithms For Robotics And Automation Manufacturing

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Abstract: The study addresses challenges in designing rotary joints for robotic arms used in rehabilitation devices and industrial settings. These joints need to be compact, lightweight, and handle significant loads. Traditional design methods are time-consuming and resource-intensive. The authors propose a new approach that combines several techniques to optimize the joint's structure. This includes methods for exploring different shapes (topology method), analysing variations (analysis of variance), simulating stress and strain (finite element method), using artificial intelligence to learn from data (adaptive neuro-fuzzy inference system), and finding the best design based on performance (water cycle moth-flame optimization algorithm). Using this approach, the researchers designed a new rotary joint. Tests showed it could withstand a torque of 357.46 Newton-millimetres and stress up to 489.98 Megapascals. The close match between predicted performance and test results (less than 1% difference) demonstrates the effectiveness of this new design optimization method.

Keywords : Rotary joint; Topology-size optimization; Finite element method; Neural-fuzzy; Water cycle moth-flame optimization algorithm; Robotics; Automation manufacturing.

I. Introduction: In the realm of robotics and automation, robotic arms often employ balancing mechanisms to minimize energy consumption. These mechanisms typically utilize helical springs or a combination of helical springs and rotary joints. Robotic arms frequently incorporate various joint types, such as linear, orthogonal, rotational, twisting, and revolving joints, to execute intricate movements. Among these, rotary joints with precise motion control are particularly sought-after in modern robotics and automation applications.

A prevailing trend in contemporary design is to minimize material usage while maintaining optimal performance. This approach not only conserves natural resources and promotes environmental sustainability but also leads to lighter and more compact joint designs. In recent years, there has been a surge of interest in developing soft robotic systems. Rotary joints that function as torsion springs are integral components in robots, mobility aids, rehabilitation equipment, and factory automation. These joints are expected to possess attributes such as compactness, lightweight design, high load capacity, and durability.

Historically, flexure-based compliant mechanisms have been employed in the design of rotary joints. However, this approach relies heavily on the designer's experience and intuition, which can be time-consuming, costly, and prone to inaccuracies. With the advancement of finite element analysis (FEA) and optimization techniques, designers can now streamline the design process, reduce costs, and enhance product quality [1].

Topology optimization has emerged as a powerful tool for conceptual structural design. By maximizing stiffness within material constraints, topology optimization can yield innovative designs. However, for flexure-based rotary joints, safety considerations dictate that stresses remain below the material's yield strength. Therefore, stress-constrained topology optimization is essential. Additionally, the optimized structure must meet specific working range requirements, which necessitates further dimensional optimization [2].

To accurately predict the behavior of the rotary joint, robust analytical methods are required. While analytical methods like pseudo-rigid-body-model, beam-constrained model, and compliance matrix are effective for small deflections and specific beam shapes, FEA offers a more versatile and accurate approach, especially for large deflections and complex geometries [3].

Surrogate modelling techniques, such as response surface methodology (RSM), artificial neural networks (ANN), and adaptive neuro-fuzzy inference systems (ANFIS), can significantly reduce computational costs and expedite the optimization process. ANFIS, in particular, has proven effective in modelling complex nonlinear relationships, making it a suitable choice for representing the behaviour of the rotary joint [4].

Meta-heuristic optimization algorithms, inspired by natural phenomena, have gained popularity for solving complex optimization problems. Water cycle algorithm (WCA) and moth-flame optimization (MFO) are two such algorithms that have been successfully applied in various engineering domains. A hybrid approach, combining WCA and MFO (WCMFO), offers enhanced exploration and exploitation capabilities [5].

While previous research has explored the design and optimization of rotary joints, there remains a need for innovative designs that prioritize material efficiency and load-bearing capacity. This study aims to address this gap by combining topology optimization, intelligent modeling, and size optimization techniques to develop a lightweight and robust rotary joint for gravity-balancing robotics and automation applications [6].

This research introduces a novel, cost-effective, and highly reliable method for designing and optimizing rotary joints specifically for gravity-balancing robotics and automation manufacturing. This hybrid optimization technique combines topology optimization, neural-fuzzy computation, and a metaheuristic algorithm [7].

Initially, topology optimization is employed to generate an initial joint structure that minimizes stiffness while adhering to volume constraints. The resulting topological joint is then refined. Subsequently, nonlinear finite element analysis (FEA) is conducted to gather data on the joint's behaviour. An improved adaptive neuro-fuzzy inference system (ANFIS) algorithm is then developed to create accurate approximate models for both fitness and constraints. The ANFIS structure is optimized to ensure maximum model accuracy. The refined joint's dimensions are then optimized using the Whale Optimization Algorithm (WOA). Finally, a post-hoc statistical analysis is performed to compare the proposed method with other meta-heuristics. The optimal predicted results are validated [8].

The paper is structured as follows:

Section 2: Problem Definition

Section 3: Proposed Hybrid Optimization Approach

Section 4: Results and Discussion

Section 5: Conclusion

II. Problem Statement and Proposed Solution:

Problem:

The design of robotic arms often involves heavy components that require significant energy to operate. To address this issue, a novel gravity-balancing mechanism is proposed, utilizing a zero-free-length spring and a rotary joint. This mechanism aims to reduce the energy consumption of the robotic arm by counteracting the gravitational forces acting on it.

Proposed Solution:

A multi-stage optimization approach is proposed to design an efficient and lightweight rotary joint for this gravity-balancing mechanism:

Topology Optimization:

Goal: Minimize the mass of the joint while maintaining structural integrity.

Method: Employ topology optimization techniques to identify the optimal material distribution within the joint.

Structural Redesign: Goal: Improve the joint's load-bearing capacity and reduce stress concentration.

Method: Redesign the joint's geometry, considering factors like thickness, length, and transition radii.

Size Optimization:

Goal: Determine the optimal dimensions of the joint to meet specific performance requirements.

Method: Utilize optimization algorithms to fine-tune the joint's size parameters.

By combining these optimization techniques, the researchers aim to develop a rotary joint that is both lightweight and robust, enhancing the overall performance and energy efficiency of the gravity-balancing robotic arm.

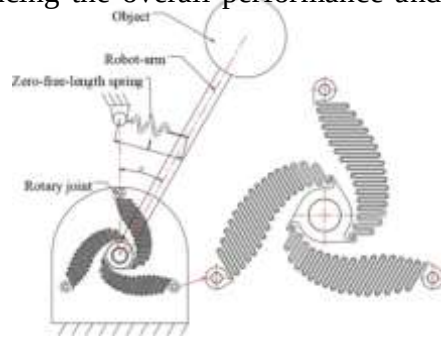


Figure 1: Schematic of gravity-balancing robot arm.

Proposed Hybrid Optimization Approach: To optimize the design of a rotary joint, a multi-step approach is proposed:

Topology Optimization: Initially, topology optimization is employed to minimize the mass of the joint while maintaining structural integrity.

Redesign: The initial design is further refined through a redesign process to enhance its flexibility.

Design of Experiments (DoE) and Finite Element Analysis (FEA): A combination of DoE and FEA is used to generate a dataset of moment reactions and resulting stresses for various design parameters.

Analysis of Variance (ANOVA): ANOVA is applied to the dataset to identify the most significant design variables that influence the moment reaction.

Adaptive Neuro-Fuzzy Inference System (ANFIS) Modelling: The optimal structure of the ANFIS model is determined using the Taguchi method to minimize the root mean square error. ANFIS is then used to create surrogate models that approximate the relationship between design variables and the moment reaction.

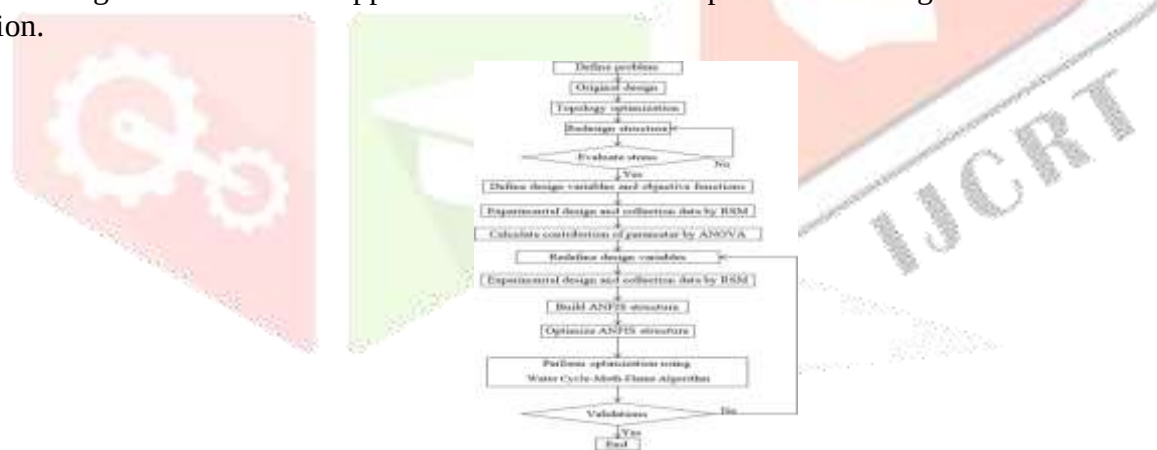


Figure 2: Flowchart of hybrid method.

Whale Optimization Algorithm (WOA): The WOA algorithm is employed to optimize the design parameters based on the ANFIS surrogate models. The goal is to maximize the moment reaction while considering other design constraints.

The entire optimization process is implemented in MATLAB R2019b. A flowchart illustrating the steps of this hybrid approach is provided in Figure 2.

Topology optimization:

Step 1: Defining the Design Problem: We are designing a new rotary joint for robotics and bioengineering. This joint needs to be compact, lightweight, strong, and capable of handling heavy loads. We'll use two optimization techniques - topology optimization and size optimization - to achieve these goals.

Step 2: Initial Design: The initial design of the joint is crucial, as it significantly impacts the final optimized design. We'll carefully consider factors like shape, structure, and material distribution to create a solid starting point.

Step 3: Topology Optimization: Traditional robotic and assistive devices often use excess material, leading to reduced performance. Topology optimization helps us identify and remove unnecessary material, resulting in a stronger, lighter, and more efficient design.

We'll use the Solid Isotropic Material with Penalization (SIMP) method and the Optimality Criteria (OC) method to optimize the material distribution within the design domain. The SIMP method assigns a density value (between 0 and 1) to each element, where 0 indicates no material and 1 indicates full material. The OC method helps us find the optimal distribution of material. By following these steps, we aim to create an optimized rotary joint that meets the specific requirements of robotics and bioengineering applications [9].

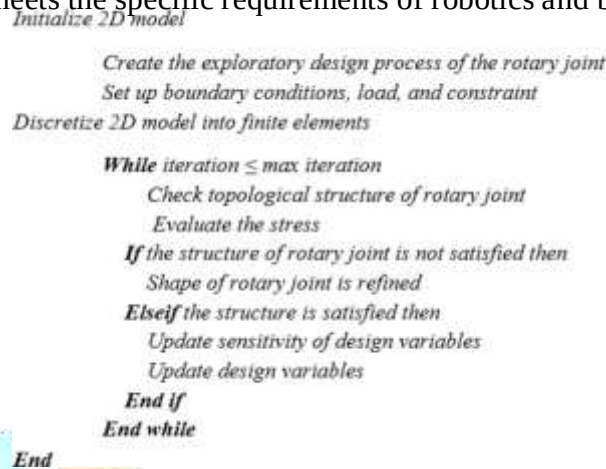


Figure 3: Pseudo code of our proposed topology.

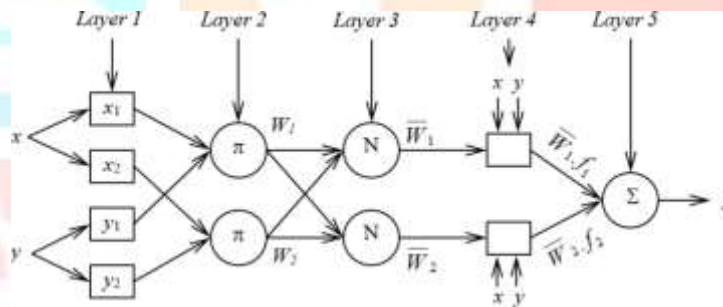


Figure 4: Layers of our proposed ANFIS prototype.

Modeling by adaptive neuro fuzzy inference system:

Step 1: Redesigning the Rotary Joint

Topology optimization provides an initial shape for the rotary joint, minimizing its volume. However, this shape may not consider other critical factors. The designer must refine the design to ensure all desired properties are met.

Step 2: Evaluating Strength

While designer experience can inform strength assessments, it's not always accurate. Finite Element Analysis (FEA) is employed to rigorously evaluate the redesigned joint. The optimal joint will balance desired rotation with minimal stress.

Step 3: Defining Design Parameters and Objectives

The goal is to maximize the joint's load-bearing capacity while ensuring stress levels remain below allowable limits. The moment reaction serves as the objective function, and equivalent stress is the constraint. The joint's geometry plays a crucial role in its performance, so all geometric parameters are considered design variables.

Step 4: Data Collection

Numerical experiments, particularly those integrating Response Surface Methodology (RSM) with FEM, are used to gather data efficiently. This approach avoids the costs associated with physical experiments.

Step 5: Assess Variable Importance

Not all design variables have an equal impact on the rotary joint's performance. To identify the most influential ones, we'll use a statistical technique called Analysis of Variance (ANOVA). This helps us eliminate variables that have minimal effect on the output, streamlining the optimization process.

Step 6: Focus on Key Variables

Based on the results from Step 5, we'll narrow down the list of design variables to focus on those with the highest impact. This reduces the complexity of the optimization problem.

Step 7: Collect Targeted Data

With a smaller set of key variables, we'll collect a new dataset. This dataset will be smaller than the original one, as we're no longer considering the less influential variables.

Step 8: Construct the ANFIS Model

To model the complex relationship between the input (design variables) and output (performance metrics), we'll use an Adaptive Neuro-Fuzzy Inference System (ANFIS). ANFIS is a powerful technique for approximating nonlinear functions.

The ANFIS model consists of five layers:

Layer 1: Fuzzification Layer: This layer transforms crisp input values into fuzzy sets using membership functions. Various membership functions (like triangular, trapezoidal, Gaussian, etc.) can be used to represent the degree of membership of an input value in a fuzzy set [10].

By following these steps, we aim to create a more efficient and accurate optimization model for the rotary joint.

Layer 2: Layer 2, a rule-based layer, generates rule activation intensities (w_i) using the outputs produced by Layer 1.

Layer 3: This layer is considered the normalized layer.

Layer 4: Layer 4 is defined the defuzzification layer.

Layer 5: It is called the last layer. Its output is ANFIS result.

Step 9: Optimize ANFIS structure

The ANFIS approximation model's accuracy depends on many factors such as the type of input membership function; the number of input membership functions; the type of output membership function; and the optimal method. Therefore, before performing the training, the ANFIS structure needs to be optimized [11].

The optimization of the ANFIS structure aims to create an approximate model with the least error. Therefore, the mean squared error (MSE) is chosen as the objective function of the optimal process [12].

This paper examines the optimization of an Adaptive Neuro-Fuzzy Inference System (ANFIS) model. The ANFIS model's performance, measured by Mean Squared Error (MSE), is influenced by several factors:

$$MSE = \frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2$$

the number of input membership functions, the type of input and output membership functions, and the optimization method.

To optimize the ANFIS, the authors employ a Taguchi method-based approach. Taguchi is a statistical design of experiments technique that efficiently explores a large design space with a limited number of experiments. In this case, the Taguchi method is used to systematically vary the ANFIS parameters, such as the number of input membership functions and the type of membership functions [13].

Once the Taguchi experiments are conducted, the resulting ANFIS models are evaluated based on their MSE. The best-performing model is selected, and an Analysis of Variance (ANOVA) is performed to determine the relative importance of each parameter in influencing the MSE. This analysis provides insights into which parameters have the most significant impact on the model's performance [14].

Results and discussion:

- Original Rotary Joint Design

The rotary joint is a crucial component of the gravity-balancing robot arm, responsible for rotational movement. A topology optimization approach was used to design its shape and architecture [15].

Two initial designs (Model 1 and Model 2) were created, differing in the presence of internal rims. Both models had an outer diameter of 100 mm, an inner diameter of 12 mm, and three 4 mm holes for fixation.

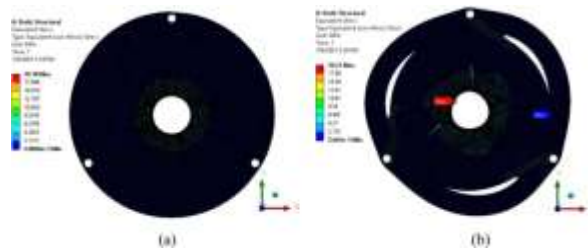


Figure : Stress distribution: (a) model 1, (b) model 2.

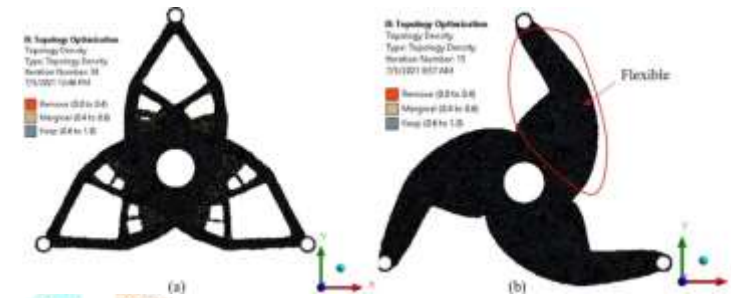


Figure : Topology results: (a) model 1, (b) model 2.



Figure : Detail design schematic of rotary joint: (a) Design case 1, (b) Design case 2.

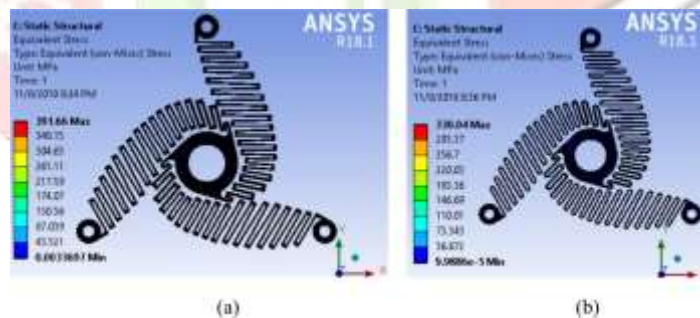


Figure : Stress test results (a) Case 1, (b) Case 2.

• Topology Optimization

Nonlinear Finite Element Analysis (FEA) was performed on both models using ANSYS R18 to determine stress distribution. The models were fixed at three points and subjected to a 5000 N-mm moment. ALT63-7075 material properties were used [16].

Mesh quality was ensured through careful meshing with Tetrahedral elements. Skewness and Orthogonal Quality metrics were used to assess mesh quality, with both models exhibiting good to very good quality [17].

Stress analysis revealed that Model 1 had stress concentration in the inner ring, while Model 2 had stress in both the inner ring and fixed hole positions. Based on these results, topology optimization was performed on

Model 2, resulting in a design with three flexible links. These links were identified as key components for elastic rotation and energy storage.

Size optimization: As mentioned earlier, Model 2 was selected for the rotary joint. While topology optimization provided a structural basis, it did not fully satisfy all the essential joint requirements. To ensure the joint's functionality, 30-degree rotation range, load-bearing capacity, and durability, a redesign process was undertaken. Building on the topology optimization results of Model 2 (Fig. 11(b)), a detailed and complete design for Model 2 was proposed, recognizing the strong correlation between the optimized structure and the desired joint performance [18].

III. Experiment Design and Data Collection:

To optimize the rotary joint's size, a full set of geometric parameters was initially considered. However, to reduce the number of variables and computational time, a numerical experiment design was conducted using the Central Composite Design (CCD) method.

Finite Element Analysis (FEA) Setup

The FEA process in ANSYS was configured as follows:

Boundary Conditions: The rotary joint was fixed at three holes.

Loading: A 30-degree rotational displacement was applied to the inner ring with a 12 mm diameter.

Meshing: Face sizing was employed to divide the mesh, with a selected element size of 0.4 mm. This resulted in a mesh with 565,283 elements and 1,011,061 nodes. The average mesh quality metric was approximately 0.368.

Data Collection

A total of eighty-one numerical experiments were carried out, as detailed in Table 2, to collect data for the optimization process. The Response Surface Methodology (RSM) integrated with the FEM was utilized for this purpose.

Contribution and sensitivity of parameters: We analyzed the data in Table 2 to understand how different factors affect the joint's performance. Table 3 reveals that the joint's thickness significantly influences stress and moment. In contrast, the radii r_2 , r_3 , r_4 and have minimal impact on the joint's behavior. Additionally, their statistical significance (p-value) is low. To simplify the design process, we removed the less influential variables (radii r_2 , r_3 , r_4) based on the ANOVA analysis. The remaining factors are considered the key design variables [19].

Selection of Key Design Variables and Problem Formulation

Based on an ANOVA analysis, the primary design variables influencing joint size were identified as:

r_1 , t_1 , t_2 , l_1 , l_2 .

Further FEA simulations narrowed down these variables to five key factors affecting the rotary joint's behavior:

Radius (r_1)

Thickness (t_1)

Thickness (t_2)

Length (L_1)

Length (L_2)

IV. Objective Function and Constraint:

Given the joint's requirement to withstand significant loads, the moment reaction (M_r) was selected as the objective function to be maximized. To ensure structural integrity, the equivalent stress (σ_{eq}) was chosen as the constraint function, aiming to keep it below the yield stress with a safety factor [20].

Design Variable Ranges: The ranges for these design variables were determined considering factors such as the desired design space, the topology optimization process, manufacturing constraints, and preliminary research findings.

Optimal results and comparison: To determine the optimal design for the rotary joint, a fitness function considering moment reaction and a constraint function for stress were established. A hybrid optimization algorithm, combining Adaptive Neuro-Fuzzy Inference System (ANFIS) with Water Cycle Algorithm

(WCA) and Moth-Flame Optimization (MFO), was implemented in MATLAB to find the optimal dimensions [21].

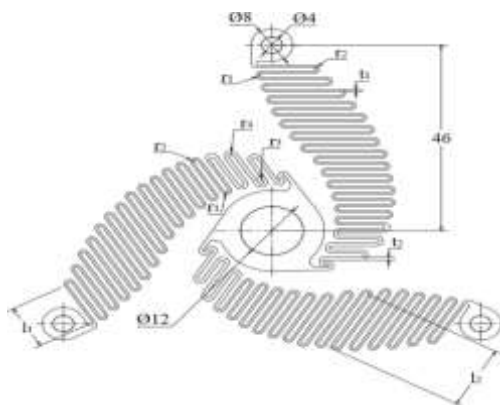


Figure : Final design schematic of rotary joint.

The WCMFO algorithm was configured with 50 raindrops, four rivers, one sea, a tolerance of 10^{-5} , and a maximum of 300 iterations. For comparison, ANFIS-based WCA and ANFIS-based Differential Evolution (DE) were also employed. To ensure reliability, each algorithm was run 30 times [22].

A post-hoc statistical analysis was conducted to compare the performance of these methods. The results in Table 11 indicate that the proposed hybrid method yielded the highest average value for the objective function (478,758) and the lowest standard deviation (22,837), suggesting superior performance and stability compared to [24] ANFIS-WCA and ANFIS-DE. This implies that the proposed method effectively converges to the optimal solution, outperforming the other two methods [23].

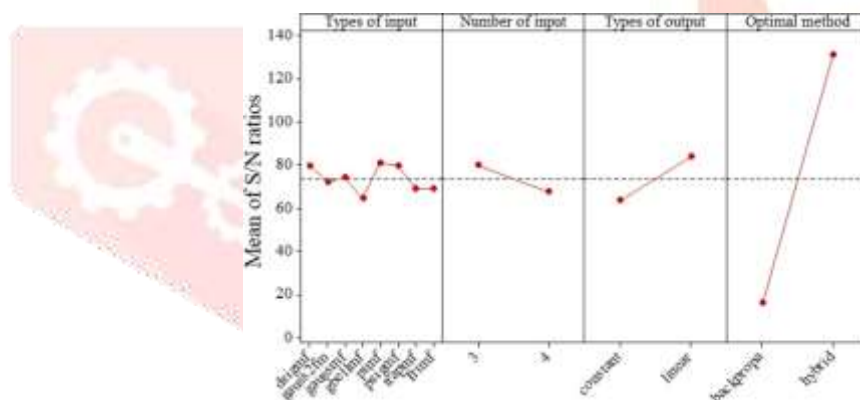


Figure : The S/N ratios value of the RSME for equivalent stress.

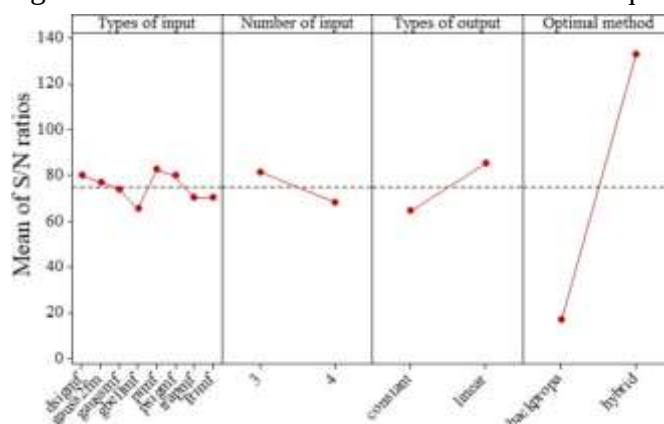


Figure : The S/N ratios value of the RSME for moment reaction.

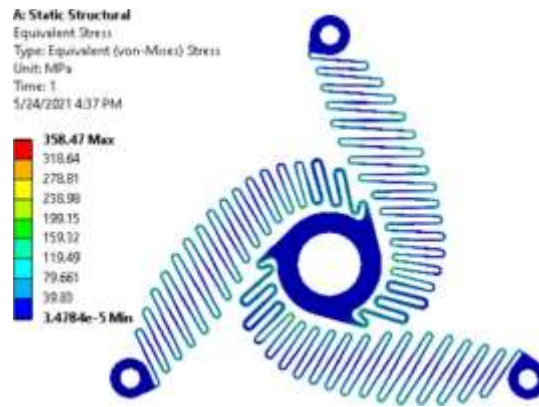


Figure : Distribution of equivalent stress of the optimal rotary joint.

Table 1: Comparison between Prediction and simulation

Optimal Prediction		FEM		Error %	
Moment reaction (N mm)	Equivalent stress (MPa)	Moment reaction (N mm)	Equivalent stress (MPa)	Moment reaction (N mm)	Equivalent stress (MPa)
358.46	489.99	358.48	487.22	0.29	0.58

V. Conclusion:

This research presents a novel hybrid optimization technique for designing rotary joints. The process involves three stages: Topology Optimization: Initial design shapes were determined using the SIMP-based CO method. Surrogate Modeling: ANFIS models, optimized using the Taguchi method, were created to predict the joint's performance. Geometric Optimization: The WCMFO algorithm was employed to refine the joint's dimensions, considering both structural strength and weight. The optimized design yielded a rotary joint with a radius of 0.8 mm, thicknesses of 0.5 mm and 0.8 mm, and lengths of 10.5 mm and 14.5 mm. This design outperformed those obtained using ANFIS-based WCA and DE algorithms, with minimal prediction errors of 0.28% for moment reaction and 0.57% for equivalent stress. Future work will involve physical prototyping using wire electrical discharge machining and experimental validation. The optimized rotary joint will be integrated into robotic arms for real-world applications.

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