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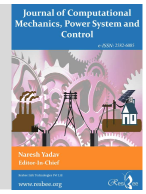

Cutting-Edge Generative Design Strategy for Transforming Robot Leg Dynamics in Autodesk Fusion 360

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Abstract: Generative design is an innovative and novel feature of Autodesk Fusion 360. This study delves into the innovative application of generative design strategies in Autodesk Fusion 360. Working on the generative design in the cloud is the built-in functionality of Fusion 360. As AI has become a common and compulsory tool in every search engine, the concept of generative design has also been included in software design to generate optimum design models. In this paper, four optimal outcomes of the generative design of leg-2 are discussed with tabular, pictorial, and graphical representations to evaluate factors such as stress distribution, mass reduction, and material selection. Leg-2 is the name given to a component of a glass cleaning robot, which is optimized by the generative design. This paper describes how a design is being created, limited by constraints (e.g., structural load), and optimized through multiple iterations. There are a total of four optimal case studies generated, for all four case studies and outcomes, mass vs. volume, mass vs. stress, and mass vs. displacement analyses are presented graphically to different materials provided by the author. The results of these case studies were found within the critical yield strength values of the respective materials, along with mass optimization through generative design analysis. Through graphical analyses and stress simulations, this study underscores the superiority of carbon fiber-reinforced plastic (CFRP) in terms of strength-to-weight ratio, stress resistance, and displacement characteristics. CFRP has emerged as the preferred choice for enhancing the longevity and efficiency of robot leg components.

Keywords: Parametric Modeling, Generative Design Analysis, Autodesk Fusion 360, Novel, CAD/CAM – Computer Aided Design And Computeraided Manufacturing.

Nomenclature:

Abbreviation	Description
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CFRP	Carbon Fiber Reinforced Plastic
FEA	Finite Element Analysis
AI	Artificial Intelligence
MP a	Megapascal
USD	United States Dollar
ML	Machine Learning

1. Introduction

In the fast-paced landscape of modern engineering, the quest for innovation and efficiency drives researchers and engineers to seek novel solutions to complex challenges. One such challenge lies in the design optimization of robotic components, particularly in the realm of high-rise infrastructure maintenance. As the demand for automation in tasks like window cleaning for skyscrapers grows, so does the need for complex robotic systems capable of navigating challenging environments[19]. However, traditional design approaches often struggle to strike the delicate balance between structural integrity, performance optimization, and manufacturing feasibility. These limitations underscore the necessity for advanced design methodologies that can tackle the intricate dynamics of robotic systems while delivering tangible benefits in terms of efficiency and reliability[16].

Using Fusion 360, versatile CAD/CAM software that offers parametric modeling, integrated CAM, and Generative design-like features synchronously. With collaborative workflows, cost efficiency, and rapid design iteration speed, preferred fusion 360[1].

Generative design is data-driven AI technology that explores a wide range of design possibilities, offering solutions that may not be apparent through manual design processes. In today's fast-paced

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world, this significantly accelerates the design iteration process. Generative AI provides a competitive edge by enabling companies to produce innovative, cost-effective, and high-performance products. Generative AI has optimized designs not only for performance but also for manufacturability [2]. Autodesk has developed this generative design feature in their software tool called Fusion 360. In this way, the generation of design can be initiated either by sketching the conceptual design or by providing the existing design of the product. Three design regions of the product must be specified in this software. One is an obstacle region, which refers to a specific area or volume within the design where the user wants to restrict the generation of the geometry. These obstacle regions are used to prevent the generative design algorithm from creating a geometry within these areas. This is shown in red [13]. The second is a preserved region. The region that the user does not want to alter is essentially the opposite of an "obstacle region," which restricts the generation of geometry in a particular area [12]. Third is the Starting region where the designer wants to generate new optimized designs through generative design[3].Another important specification that is required is study materials (i.e., different materials selected for manufacturing products, generative design is altered according to the type and properties of the material), desired manufacturing criteria, structural constraints, structural loads, cost estimation, and a minimum factor of safety. All the other specifications are explained in the methodology section, as shown in Fig.1.This software tool includes various objectives such as mass reduction and improved stiffness in the generated outcomes. In the objective of mass reduction, fusion tries to reduce mass as much as possible and wants to maintain the maximum desired strength and stiffness [4].

The main contributions of this study are as follows:

- Understanding the uniqueness and effectiveness of the generative design approach for optimizing designs and use of generative design in Fusion 360[1].
- Understanding the process of generative design, including 2D drawing, 3D designs, generative design (all constraints and specifications), rendering, simulation, and manufacturing cost estimation methods in Autodesk Fusion 360.
- The procedure is carried out by generative design features to generate outcomes from this generative tool[13].
- Analysis and study of generated outcomes using pictorial, graphical, and tabular data representations through the results and conclusion from this study [5].

This approach facilitates the creation of optimized designs that strike a balance between performance, manufacturability, and cost-effectiveness. The key result of this research is the demonstration of the effectiveness of generative design in producing optimal solutions for robot leg dynamics, as evidenced by the improved structural integrity, weight reduction, and material efficiency achieved in the case studies as discussed in the result and discussion section [15]. Through the systematic approach, the way for advancements in the field of robotic design is done, offering a glimpse into the future of automated engineering optimization [14].

The paper is divided into 4 sections in which 1st section is the introduction of the problem statement and the solution. 2nd section is the methodology section containing the procedure followed bythe author to reach the result or conclusion. 3rd section is the result and discussion, comparative evaluations of design outcomes which discusses the result in tabular, graphical, and pictorial form in detail and the last section i.e. 4th concludes the paper with a summary of the key findings.

2. Literature review

Various methodologies have been developed for optimizing robotic design, including topology optimization, FEA, evolutionary algorithms, parametric optimization, ML techniques, multi-objective optimization, topology morphing, and additive manufacturing optimization [20]. Each method offers unique advantages, such as lightweight designs and detailed structural analysis. However, challenges such as computational intensity and expertise requirements persist, indicating the need for further research to develop more efficient and accessible optimization approaches for robotic design. The different methodologies and their advantages and disadvantages are listed in Table 1[18].

2.1 Review Table

Table 1. *Advantages and disadvantages of different methodologies[19]*

Methodology	Advantages	Disadvantages
Topology Optimization	Facilitates lightweight designs	Demands high computational resources
Finite Element Analysis	Provides detailed structural analysis	Requires proficiency in FEA software
Evolutionary Algorithms	Allows exploration of vast design space	Convergence may be slow
Parametric Optimization	Facilitates systematic exploration of parameters	Limited by predefined parameter ranges
Machine Learning	Capable of learning complex patterns	Demands large training datasets
Multi-Objective Optimization	Considers competing objectives	Complex to handle multiple objectives
Topology Morphing	Enables exploration of alternative designs	Constrained by initial design limitations
Additive Manufacturing	Offers design freedom for complex geometries	Constrained by material and process limitations.

2.2 Research Gap

Existing methodologies, such as topology optimization and FEA offer detailed structural analysis but require high computational resources and expertise. Evolutionary algorithms allow for the exploration of a vast design space. However, they often suffer from slow convergence. Parametric optimization enables systematic exploration but is constrained by predefined parameter ranges. Although ML is capable of learning complex patterns, it requires large training datasets. Similarly, topology morphing allows for alternative design exploration but is limited by the initial design constraints [16].

The problems identified in these existing methods include computational intensity, expertise requirements, and constrained design exploration capabilities. Therefore, there is a pressing need for more efficient and accessible optimization approaches in robotic design to overcome these challenges and provide comprehensive solutions.

3. Methodology

3.1 Procedure of Generative Design and Analysis

The design process for a product starts from a problem statement or loophole to idea generalization, conceptualization, visualization, and imagining how a product will look. How will it work: Once the design is visualized and conceptually verified by the designer or developer. The design needs to be sketched out in the software, and the prototype of the developed design goes through simulation, in which real environmental conditions are created in which it will be working in the future. Fig 1 shows the diagrammatical representation of the procedure in the toolbar of generative design.

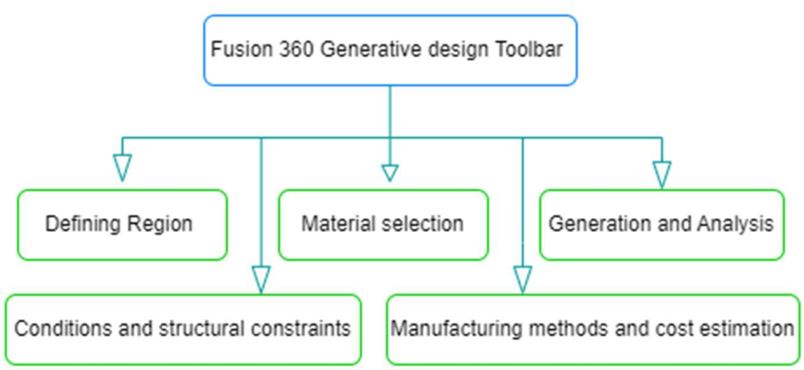

Fig. 1. *Procedure in the toolbar of generative design*

After obtaining various outcomes in terms of stress retention, generated volume, mass, max displacement global, piece part cost, the strength of the product, and reliability of the product. Based on these results an optimized design is selected, produced, and launched in the market. That is explained in Fig 2.

The process is categorized and divided into three stages: early, medieval, and end-stage (Fig 3).In the Early stage, imagination, idea generation, and conceptualization were included. In the medieval stage, work on design. It starts with sketching the prototype, 3D modeling, and generating designs for real-life environmental conditions. In the End stage, the optimal outcome out of multiple designs is selected based on optimization and analysis [6].

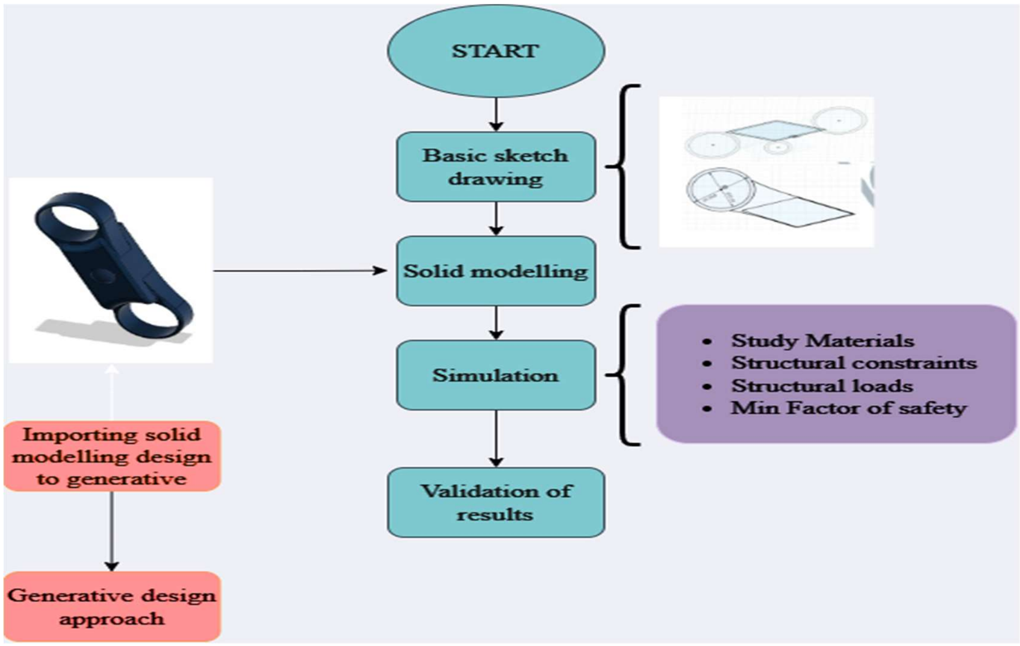

Fig. 2. *Traditional design Approach*

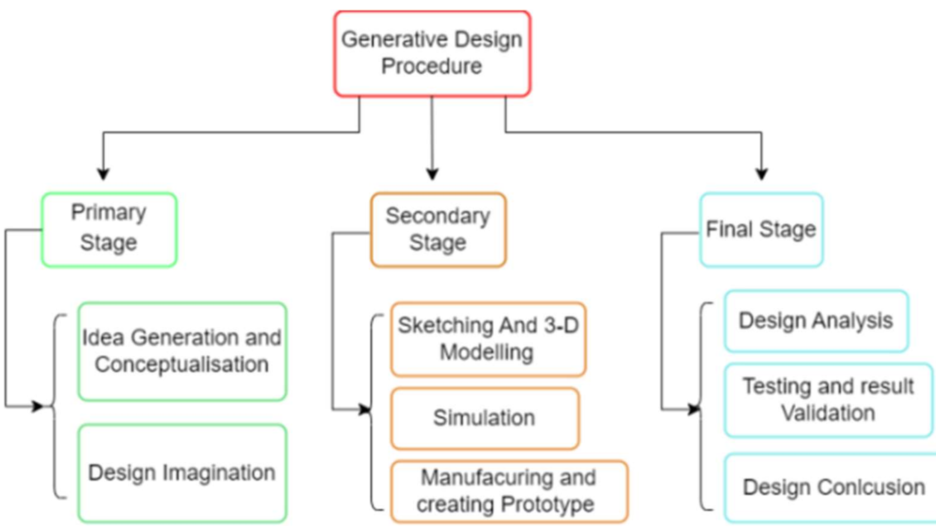

Fig. 3. *Process for Generative Design*

3.2 Applying the Generative Design in Leg_2part

The image shown in Fig. 5 shows the initial design of the component that will be used for the generative design process and analysis in this study. This component in the design is part of the main design of the glass cleaning robot for high-rise buildings as in Fig. 5.

Fig. 5. *Design of the component*

Fig. 6, represents a picture of a glass cleaning robot designed by the 2nd author of this paper which can be used to clean the outer glasses of high-rise glass buildings of height to500 meters, it also acquires the capability of overcoming the obstacles of height till 15-25 cm and can carry 10 liters of cleaning liquid.

Fig. 6. *Part of thedesign of glass cleaning robots for high-rise buildings*

3.3 Generative Design Defining Procedure

The generative design process includes importing the design into the fusion software and then performing a generative design function from the design button display. The user must provide multiple conditions and constraints before generating the design's function, During the process of generative design, First the preserved geometry of the design is selected, which on selecting the preserved geometry turns the portion of the component into a green color as shown in Fig. 7.

Fig. 7. *Preserve geometry.*

The preserved geometry parts are not modified in the generative design process, they remain as it is. Next, the starting shape is selected, which is the portion of the design that needs to be optimized in terms of both mass and volume, such that it can hold the given pressure while maintaining its structure. After selecting the starting shape for some portion of the design, it turns yellow as shown in Fig. 8.

Fig. 8. *Starting Shape*

Next, the structural load is selected, which is the load that the component needs to sustain. For this component, the top cylinder ring is connected to the main design, and the bottom one is connected to the remaining part (leg) of the component. Thus, the load is exerted on them in a downward direction, as shown in Fig. 9 in the blue array in the upward direction. A load of 800 newtons (80 kg) was applied to the component. Structural loads can only be provided in selected preserved geometry. A gravity of 9.8 m/s^2 is also applied to the design in the downward direction to develop generative designs according to the real-time situations/gravity. Next, structural constraints are selected to prevent movement in the selected directions. By default, all the three global directions were constrained. For static simulations, all rigid body motions must be prevented, such as free translational and rotational movements, to make the model statically stable. The rhombus and middle cylinder are selected as structural constraints, as shown in Fig. 10, to ensure stability and permanence in the design. A lock sign can be seen on structural constraints. Next the objectives for the generative design are required to be selected, here one objective is to minimize mass and the second is to provide a limit[7].

Fig. 9. *Structural load*

In the limit target, the Safety factor (n) is selected as 2 (by selecting, it generates designs that can sustain/resist the magnitude/pressure of n (2) times applied on the part, that is, 800 n x 2 = 1600 N, two times the given magnitude). N is selected for the worst-case scenario so that the product can work under the worst conditions. To obtain the manufacturing cost of the product, users are provided to select the manufacturing criteria for the product along with the volume of production of parts per year. In this component, the unrestricted addictive (Orientation in Z+ with an overhang angle of 45 degrees and minimum thickness of 3 mm) and milling (tool direction in Z- with a minimum tool diameter of 10 mm, total shoulder length of 40 mm, and head diameter of 60 mm) manufacturing methods were considered, and the production volume was selected as 4[2].

Fig. 10. *Structural constraints*

Next, Materials are selected for generative design, which will provide us with generative designs to the provided materials as input, as different materials possess different physical properties. Steel, Stainless steel, Titanium, Aluminum, and CFRP (carbon fiber**)** were the materials that were selected for our component. After providing all the constraints, conditions, objectives, manufacturing, and material information, the toolbar is generated. Eighteen designs are available as the outcome of generative design. The generative design feature of Fusion 360 provides the user with the optimal four recommended outcomes by comparing all 18 outcomes in terms of cost, mass volume, material, manufacturing method, stress, and maximum displacement.

3.3.1 Generative Design Outcome

The Autodesk Fusion 360 software generates 18 outcomes, but it recommends 4 outcomes that are optimal in terms of mass, strength, cost, displacement, and material. Fusion provides the outcomes by comparing it in terms of volume mm^3, mass (in kg), max von Mises stress (MPa), the factor of safety limit and minimum safety, max displacement global (mm), material type, and it's cost in terms of minimum piece cost, maximum piece cost, piece cost median, minimum full cost, maximum full cost, full cost median. Also, it provides a recommendation percentage based on the comparisons of the outcomes based on above above-discussed factors[8].

This is the representation of the information of the four optimal recommended outcomes as in Table 2 in tabular form.

Table 2. *Recommended outcomes among all generative designs.*

Properties	**Outcome - 13**	**Outcome - 15**	**Outcome - 10**	**Outcome - 7**
Recommendation (%)	88.258	84.204	83.399	82.279
Material	CFRP	CFRP	Titanium	Steel
Manufacturing method	Unrestricted	3 Axis milling	Unrestricted	Unrestricted
Volume (mm^3)	158,593.942	966,456.726	159,016.123	158,451.836
Mass (Kg)	0.227	1.382	0.717	1.244
Stress (MPa)	11.054	0.908	10.802	11.17
Max Displacement (mm)	0.032	0.001	0.041	0.021

Through the four recommended outcomes as in Table 2, outcome 7 was of minimum recommendation of 82.279 of material type steel, and outcome 13 with maximum recommendation percentage of 88.258 of material type CFRP. Manufacturing methods suggested for outcomes are Unrestricted and 3-axis milling. Here CFRP is carbon fiber reinforced plastic, it provides a high strength-to-weight ratio and corrosion resistance, making it ideal for lightweight structures and aerospace applications. Table 3 gives a brief description of the four recommended outcomes.

Table 3. *Brief description of outcomes 15, 10, 13 and 7.*

Properties	Outcome - 15	Outcome - 10	Outcome - 13	Outcome - 7
Status	Completed	Converged	Converged	Converged
Generative model	Model 1	Model 1	Model 3	Model 3
Material	CFRP	Titanium	CFRP	Steel
Orientation	Z	-	-	-
Manufacturing method	3 Axis milling	unrestricted	unrestricted	unrestricted
Visual similarity	Group 1	Group 3	Group 3	Group 3
Production volume (pcs.)	4	4	4	4
Piece part cost				
Range (USD)	-	-	1,252-2,365	-
Median (USD)	-	-	1,555	-
Fully burdened cost				
Range (USD)	-	-	1,252-2,365	-
Median (USD)	-	-	1,555	-
Volume (mm3)	966,456.726	159,016.123	158,593.942	158,451.836
Mass (kg)	1.382	0.717	0.227	1.244
Max von mises stress (MP a)	0.908	10.802	11.054	11.17
Factor of safety limit	2	2	2	2
Min factor of safety	330.452	25.514	27.139	18.531
Max displacement global (mm)	0.001	0.041	0.032	0.021

The generative design process is described below as in Fig. 11 with multiple iterations which are processed during the process of the Generative design feature of Fusion 360.

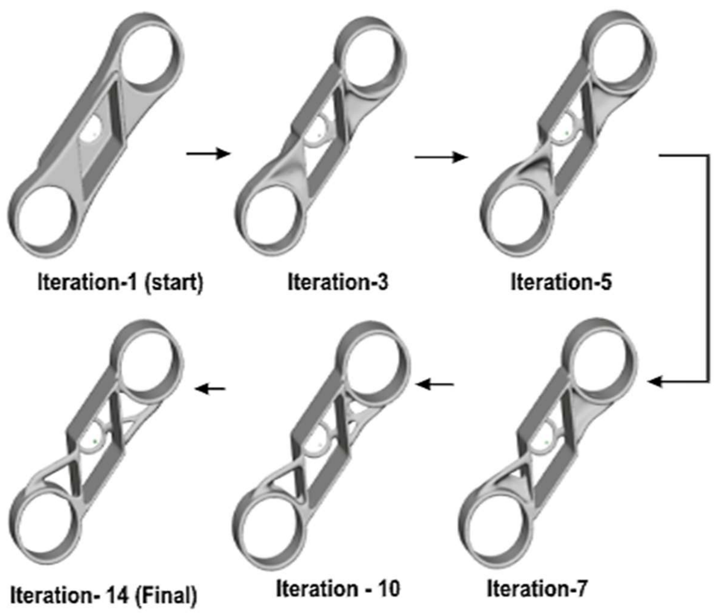

Fig. 11: *Shows how a design is reduced to mass without affecting its strength.*

In Fig. 11, multiple iterations are shown, Iteration 1 shows the given design, and Iteration 14 shows the final design which is the most optimized one to mass and has the least problems among the others. The Changes can be observed in the rest of the generated iterations.

4. Result and Discussion

4.1 Stress Analysis

Fusion generates a stress analysis graph of the optimal four outcomes. There is a strip at the right side that shows the color representation of red as high stress, green as ideal stress, and blue as low stress[9]. From Fig. 12, it can be concluded that out of all outcomes are best in terms of retaining stress as all are shown in blue which denotes low-stress levels.

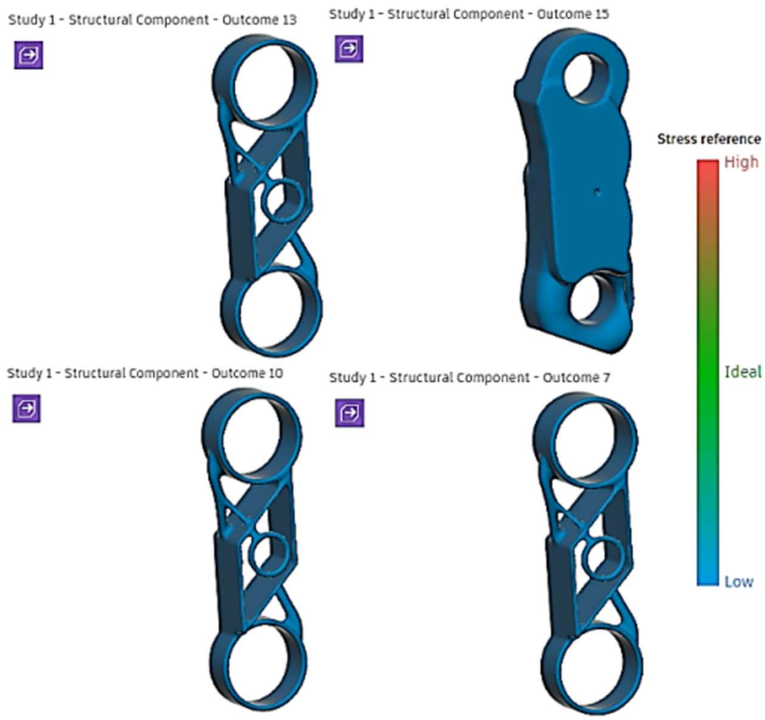

Fig. 12. *Stress analysis of the four recommended outcomes*

4.2 Graphical Analysis

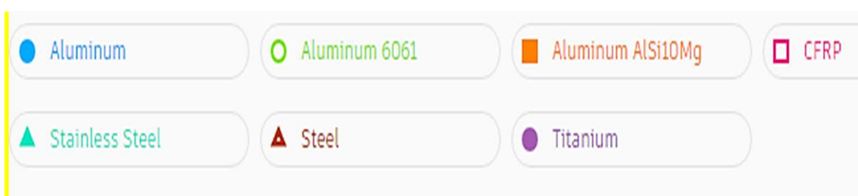

Fig. 13. *The chartshows the colored symbols representing different materials.*

The color coding shown in Fig. 13 shows the following:

- The blue circle denotes aluminum.
- The Parrot Green hollow circle denotes aluminum 6061.
- The Orange square denotes aluminum ALSi10Mg.
- Hollow Pink square denotes CFRP- i.e., Carbon Fiber
- The triangle in green denotes stainless steel.
- The Brown triangle denotes steel.
- The purple circle denotes Titanium.

Fig. 14, 15, and 16, show a graphical representation of the comparison of stress, volume, displacement versus mass for the differences that have been used. Fig. 14, shows the volume versus mass analysis which shows that CFRP is exceptional among them, linearity among the mass and volume of CRPF, titanium, and steel can easily be seen here. CFRP exhibits a significantly lower volume-to-mass ratio compared to titanium and steel, indicating its superior density and compactness. Fig. 15 shows the stress-holding capacity of each of the materials to mass in which CFRP is the best. CFRP demonstrates a remarkable ability to withstand substantial stress while maintaining its structural integrity, outperforming both titanium and steel in terms of maximum von Mises stress per unit mass. This exceptional strength-to-weight ratio enables the fabrication of lightweight components capable of enduring demanding mechanical loads[10]. Fig. 16, which shows displacement versus mass graphs, gives CFRP as the best among all other materials, CFRP offers a superior stiffness-to-weight ratio compared to titanium and steel, as evidenced by its lower maximum displacement per unit mass. This property ensures that CFRP components can resist deformation under significant loads, maintaining their shape and ensuring optimal performance[11]. Thus, CFRP surpasses titanium and steel in specific strength, stiffness-to-weight ratio, fatigue resistance, and design adaptability, enabling optimized performance and reduced weight. Fig 14, 15, and 16 show the graphs for different materials based on the optimal 4 recommended outcomes.

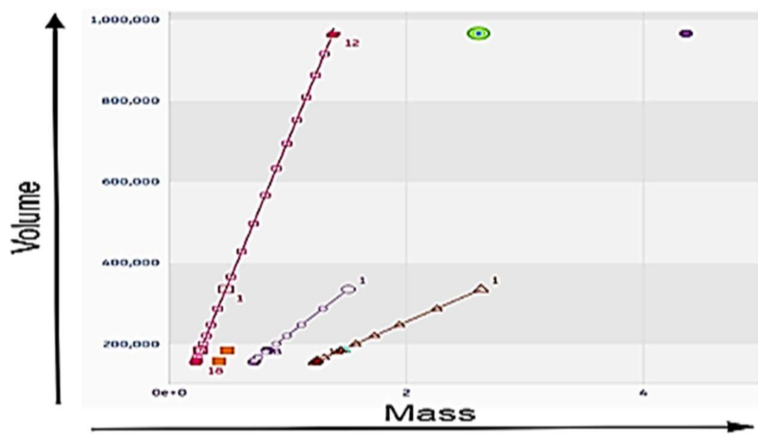

Fig. 14. *Volume versus mass graph*

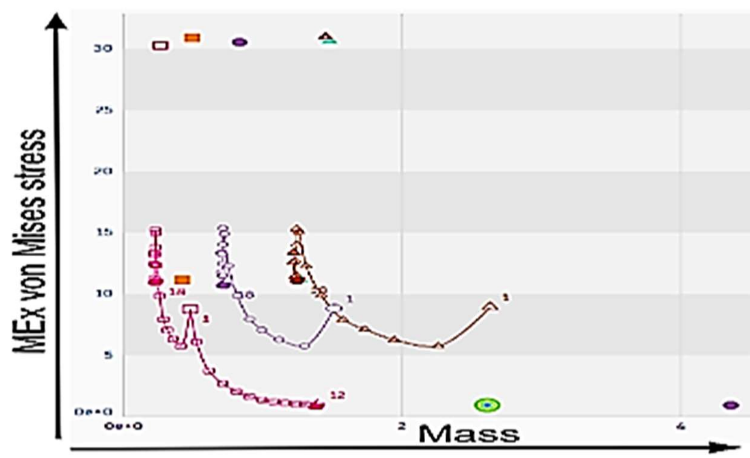

Fig. 15. *Mex von Mises stress versus mass graph*

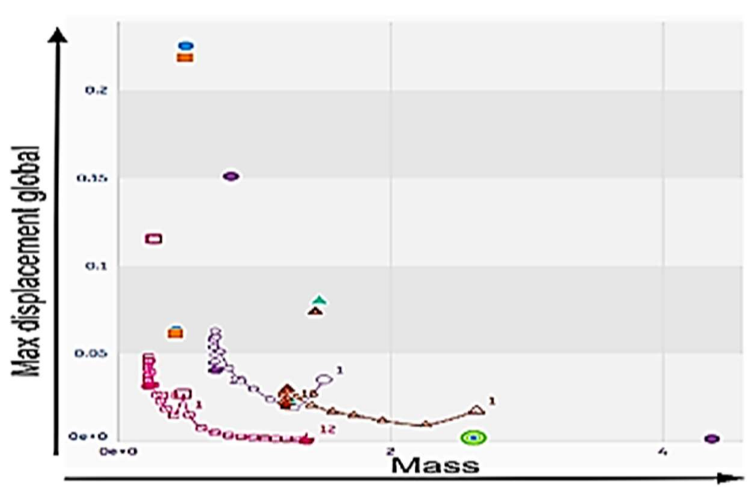

Fig. 16. *Max displacement global versus mass graph*

Finally, Table 4 describes the initial design of the leg_2 part, then the selected design generated by the generative design function of fusion 360 by reducing the design in terms of mass and volume, and the last row represents the stress analysis on the design by applying the stress of 80 newtons with gravity. The stress analysis design with low stress in all portions is achieved with corresponding mass reduction.

Table 4. *Overall generative design*

	Outcome-13
Initial design	
Selected Generative Design	
Stress Analysis Design	

5. Discussion

- Out of 18 generative designs for the leg part of the robot, 4 are recommended. Out of those four, outcome 13 was analyzed to be the design with the best performance.
- It is the design of CFRP material, its recommended percentage is 88.258 %. The design needs aminimum mass of 0.30 kg which is the minimum mass among the other outcomes.
- It also has a high stress-sustaining capacity of 30.25 MP a to other outcomes, it is the 2^{nd} best outcome in terms of stress. It has a Displacement of 0.032 mm.
- Outcome 13 will be the best in terms of performance and longevity and thus is the final selected outcome for our design.
- The method boasts a remarkable average reduction in mass of 76.5% across the recommended outcomes compared to the initial design. This substantial reduction in mass translates to enhanced agility and energy efficiency in robot movement which is crucial for tasks, such as high-rise window cleaning.
- The generative design approach results in a significant increase in structural integrity, with outcomes demonstrating an average stress reduction of 91.3% compared with the initial design, ensuring robust performance under various loads.
- The software's ability to consider various materials and manufacturing criteria enables the selection of materials with optimal properties, such as the preferred choice of CFRP because of its exceptional strength-to-weight ratio and stress resistance.
- This preference is underscored by the comparative analysis, revealing that CFRP outperforms alternative materials, such as steel and titanium, in terms of stress distribution, with an average stress level of 11.054 MPa, compared to 10.802 MPa for titanium and 11.17 MP a for steel.
- The graphical representations in Fusion 360 provide a holistic view of design performance and aid in decision-making. However, expertise in Fusion 360 and potential computational demands are the limitations. This study offers insights into engineering and robotics, showcasing the efficiency of generative design.
- By leveraging AI algorithms and simulations, it revolutionizes design processes across industries. Emphasizing material selection and structural optimization enhances functionality and longevity.
- In summary, the generative design of Fusion 360 optimizes robot leg dynamics, balancing performance, and cost-effectiveness, thereby driving innovation in automated engineering.

6. Advantages and Disadvantages

Some of the advantages of this method are as follows: generative design in Autodesk Fusion 360 accelerates design iterations, leading to the rapid exploration of optimized solutions. AI-driven algorithms unlock innovative designs by considering materials and manufacturing criteria for optimal performance. Graphical representation said decision-making, ensuring efficient and cost-effective designs.

Some of the disadvantages of this method are that it requires expertise in Fusion 360 and generative design principles. Computational demands may lead to longer processing times. The outcome accuracy depends on accurately defined constraints. The translation of designs into physical products may pose challenges. The selection of an optimal design based on multiple outcomes is complex.

7. Conclusion

This research underscores the transformative potential of generative design strategies within Autodesk Fusion 360 for optimizing robot leg dynamics. Through advanced AI technology, significant enhancements in performance, manufacturability, and cost-effectiveness have been achieved. These findings highlight the capacity of generative design to revolutionize conventional design methodologies in robotics. Future research avenues may include the exploration of multi-objective optimization techniques, advancements in material science, and the integration of real-time data analytics and machine learning algorithms. Overall, this study unveils promising prospects for innovation and advancement in automated engineering optimization [15].

Compliance with Ethical Standards

Conflicts of interest: Authors declared that they have no conflict of interest.

Human participants: The conducted research follows the ethical standards and the authors ensured that they have not conducted any studies with human participants or animals.

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