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Generative Design as a Design Exploration Method for Rocker-Bogie Mechanism

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ABSTRACT
The paper presents the work carried out in exploring design alternatives and finding an optimal solution for the design of Rocker link done using Conventional Design methods. A thorough literature review of the mechanism has been carried out, followed by the design of the mechanism. Various computations are made in relation to the linkages and based on the calculations, a model has been designed in Fusion 360, and structural analysis is carried out in Ansys to determine the strength and the factor of safety of the links with respect to the load acting on them.The same mechanism has been redesigned using Generative Design without compromising the strength and safety of the mechanism. Furthermore, analysis has been carried out. The analysis and the prototype results of both the designs are compared.
***Keywords*–**Generative Design, Design Exploration, Rocker-Bogie Mechanism

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I. INTRODUCTION

Over the past decade, the rocker-bogie suspension design has become a proven mobility application known for its superior vehicle stability and obstacle-climbing capability. [1]A rocker-bogie mechanism is a type of suspension system commonly used in mobile robots and vehicles. It has no springs and stub axles for each wheel allowing the rover to climb over obstacles, such as rocks that are up to twice the wheel's diameter in size while keeping all six wheels on the ground.

The design of this suspension mechanism was first initiated by NASA as part of their Mars rover Sojourner in 1988, and has ever since then been their favored design for rovers. Furthering to this initiation, the mechanism has been incorporated in 2003 Mars Exploration Rover mission robots Spirit and Opportunity, on the 2012 Mars Science Laboratory (MSL) mission's rover Curiosity and the Mars 2020 rover Perseverance.

1.1 Parts of mechanism

1.1.1 Rocker

The "rocker" part of the suspension comes from the rocking aspect of the larger, body-mounted linkage on each side of the rover. These rockers are connected to each other and the vehicle chassis through a differential. Relative to the chassis, the rockers will rotate in opposite directions to maintain approximately equal wheel contact. The chassis maintains the average pitch angle of both rockers. One end of a rocker is fitted with a drive wheel, and the other end is pivoted to the bogie.

1.1.2 Bogie

The "bogie" part of the suspension refers to the smaller linkage that pivots to the rocker in the middle and which has a drive wheel at each end. Bogies were commonly used as load wheels in the tracks of army tanks as idlers distributing the load over the terrain, and were also quite commonly used in trailers of semi-trailer trucks. Both tanks and semi-trailers now prefer trailing arm suspensions.

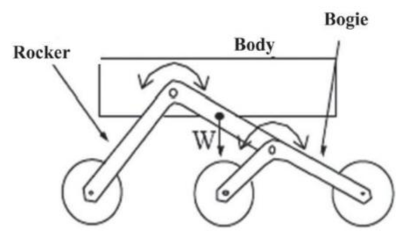


Fig.1: Rocker-Bogie Mechanism and its motile joints

1.2 Methodology

This paper presents a study on the application of Generative Design in Design Exploration and Design Optimization processes. The study has been carried out on Rocker link. The design phase has been carried out under two phases, namely:

- Conventional Design
- Generative Design

Section 2 covers the Conventional Design aspect, where the dimensions for the Rocker link has been illustrated along with the 3D design of the link, followed by the analysis of the part to check for a certain load condition.

Section 3 covers the phase of Generative Design which includes the study set-up process and the design generation, followed by the analysis of the newly-generated design under load conditions like that used in Conventional Design phase.

II. CONVENTIONAL DESIGN

2.1 Design Calculations and CAD Model

The important factor in the design of rocker bogie mechanism is to determine the dimensions of Rocker and Bogie linkages, and the angle between them. The lengths and angles of the mechanism can be changed as per requirement [2].

The dimensional calculations were done with the wheelbase (the distance between the foremost and the rearmost wheels) fixed to 360mm, and the angles of the linkages set to 90°. All the dimensions were further calculated using Pythagoras theorem, and the same have been shown in Fig. 2. The links were then modelled on Autodesk Fusion 360.

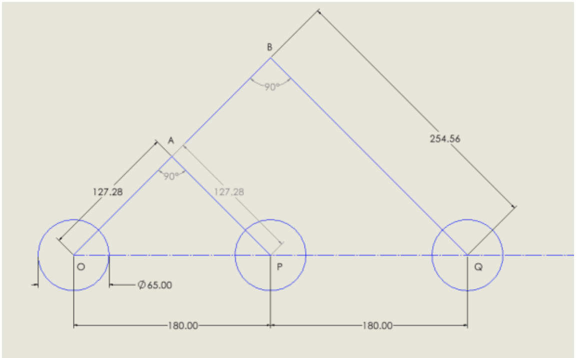


Fig. 2: Design Dimensions of Mechanism

Fig. 3: 3D View of Rocker Link - Conventional Design

2.2 Analysis

Static Structural Analysis has been carried out to understand the performance of the part under steadily applied loads.

The Rocker links are connected to the main chassis. At part-level, the forces that act on the link are the reaction forces and forces due to surface irregularities. The forces due to surface irregularities have been neglected in this case study; the reaction forces are the weight of the vehicle acting upwards and transmitted through the arms of the links. The weight of the rover (including payload) is assumed to be 150N, which gets divided in the arms of the Rocker and Bogie links based on the linkage angles.

The distribution of the force in the rocker arms has been depicted in Fig. 4 The forces have been calculated using Analytical method through the methods of Equilibrium, and the same have been verified for correlation with Simulation results by performing a Static Structural Analysis run on the part in Solidworks Simulation. 2-D simplification of the model was used, since the problem involved finding the forces only in two directions. Fig. 5 shows the forces calculated through Simulation method.

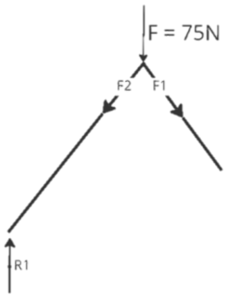


Fig. 4: Distribution of Force in Rocker Link

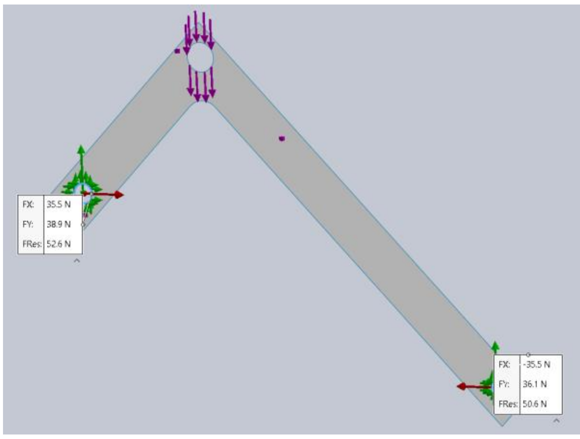
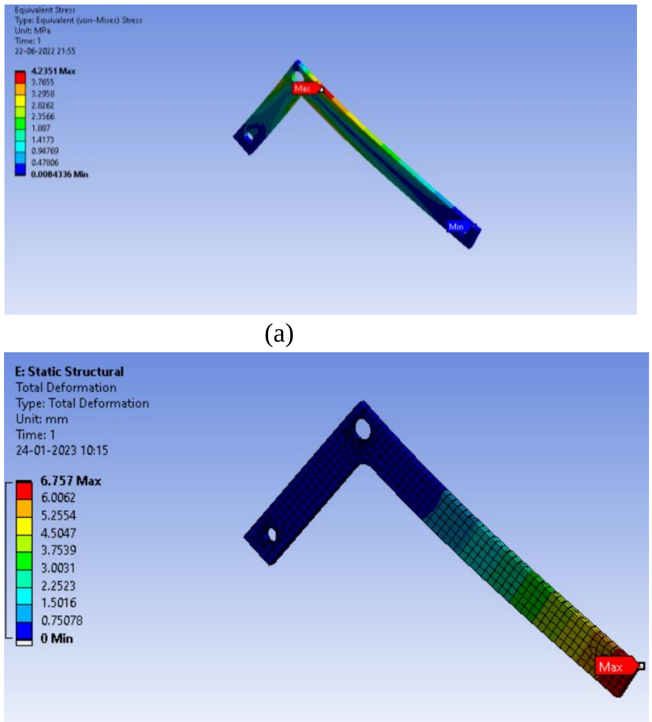


Fig. 5: Reaction Forces calculated using Solidworks Simulation

Table 1 indicates the forces in the Rocker arms and the reaction force at rocker-wheel mounting point. With the analytical calculation-based forces and a fixed support at the Rocker to Chassis mounting point, the maximum deformation and the von Mises stress are simulated. Table 2 shows the values of the Maximum and Minimum values of Deformation and von Mises Stress induced.

Table 1: Boundary Loading Conditions for Rocker Link

Force	**Magnitude (Analytical) (N)**	**Magnitude (Simulation) (N)**
F_1	53.04	52.6
F_2	53.04	50.6
R_1	37.5	36.1



(b)

Fig. 6: Rocker Link - (a) Stress (b) Deformation

Table 2: Analysis Results - Conventional Design

	Total Deformation (mm)	Equivalent Stress (MPa)
Maximum	6.757	4.23
Minimum	0	0.008

Consideration of Factor of Safety has been done with the consideration of various factors, such as:

- Material used.
- Manufacturing or Machining processes used.
- Application of the parts.

Table 3 indicates the general recommendations for the choices of Factor of Safety.

Table 3: Recommendations for Factor of Safety based on Applications

Applications	Factor of Safety
For use with highly reliable materials where loading and environmental conditions are not severe and where weight is an important consideration	1.3 - 1.5
For use with reliable materials where loading and environmental conditions are not severe	1.5 - 2
For use with ordinary materials where loading and environmental conditions are not severe	2 – 2.5
For use with less tried and for brittle materials where loading and environmental conditions are not severe	2.5 - 3
For use with materials where properties are not reliable and where loading and environmental conditions are not severe, or where reliable materials are used under difficult and environmental conditions	3 - 4

Considering a Factor of Safety of 4,

$$Allowable\ Stress\ = \frac{Tensile\ \ Stress}{FOS} \qquad (1)$$

$$Allowable\ Stress\ = \frac{44.81}{4}\ =\ 11.2\ MPa$$

$$Induced\ Stress\ \leq\ Allowable\ Stress$$

Hence, the design is safe.

III. GENERATIVE DESIGN

Generative Design is a design-exploration tool. Unlike Topology Optimization, which requires a design input which provides to be a starting point for the material reduction process, Generative Design creates lots of designs in an evolutionary way. Topology Optimization is useful when we have a fixed design set space and the primary aim is to make it lightweight; whereas, Generative Design is useful when the aim is to explore multiple design alternatives for a design idea, where one wants to explore designs which might be outside of the traditional design thinking of individuals.

3.1 Setting Up the Study

The study set-up is a very crucial process; the inputs provided to the algorithm during the set-up are what drives the entire Design Exploration study.

Preserve Geometry:

Being one of the geometry types in the Design space, preserve geometry feature can be used to assign and identify bodies which are to be incorporated as-it-is in the final design. These bodies (or sections) mostly include sections that are essential for the performance and functionality of the designs.

Any loads and constraints should be applied to the preserve geometry. It assures that the design is appropriate for its intended environment. Fig. 7 indicates the regions to be preserved in the final design, since these regions are the primary connecting regions with Bogie Link and the main chassis body.

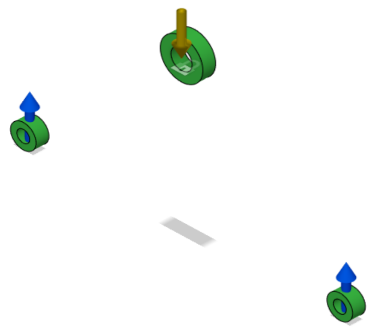


Fig. 7: Preserve Geometry Set-Up

Obstacle Geometry:

Obstacle Geometry feature can be used to identify regions of the design where material should not be added during the generation of design alternatives. This feature is very essential in defining regions of connection points, such as holes for bolts. Fig. 8 depicts the regions of the design marked for

Obstacle Geometry, since these obstacle areas create material-free areas for locating bolts during the assembly of rocker and bogie links, and rocker link and chassis.

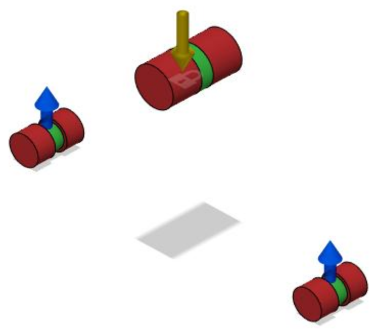


Fig.8: Obstacle Geometry set-up

Choice of Materials and Manufacturing Methods:

The Generative Design algorithm allows for the input of materials and manufacturing methods as additional inputs in the study setup.

Multiple Materials and Manufacturing methods can be chosen. The algorithm generates a set of design results that are best suited for the relevant material and manufacturing method for each material and method specified. Choosing "Unrestricted" as the manufacturing method will generate a set of outcomes that are not structurally constrained for any manufacturing method. Unrestricted choice is highly recommended during the early stages of design process to explore various design alternative concepts and multiple prototyping methods.

With the idea of Rapid Prototyping the design by means of Additive Manufacturing (Fused Deposition Modelling), PLA and ABS were provided as the materials input to the algorithm. For the manufacturing methods, Additive Manufacturing was the chosen option in addition to the "Unrestricted" choice (due to the reasons suggested as before).

3.2 Study Outcomes

The Generative Design Algorithm differentiates between two types of solutions: "completed" and "converged." The "completed" outcomes refer to those that did not meet the design requirement set up initially or failed to generate a fully converged result through optimization. Even though these results are provided to the user, caution should be exercised when considering them as they might not be suitable for the intended application.

The algorithm presents the design data in various modes – with each mode depicting the required information in different ways. The designer is free to switch between the modes to ultimately make a careful decision on choosing the desired alternative. Fig. 9 depicts the different outcomes generated for the study.

The Pictorial Representation helps the designer to identify visual changes in the form (shape) of the design. This plays an important role in choosing designs where aesthetics has utmost importance.

The Graphical Representation is used primarily to graphically identify the key differences between the different design outcomes in terms of various properties of the design structure such as – Minimum Factor of Safety, Mass, Maximum Stress Induced, etc.

Table 4 further indicates the properties of the various design outcomes generated during the study. "Recommendation" indicates the recommendation of the design outcome given by the AI algorithm, based on all the previous iterations the outcome has undergone, and the developments over the various iterations.

(a)

(b)

Fig. 9: Various Outcomes Generated (a) Pictorial Representation (b) Graphical Representation

Table 4: Properties of Different Outcomes

Name	Recommendation	Material	Manufacturing method	Mass (kg)	Max von Mises stress (MPa)	Min factor of safety	Max displacement global (mm)
Outcome 1	73.15	PLA	Unrestricted	0.0298	3.159	8.358	1.591
Outcome 3	38.89	PLA	Additive	0.0302	3.247	8.131	1.769
Outcome 5	37.65	PLA	Additive	0.0301	3.335	7.915	1.816
Outcome 6	41.18	PLA	Additive	0.0301	3.367	7.842	1.712
Outcome 8	61.87	ABS Plastic	Unrestricted	0.0276	3.051	6.556	2.143
Outcome 9	35.64	ABS Plastic	Additive	0.0270	3.179	6.292	2.213
Outcome 10	36.56	ABS Plastic	Additive	0.0257	3.310	6.042	2.262
Outcome 11	39.51	ABS Plastic	Additive	0.0257	3.792	5.275	2.774
Outcome 14	37.23	ABS Plastic	Additive	0.0268	3.552	5.630	2.645

Fig. 10 shows the method of enhancement of design outcome over various iterations. Based upon the design study inputs, the algorithm tries to improve the pattern of material direction and the shape of the design at every iteration, so that the maximum stress generated and the maximum displacement the part undergoes is always lesser than or equal to the previous iteration.

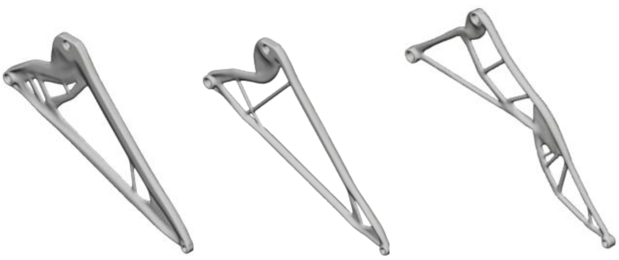


Fig. 10: Development of Design over iterations

Based on comparison decision taken from among the Pictorial Representation, Graphical Representation and the Tabular Outcome, Outcome 1 was chosen as the design choice for the study. To keep the design safe, considering fabrication errors, the design outcome was further processed with some material added which contributed to the rigidity of the part against bending load acting. Fig. 11 depicts the final design of the Rocker Link.

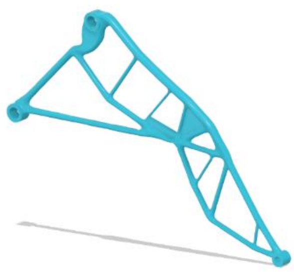
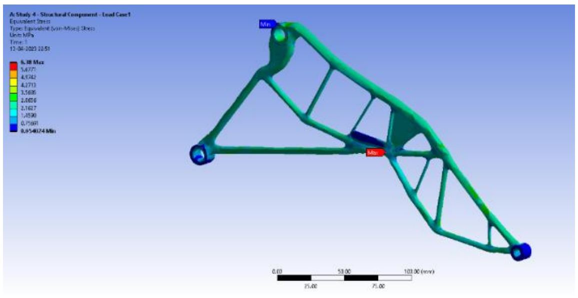
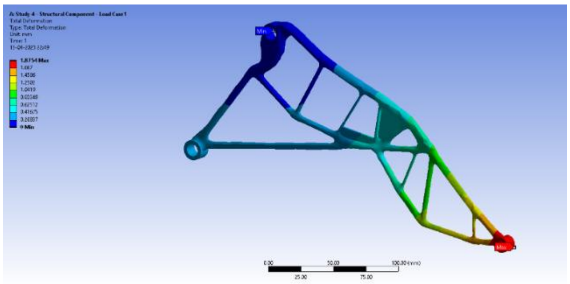


Fig. 11: Design Outcome for Rocker Link

With the same boundary conditions as from Section 2.2, static structural analysis was carried out on the redesigned Rocker link to check for the maximum displacement and von mises stress. Table 5 lists the maximum and minimum values of the displacement the part undergoes and the stress induced.



(a)



(b)

Fig. 12: Redesigned Rocker Link - (a) Stress (b) Deformation

Table 5: Analysis Results - Generative Design

	Total Deformation (mm)	Equivalent Stress (MPa)
Maximum	1.8754	6.38
Minimum	0	0.054

IV. TEST RESULTS

The designs through conventional and generative design methods were prototyped to verify the designs practically and provide a comparison on weight reduction. Table 6 indicates the weights of both the parts. Upon prototyping the designs by means of Fused Deposition Modelling, the optimized design was found to weigh 61% lesser than the original design.

Table 6: Comparison of Weights of Parts

	Standard Design	**Generative Design**
Rocker Link	84.62 g	33 g (**61.002% reduction**)

Table 7 indicates the comparison of Structural analysis results of the two designs.

Table 7: Comparison of Results of Structural Analysis

		Von-Mises Stress (MPa)	**Displacement (mm)**
Rocker Link	Standard Design	4.23	6.757
	Generative Design	6.38	1.8754

V. CONCLUSIONS

The primary aim was to redesign the rocker link, and optimize the weight of the same. The redesign of the links must be such that they have to be structurally safe, despite the reduction of weight. Several advantages of generative design over traditional design methodologies include:

- Design Exploration: Generative design allows designers to experiment with a wide range of design options.
- Optimization and Efficiency: Generative design methods can optimize designs based on certain performance parameters like as weight, strength, or material utilization.

Regardless of the ongoing development of structural optimization software tools, designers' experience will always be an important part of the design process. The ability to analyze design problems and discover driving elements that play a significant role in achieving a high-quality solution is indeed a human talent that the AI technologies cannot readily replicate. The outcomes of this study demonstrate that the capabilities provided by the AI framework enable the use of the considered tool in real-world circumstances. The optimization results are equivalent to the traditional tools currently routinely used in the design.

With the continuous advancement of the AI models and developing experience of designers with the models, they can be used to further optimize the designs of Rocker and Bogie links with the consideration of other dynamic loading factors those excluded in this study. This would lead to generation of much-improved designs which would solve the functionality with better results.

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