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Enhancing Hand Efficiency of Smart Glass Cleaning Robot through Generative Design Module

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***Abstract*—**This article explores the domain of generative design in order to enhance the development of robot designs for innovative and efficient maintenance approaches for tall buildings. This study aims to optimize the design of robotic hands by focusing on minimizing mass and volume while ensuring they can withstand the specified pressure with equal strength. The research procedure is structured and systematic. The purpose of optimization is to enhance the efficiency of the robot and reduce the manufacturing expenses. The project seeks to investigate the application of generative design in order to optimize products. Autodesk Fusion 360 offers the capability to immediately apply the generative design functionality to the solid model. The effort involved creating a solid model of the Smart Glass Cleaning Robot and optimizing one of its components, the Hand, using generative techniques. The article has thoroughly examined the designs, outcomes, and procedure. These loads serve as a benchmark for creating designs that can endure the necessary level of pressure and preserve their structural integrity. The efficacy of the generative design process is contingent upon the selection of materials, as different materials possess distinct physical attributes. The study utilizes five different materials, namely Steel, Stainless Steel, Titanium, Aluminum, and CFRP (Carbon Fiber Reinforced Polymer), in order to investigate a range of design possibilities.

***Keywords*—**Generative design, mass and volume optimization, material strength analysis, generative design, smart glass cleaning robot.

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I. INTRODUCTION

ALL skyscrapers serve as distinctive icons of metropolitan environments in contemporary architecture. These towering structures pose unique maintenance obstacles that require innovative solutions to maintain their effective and secure upkeep [1]. The study article investigates the use of a generative design tool and its application technique on a solid model, in order to find effective and novel maintenance strategies for tall buildings. The steps have been further elaborated in the same. The hand of the Smart Glass Cleaning Robot incorporates generative design to achieve optimal strength while maintaining its original functionality [16].

The cleaning of vertical surfaces on skyscrapers is essential for maintaining their aesthetic attractiveness and structural soundness. The creation of these robotic hands involved meticulous efforts to maximize efficiency in terms of size and weight, while also ensuring their ability to endure significant external forces without compromising their structural integrity. Preserved geometry is a crucial element of the generative design technique, serving as the initial choice to begin the systematic and structured research process. This surviving geometry consists of one cylinder and three cuboids, serving as the fundamental basis for all subsequent designs. Once chosen, these characteristics remain unchanged throughout the generative design process, serving as a standard for fostering creativity. Selecting the initial shape is a crucial stage in the process of optimizing mass and volume, and it is the subsequent step towards achieving an optimum design for a robotic hand. The design undergoes systematic testing to simulate the exact structural loads encountered during real-world high-rise glass cleaning operations.

The generative design process is driven by these structural loads to create robotic hands that can endure the necessary pressure without compromising their structural integrity [2]. In order to achieve mass and volume optimization, it is necessary to carefully choose the basic shape while designing a robotic hand [3]. To ensure a realistic representation of the stresses experienced during real-world high-rise glass cleaning operations, several components of the design undergo systematic testing under structural loads. The generative design method is directed by the structural stresses to produce robotic hands that can endure the required pressure while maintaining their structural integrity. The purpose of this introduction section is to establish a systematic examination of generative design and its application in improving the functionality of robotic hands for the maintenance of tall skyscrapers. This research offers the potential to facilitate innovative solutions for the intricate demands of maintaining vertical surfaces in skyscrapers. The primary objective is to achieve efficiency in terms of mass and volume, while also assuring structural integrity.

II. BRIEF DESCRIPTION

This study explores the application of generative design principles to enhance the performance and efficiency of robotic hands employed in high-rise glass cleaning robots. The research systematically utilizes key parameters to achieve optimization, ensuring these critical elements are carefully considered in the design process. The design shown in Fig. 1 is a Smart Glass Cleaning robot Hand part in which the study has been done. The optimization of hand led this design high strength with optimum mass of the body part. The procedure for applying Generative design has been discussed in this article. Using Autodesk Fusion 360 the result is generated and represented in the result analysis section in the article [4]. The analysis of generative design in many parts of glass cleaning robot has been explored in the past [16]. The details of generative design used in the present research are discussed in

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the ensuing sections.

A. Preserved Geometry: A Foundational Framework

The initial structure of the hand par is described in Fig. 1 and Fig. 2 shows how choosing preserved geometry is the first step in the process. One cylinder and three cuboids make up this basic framework; they were picked out as stable components that would not change during the generative design process as shown with green color. These structural elements are guaranteed to keep their original shape and configuration thanks to the principle of preserving geometry, providing a solid foundation for subsequent design iterations [5].

Fig. 1 Hand (Smart Glass Cleaning Robot)

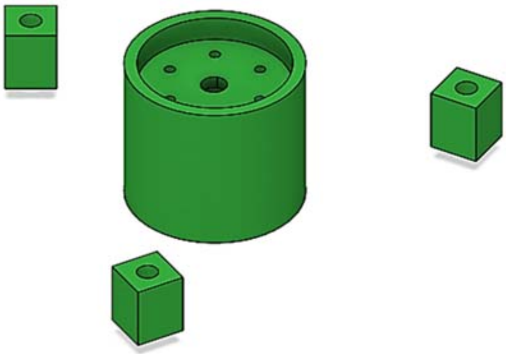


Fig. 2 Preserved Geometry

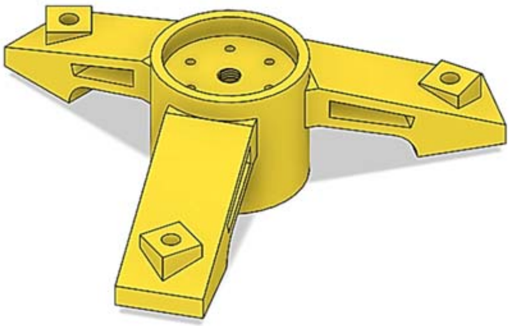


Fig. 3 Starting Shape

B. Starting Shape for Mass and Volume Optimization

After confirming that the geometry is preserved, focus shifts to choosing the initial shape, which is shown in Fig. 3 with yellow color. This selected shape represents the body to be optimized in terms of mass and volume while also ensuring that it can steadfastly withstand the specified pressures [6].

C. Structural Loads, Constraints, and Design Objectives

The central cylinder and the three cuboids located at the component's legs will strategically receive structural loads totaling 800 Newtons (80 kilograms) as part of this research is shown in Fig 4 as shown with blue color arrows in upward direction. Structural loads are provided only in selected preserve geometry. Gravity of 9.8 m/s^2 is also applied on the design in downwards direction, so as to develop the generative designs according to the real time situations/gravity. This simulation replicates actual pressures, serving as a fundamental guide for developing designs that can withstand specified pressure magnitudes without losing structural integrity. Additionally, the central cylinders are referred to as structural constraints, guaranteeing their permanent attachment to the leg and thereby effectively immobilizing particular design components as shown in Fig 5. Mass reduction and the incorporation of a 2-safety factor are among the design goals. The generated designs can withstand pressure magnitudes twice as great as the applied force thanks to the safety factor of 2, which improves reliability and safety [7], [8].

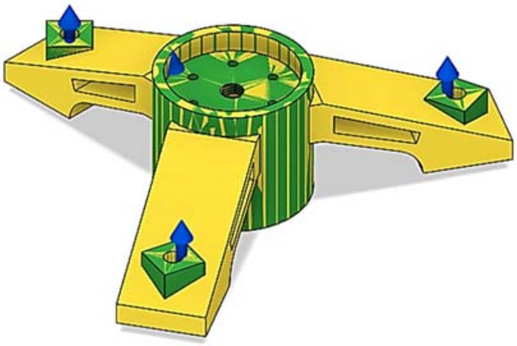


Fig. 4 Structural Load

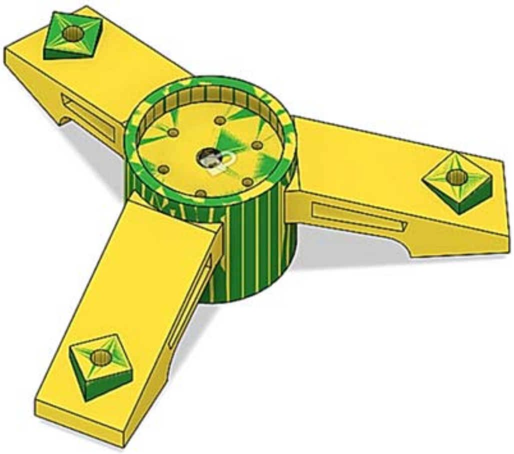


Fig. 5 Structural Constraint

D. Manufacturing and Material Considerations

Manufacturing considerations include cost estimation with a production volume of 4, as well as the investigation of different manufacturing processes, such as additive, milling, and unrestricted. The variety of materials used, including steel, stainless steel, titanium, aluminum, and CFRP, reflects the understanding of the distinctive physical characteristics linked to various materials.

III. RESULT AND DISCUSSION

A. Optimal Robotic Hand Designs for High-Rise Glass Cleaning: A Comprehensive Evaluation

The important task of choosing the best robotic hand designs for high-rise glass cleaning applications is explored in this research paper. The study makes use of generative design methodologies to create a pool of 18 original designs in the interest of effectiveness and dependability. The next step is to carefully assess these designs, with a particular focus on mass and volume reduction, stress-sustaining capability, and safety considerations [9], [10]. Through this method, the top four suggested designs are determined, each of which represents the apex of robotic hand engineering.

1. Mass and Volume Optimization

The evaluation focuses on mass and volume efficiency. The importance of minimizing weight and maximizing space utilization for high-rise glass cleaning tasks cannot be overstated. Carefully evaluating each design's capacity to achieve these goals, ensuring it meets stringent specifications for vertical surface maintenance [11].

2. Strength and Safety Assessment

Examining the designs for stress-sustaining ability and safety features simultaneously. These elements are essential for determining a design's capacity to withstand pressures encountered in the real world while maintaining structural integrity and guaranteeing the security of glass cleaning operations carried out at heights [12].

B. The Top Four Recommended Designs:

1.Outcome 13 - CFRP Excellence

Design outcome 13 stands out as a top option because it demonstrates exceptional mass and volume optimization along with a strong capacity to withstand stress and a high safety factor is shown in Fig. 7. This design, which is made of CFRP, strikes the perfect balance between strength and efficiency, making it a strong contender for high-rise glass cleaning.

2.Outcome 15 - Carbon Fiber Durability

With its carbon fiber construction, Outcome 15 dazzles in its ability to reduce mass and volume while maintaining strength as shown in Fig. 7. It demonstrates to be a formidable option for high-rise applications with an impressive stress-sustaining capacity and a high safety factor.

3.Outcome 14 - Stainless Steel Reliability

Design outcome 14, made of stainless steel, exhibits admirable mass and volume efficiency while maintaining a solid capacity for withstanding stress and a high safety factor. Due to its dependability and toughness, it is a dependable option for the demanding high-rise glass cleaning tasks.

4.Outcome 10 - Titanium Strength

Titanium-based Outcome 10 excels in its ability to sustain stress while maintaining effective mass and volume characteristics. It is a superb choice for high-rise maintenance projects due to its high safety factor, which guarantees dependability in demanding tasks.

TABLE I
COMPARISON OF FOUR RECOMMENDED OUTCOMES

Properties	Outcome - 13	Outcome - 15	Outcome - 14	Outcome - 10
Recommendation %	96.708	88.569	88.394	75.181
Material	CFRP	CFRP	CFRP	CFRP
Manufacturing method	Unrestricted	3 axis milling	Addictive	Unrestricted
Volume (mm^3)	115,382.011	298,263.525	148,172.327	115,373.806
Mass (kg)	0.165	0.427	0.212	0.52
Stress (Mpa)	86.297	35.513	130.607	87.164
Max displacement (mm)	0.234	0.081	0.269	0.304

C. Stress View

The "Stress View" of the four suggested robotic hand designs offers useful information about how well and how resiliently they perform structurally under external forces. The stress reference is shown in Fig. 8. In this, the blue color represents low stress and green ideal and red as the highest stress on the part surface. As it is clear from the same figure, the recommended outcomes are generated with low stress to give maximum efficiency at the real environment constraint This section delves into the stress analysis of each design, highlighting how well-suited they are for high-rise glass cleaning applications because they can withstand high pressures while maintaining structural integrity [13]-[15].

1. Outcome 13 - CFRP Excellence

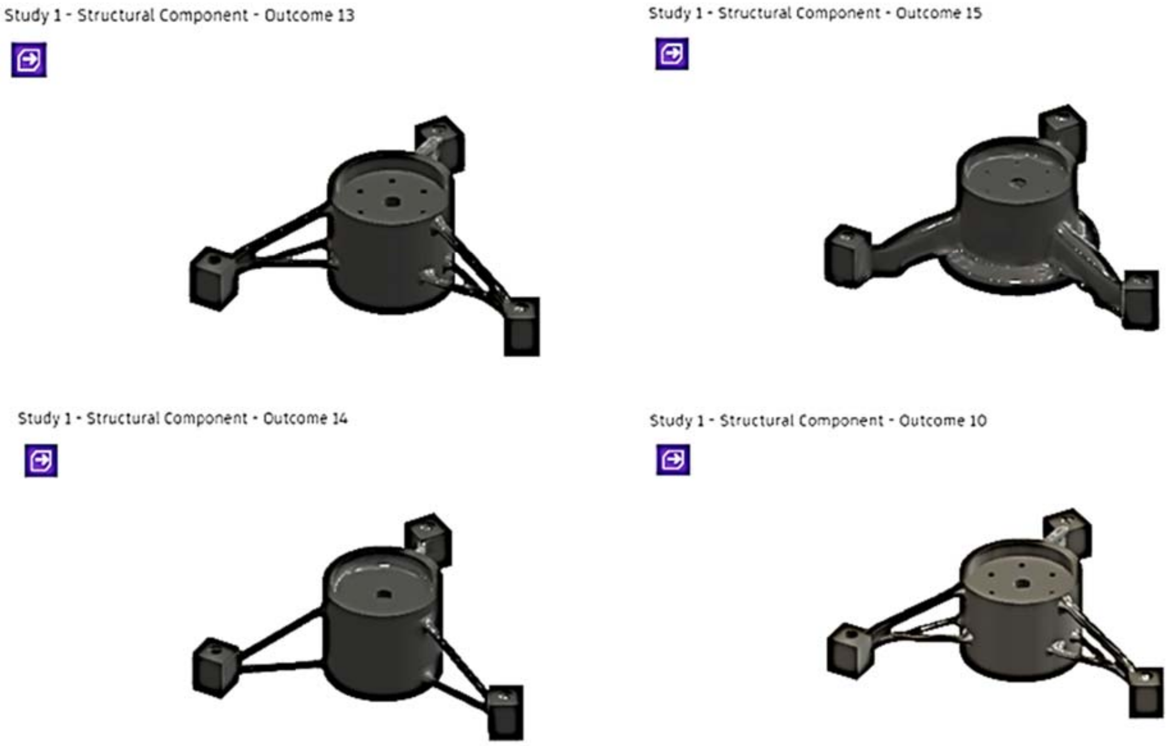
Design Outcome 13's CFRP construction exhibits excellent stress distribution properties. The stress view demonstrates the CFRP's exceptional strength-to-weight ratio by displaying an evenly distributed load-bearing pattern across its components. This design has few areas where stress is concentrated, indicating that it can withstand high pressures gracefully. Due to the inherent characteristics of CFRP, this design has an impressive capacity to withstand stress, making it suitable for the demanding requirements of high-rise glass cleaning.

2. Outcome 15 - Carbon Fiber Durability

The carbon fiber-based outcome, Outcome 15, exhibits notable stress resilience throughout its entire structure. The stress view displays an even distribution of forces, demonstrating the design's effectiveness at distributing loads. The absence of stress concentrations demonstrates the design's robustness, which is reinforced by the use of carbon fiber. It is a reliable option for high-rise glass cleaning missions because it can withstand significant pressures without losing structural integrity.

3. Outcome 14 - Stainless Steel Reliability

Design Outcome 14 is made of stainless steel and displays a stress view with a consistent load distribution. Stainless steel's inherent strength ensures that stress is distributed evenly among the parts, reducing localized stress concentrations. The stress analysis of this design demonstrates its ability to withstand substantial pressure without deforming or compromising. Because of its toughness and resilience, stainless steel is a dependable material for cleaning high-rise glass under difficult circumstances.

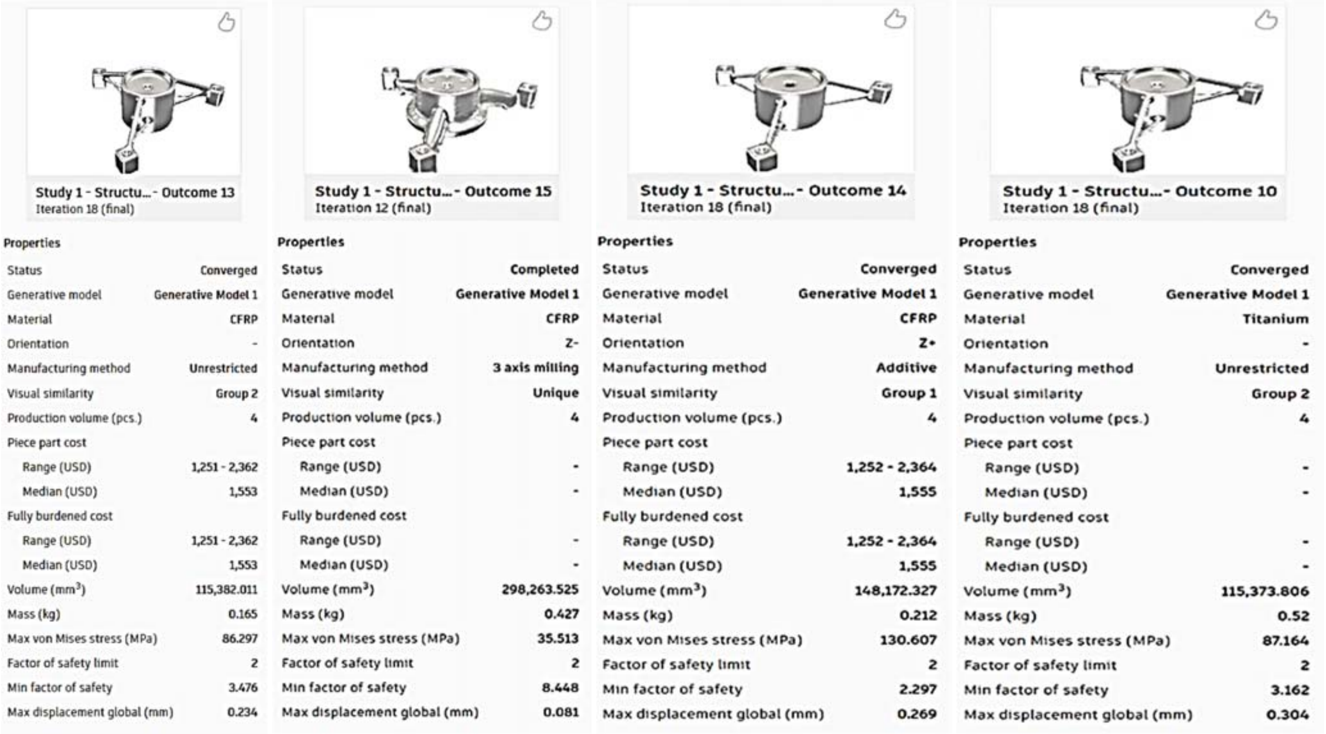

Study 1 - Structural Component - Outcome 13

Study 1 - Structural Component - Outcome 15

Study 1 - Structural Component - Outcome 14

Study 1 - Structural Component - Outcome 10

Fig. 6 Structural component of the four recommended outcomes


Study 1 - Structu... - Outcome 13
Iteration 18 (final)

Properties

Status	Converged
Generative model	Generative Model 1
Material	CFRP
Orientation	-
Manufacturing method	Unrestricted
Visual similarity	Group 2
Production volume (pcs.)	4
Piece part cost	
Range (USD)	1,251 - 2,362
Median (USD)	1,553
Fully burdened cost	
Range (USD)	1,251 - 2,362
Median (USD)	1,553
Volume (mm^3)	115,382.011
Mass (kg)	0.165
Max von Mises stress (MPa)	86.297
Factor of safety limit	2
Min factor of safety	3.476
Max displacement global (mm)	0.234

Study 1 - Structu... - Outcome 15
Iteration 12 (final)

Properties

Status	Completed
Generative model	Generative Model 1
Material	CFRP
Orientation	Z-
Manufacturing method	3 axis milling
Visual similarity	Unique
Production volume (pcs.)	4
Piece part cost	
Range (USD)	-
Median (USD)	-
Fully burdened cost	
Range (USD)	-
Median (USD)	-
Volume (mm^3)	298,263.525
Mass (kg)	0.427
Max von Mises stress (MPa)	35.513
Factor of safety limit	2
Min factor of safety	8.448
Max displacement global (mm)	0.081

Study 1 - Structu... - Outcome 14
Iteration 18 (final)

Properties

Status	Converged
Generative model	Generative Model 1
Material	CFRP
Orientation	Z+
Manufacturing method	Additive
Visual similarity	Group 1
Production volume (pcs.)	4
Piece part cost	
Range (USD)	1,252 - 2,364
Median (USD)	1,555
Fully burdened cost	
Range (USD)	1,252 - 2,364
Median (USD)	1,555
Volume (mm^3)	148,172.327
Mass (kg)	0.212
Max von Mises stress (MPa)	130.607
Factor of safety limit	2
Min factor of safety	2.297
Max displacement global (mm)	0.269

Study 1 - Structu... - Outcome 10
Iteration 18 (final)

Properties

Status	Converged
Generative model	Generative Model 1
Material	Titanium
Orientation	-
Manufacturing method	Unrestricted
Visual similarity	Group 2
Production volume (pcs.)	4
Piece part cost	
Range (USD)	-
Median (USD)	-
Fully burdened cost	
Range (USD)	-
Median (USD)	-
Volume (mm^3)	115,373.806
Mass (kg)	0.52
Max von Mises stress (MPa)	87.164
Factor of safety limit	2
Min factor of safety	3.162
Max displacement global (mm)	0.304

Fig. 7 Selected Outcomes- CFRP Excellence, Carbon Fiber Durability, Stainless Steel Reliability, Titanium Strength

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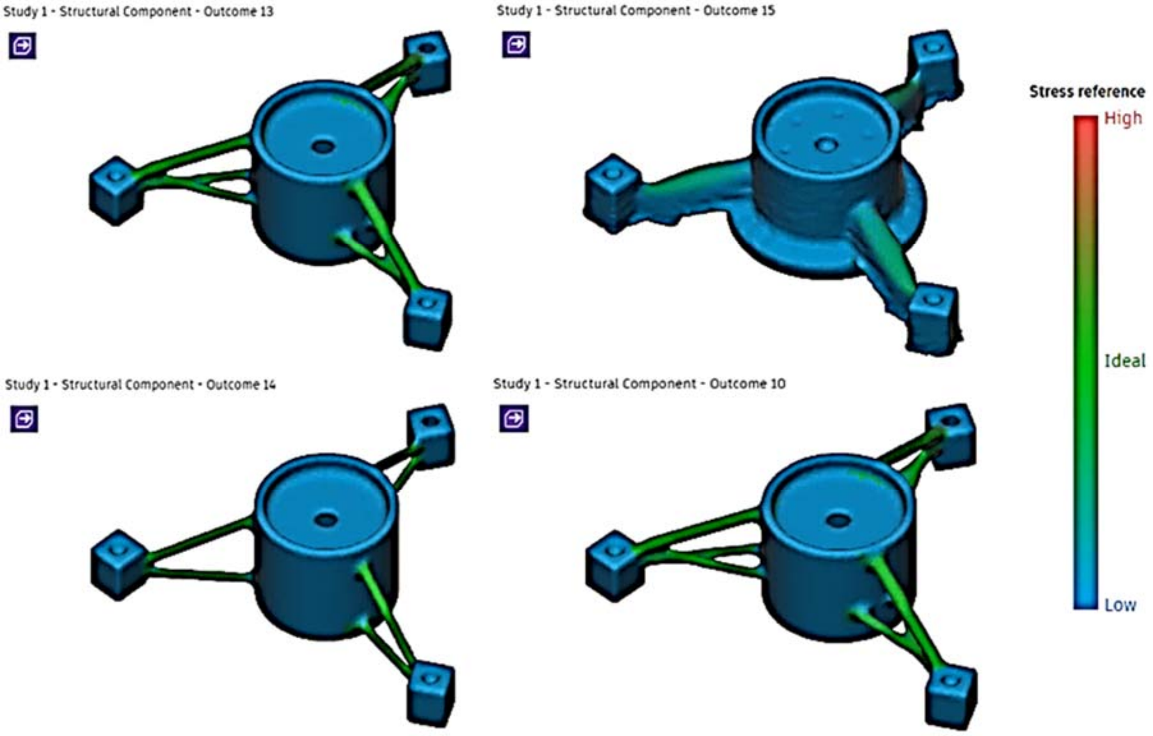


Fig. 8 Stress analysis of the four recommended outcomes

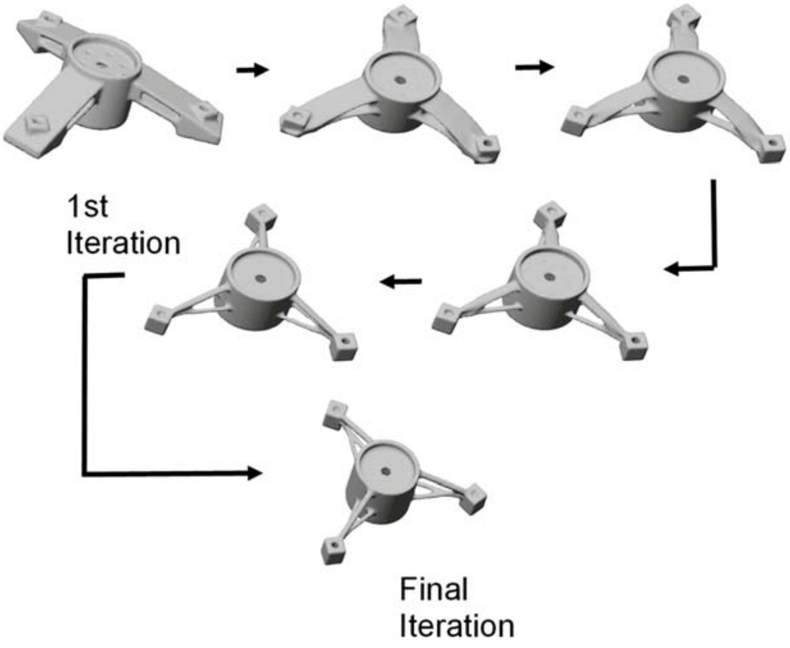


Fig. 9 Iteration process of the component

4. Outcome 10 - Titanium Strength

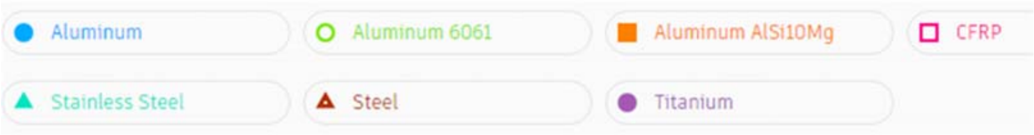
A stress view of Outcome 10, which was made of titanium, attests to its incredible strength. The analysis reveals a uniform distribution of stress throughout the design with no obvious areas of high stress. Titanium exhibits a remarkable strength-to-weight ratio because it can withstand high pressures without losing its structural integrity. This design is an excellent example of the toughness needed for high-rise glass cleaning, where durability and dependability are crucial.

IV. RESULT ANALYSIS

Graphs on mass, volume, stress, displacement for different materials based on best 4 outcomes are shown in Figs. 11-13. For a thorough understanding of the performance of the top four suggested robotic hand designs (Outcomes 13, 15, 14, and 10), it is essential to examine a number of critical factors, such as mass, volume, stress, and displacement. Describing the graphs in Figs. 11-13 demonstrates the variation of material used in robotic hand design.

Fig. 10 is showing the color coding of different materials which were shown in the graphs. It is clearly visible that the CFRP represented by pink color shows the best outcome.

The result shows that the CFRP is giving maximum efficiency the result has been describer in terms of graphical representation. Figs. 12 and 13 clearly represent that CFRP material has high stress and displacement capacity with very less mass as compared with other material making it best choice to use in hand while manufacturing.



● Aluminum
○ Aluminum 6061
■ Aluminum AlSi10Mg
☐ CFRP
▲ Stainless Steel
△ Steel
● Titanium

Fig. 10 Color code of materials

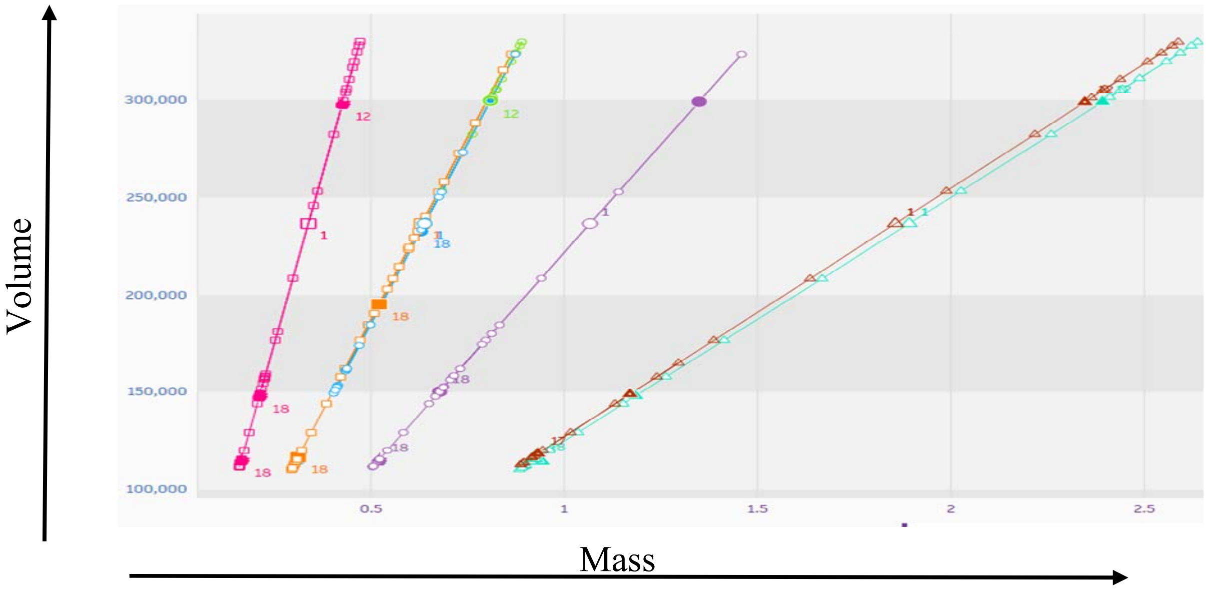


Fig. 11 Volume versus mass graph

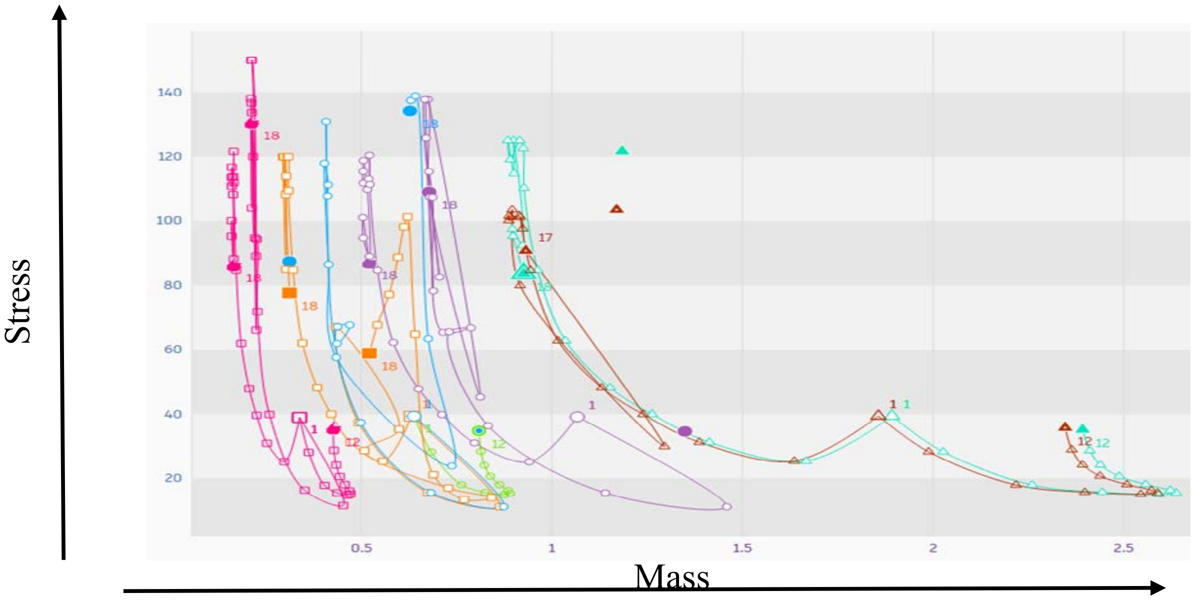


Fig. 12 MEx von Mises stress versus mass graph

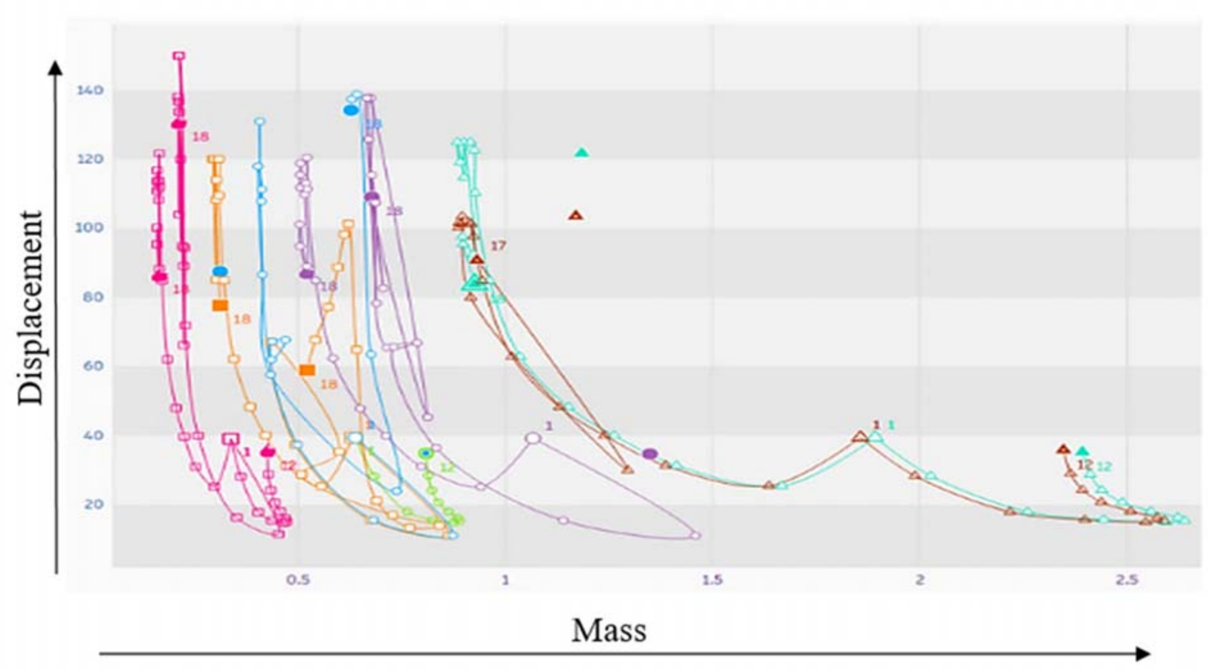


Fig. 13 Max displacement global versus mass graph

V. CONCLUSION

The conclusions drawn from this research are summarized as follows since it is focused on applying generative design on hand to optimize the robot in terms of mass and volume with material analysis in the Smart Glass Cleaning Robot:

1. The material analysis of seven materials has been done and the stress analysis of those materials is also being studied.
2. In addition, since the Outcome-13, made of CFRP, is the undisputed winner in the race to create the ideal robotic hand for cleaning high-rise windows. It surpasses all competitors with an astounding recommendation rating of 96.708%, solidifying its supremacy. The validation of results from prior studies using Autodesk Fusion 360 is regarded as successful and reliable.
3. Volume efficiency of outcome-13 is the pinnacle of compactness, requiring just 115,382.011 mm^3 of space. In high-rise maintenance, where confined spaces necessitate agile designs, this exceptional volume efficiency is crucial.
4. Mass optimization of outcome-13 is incredibly light, weighing just 0.165 grams. This quality is essential for ensuring effortless maneuverability, which is a crucial requirement when scaling tall skyscrapers.
5. Structural Resilience of Outcome-13's exceptional structural integrity is its most notable quality. It outperforms others with a maximum stress capacity of 86.297 MPa, indicating an unmatched strength-to-weight ratio. To withstand the demanding forces encountered during high-altitude operations, this resilience is essential.
6. The generated shapes with stress analysis and material strength of the hand part are determined using the Generative Design Module in Autodesk Fusion 360.
7. Minimal displacement 0.234 mm of outcome-13 ensures that it will remain stable under heavy loads without compromising structural robustness.

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