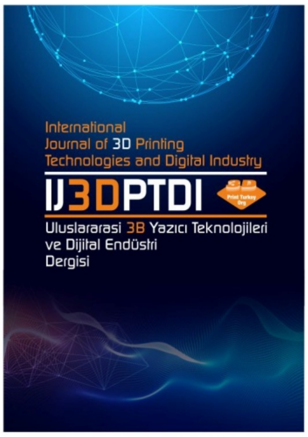

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AN INTELLIGENT SNOW REMOVAL ROBOTIC SYSTEM: TOPOLOGY BASED STRUCTURAL LIGHTWEIGHTING AND POWER CONSUMPTION ANALYSIS

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ABSTRACT

This study involves a thorough investigation encompassing the comprehensive design, development, topology optimization and power analysis of a mobile snow removal robotic system. The creation of all subcomponents and assembly models was undertaken using Computer-Aided Design (CAD) tools. The electronic hardware, including components such as batteries, Raspberry Pi, and motor drivers, were selected. The assembly of these parts was then conducted, with the objective of integrating them into the overall structure. Finite element analyses (FEA) were performed to evaluate the system's structural strength and stability. The objective of topology optimization was to minimize the weight and energy consumption of the mobile robot. As a result, an optimized structure achieving a 7% weight reduction and 9% energy savings was developed. A novel feature of this study is the integration of a custom-designed Python-based power analysis tool, enabling precise energy consumption comparison between optimized and non-optimized structures. These combined methods demonstrate a significant improvement over the existing snow removal robotic system.

Keywords: CAD-based Snow Removal Robot, Energy-Efficient Mobile Robot, FEA Simulation, Power Consumption Analysis, Structural Lightweighting, Topology Optimization.

1. INTRODUCTION

There is no universally accepted definition of a robot. However, there are certain characteristics and qualities that can be used to determine whether a device or machine can be considered a robotic system. It is imperative that a robot be capable of environmental awareness, mobility, and energy source utilization. If circumstances require, it is important that the subject has the intelligence to meet the necessary requirements [1-2]. Mobile robots have the capacity to execute a wide range of tasks that are typically undertaken by humans. These tasks may include surveillance, reconnaissance, patrol, firefighting, search and rescue operations, internal security, care work, and entertainment [3-4]. Motion of robotic systems is highly dependent on the planned operating environment. These operating environments can be categorized as air, water and terrestrial. While propellers and screws are generally more useful for operation in aquatic and aerial environments, wheels, tracks, legs and their combinations can be chosen for terrestrial conditions. In addition to conventional locomotion mechanisms, an additional apparatus has been developed for biologically inspired robots, namely adaptive legs [5-7].

In the context of ground mobile robotic systems, a range of mechanical structures and mechanical architectures have been put forward for both academic and industrial research. The classification of these structures is based on three primary categories: W (wheeled), T (tracked), and L (legged). In addition, four hybrids have been derived from the network, namely LW (leg-wheel), LT (leg-track), WT (wheel-track) and LWT (leg-wheel-track) [8-10].

Nowadays, computer-based and machine learning tools have a pivotal role in the design, analysis and optimization of structures. Solid modelling, utilizing CAD (Computer Aided Design) methodologies, enables designers to define components and assemblies, subsequently employing the geometry for simulations, analyses and prototyping. Computer-aided engineering (CAE) methodologies encompass virtual prototype simulations and static, kinematic and dynamic analyses [11-13].

Topology optimization is a commonly used practice in product design processes including the automotive and aerospace sectors. The aim of topology optimization is to optimize material distribution within a specified design space; The objectives are to maximize the strength and natural frequencies of the design while decreasing the weight. In the optimization process, the designed volume is divided into smaller elements, a finite element analysis (FEA) model is created, and boundary conditions are respectively applied to perform the FEA. During the analysis process, it is observed that the elements show intermediate density values. The values examined converge to 1 or 0 through a penalization process where the power law is used to penalize elements with higher density [14-17]. The general process diagram of topology optimization is presented in Figure 1.

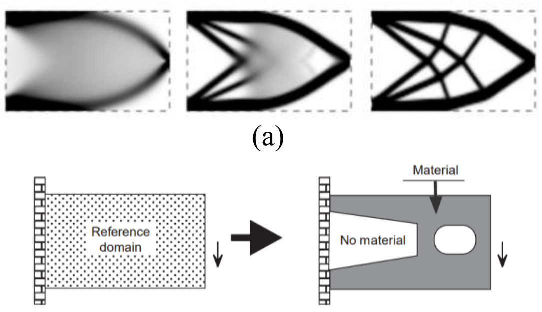

Figure 1. (a) Interpolation (b) The general scheme [13].

Two widely preferred methods for determining the distribution of elements in topology optimization are the Solid Isotropic Material Penalization (SIMP) and the Evolutionary Structural Optimization Technique (ESO).
The SIMP method calculates an optimum material distribution within a given design space for specific load cases, boundary conditions, manufacturing constraints and performance requirements. The density distribution of the material within a design space, denoted by ρ, is discrete and each element is assigned a binary value. For each element, the assigned relative density may vary between a minimum value, denoted by ρmin, and 1, thus allowing intermediate densities to be allocated for elements characterized as porous elements. It has been established that, due to the perpetual nature of the material's relative density, the material's Young's modulus in each element is concomitant with continuous change. The relationship between each element e and the material's relative density factor, denoted as ρe, as well as the isotropic model's Young's modulus of elasticity, denoted by E_0, is calculated by means of a power law [14-15,18].

$$E(\rho_e) = \rho_e^{\rho}\ E_0 \tag{1}$$

Where:
ρ: The density distribution of material
ρe: For each element "e" the relation between the material relative density factor
E_0: Young modulus of elasticity of the isotropic material

The stress-based ESO method is typically characterized by the utilization of von Mises stress for the extraction process. Initially, a piece of material of sufficient size to cover the designated area of the final design is divided into a fine mesh of finite elements. The application of loads and boundary conditions is a fundamental aspect of the analysis, which involves the execution of a stress analysis utilizing a finite element program. Given that the structure is composed of numerous minute components, the extraction of material can be readily illustrated by any available method. The stress level at each point can be measured by calculating the average of all stress components. In this context, the von Mises stress is one of the most frequently used criteria for isotropic materials. The von Mises stress is defined as follows in the context of plane stress problems:

$$\sigma^{vm} = \sqrt{\sigma x^2 + \sigma y^2 + \sigma x \sigma y + 3\tau^2 xy} \tag{2}$$

In the context of the given problem, σx and σy are defined as the normal stresses in the x and y directions, respectively, and τ_{xy} is represented as the shear stress. The stress level of each element is determined by comparing the von Mises stress of ${\sigma_e}^{vm}$ element with the maximum von Mises stress of the whole structure ${\sigma_{max}}^{vm}$. At the conclusion of each finite element analysis, elements that satisfy the following condition are eliminated from the model:

$$\frac{\sigma_e^{vm}}{\sigma_{max}^{vm}} < RRi \quad (3)$$

RRi is the current rejection rate (RR). The commonly accepted limit value for RR is 25 %. The finite element analysis and element removal cycle is iterated using the same RRi value until a steady state is attained. This indicates that no additional elements are being removed during the current iteration. At this stage, the evolutionary rate (ER) is introduced and added to the rejection rate. As the rejection rate increases, it becomes evident that the finite element analysis and element removal cycle are reinitiated until a new steady state is attained [19-20].

Given its proven effectiveness in reducing weight and improving mechanical performance, topology optimization is highly relevant for mobile robotic systems that operate under dynamic and energy-demanding conditions. For snow removal robots reducing structural weight enhances maneuverability on slippery and uneven snow-covered terrain, which directly impacts operational stability and control. Additionally, minimizing energy consumption is critical for ensuring sustained functionality in cold environments, where power supply options are limited and batteries suffer from decreased efficiency. These factors make energy-aware structural design a necessity rather than a preference in such applications. Therefore, applying topology-based methods in the structural design of snow removal robots can lead to lighter, more energy-efficient, and cost-effective solutions.

The optimization techniques discussed such as the Solid Isotropic Material Penalization (SIMP) and Evolutionary Structural Optimization (ESO) methods not only provide a theoretical basis for optimal material distribution but also serve as a practical guide to achieving the key design goals of our system: weight reduction, power savings, and structural safety under real-world loads.
Sreeramoju et al. [21] conducted an optimization study. They made a comparison between three different materials. The objective of this study was to provide a selection guide for the material of the drone chassis.

The composition of aluminum A356 T6, aluminum 6061 and ABS plastic materials were analyzed. The results showed that a 35% reduction was gained through optimization. Sobocki et al. [22] concentrated on an industrial application example of topology optimization for a spray tank bracket. The solid isotropic punishing material (SIMP) method was employed under static loads. The integration of finite element analysis (FEA) and topology optimization methodologies resulted in the development of a structure that was both lightweight and durable.

Yao et al. [23] demonstrated a static structural analysis of load-bearing frames. In addition, topology optimization processes were employed to improve the frame design for the parameters of deformation and uniform stress distribution. The results demonstrated that the total mass, deformation and stress were 8.7%, 88.2% and11.7%, respectively.

Snow removal vehicles boast a wide array of applications, along with the ability to swiftly remove snow and exhibit exceptional maneuverability [24]. The most common vehicle used for snow removal is the snow blower. In recent years, there has been a significant increase in the use of robotic systems. This development has led to the creation of mobile systems designed specifically for snow removal. The most prominent product on the market for snow removal is Snowbot. It is an autonomous snow removal robotic system developed by Hanyang Robotics [25].

Despite the growing interest in autonomous snow removal systems, most existing solutions rely on conventional structural designs without optimization for weight or energy efficiency. There is a lack of integrated approaches that combine CAD modeling, finite element analysis, topology-based structural refinement, and power consumption evaluation in a unified framework. This study addresses this gap by proposing a holistic design and evaluation methodology for a snow removal robot, incorporating both structural topology optimization and a novel energy analysis tool for real-time design feedback and improvement. The present work is a research study for the design and development of a snow removal robot system. The creation of the sub-assemblies and the assembly model was conducted using Computer Aided Design (CAD) tools. Finite element analyses (FEA) were used to evaluate the structural integrity and stability of the system. Then, topology optimization was applied to reduce the weight and energy consumption of the snow removal robot system. A power analysis tool was also proposed to calculate and to compare the energy consumption of structures.

2. MATERIALS AND METHODS

2.1. Design of the Snow Robotic System

In this section, the robotic structure was designed using Fusion 360 software. The components of the assembly, such as the bottom frame, the brush cover module, and the crawler structure, have all been created and assembled correctly. The integration of hardware layouts into the structure is a crucial aspect of the process. The materials of the bottom-frame and brush cover have been selected to be aluminum 6061. The structure was designed to be modular, facilitating ease of assembly. The assembled structure of the snow removal robotic system is illustrated in Figure 2

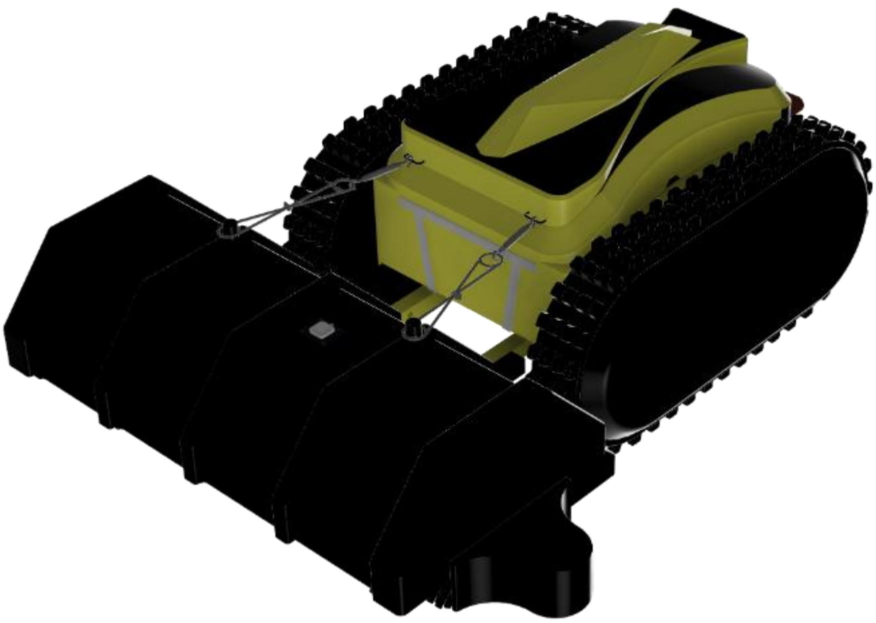

Figure 2. The assembled structure of the snow removal robotic system.

Following the 3D design process, engineering drawing documents including part list and exploded view, and an overall dimension were produced. Those documents were useful for identifying and sourcing the required parts and hardware. Two DC wiper motors of 24V, 20A, 8 Nm torque and 60 rpm were selected to move the robotic system. An appropriate assembly and layout of the crawler modules was designed. The motion control unit was designed with two motor driver boards with a maximum current source of 30 Amperes, Raspberry pi 5, and Arduino Mega 2560. Two 24 V, 4A compact induction motors (CIMs) were integrated to rotate the snow brush. Five proximity motion sensors and a compass module were used to control the movement of the robotic system. A 24V 40 Ah lithium battery was chosen as the power source for the system. The part list exploded view and overall dimensions of the snow removal robot system structure are shown in Figures 3 and 4, respectively.

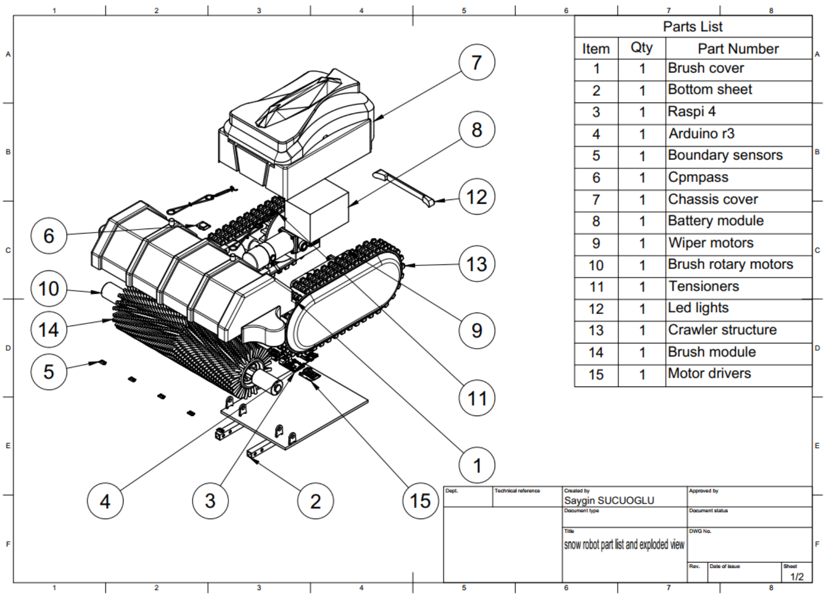

Figure 3. Part list and exploded view.

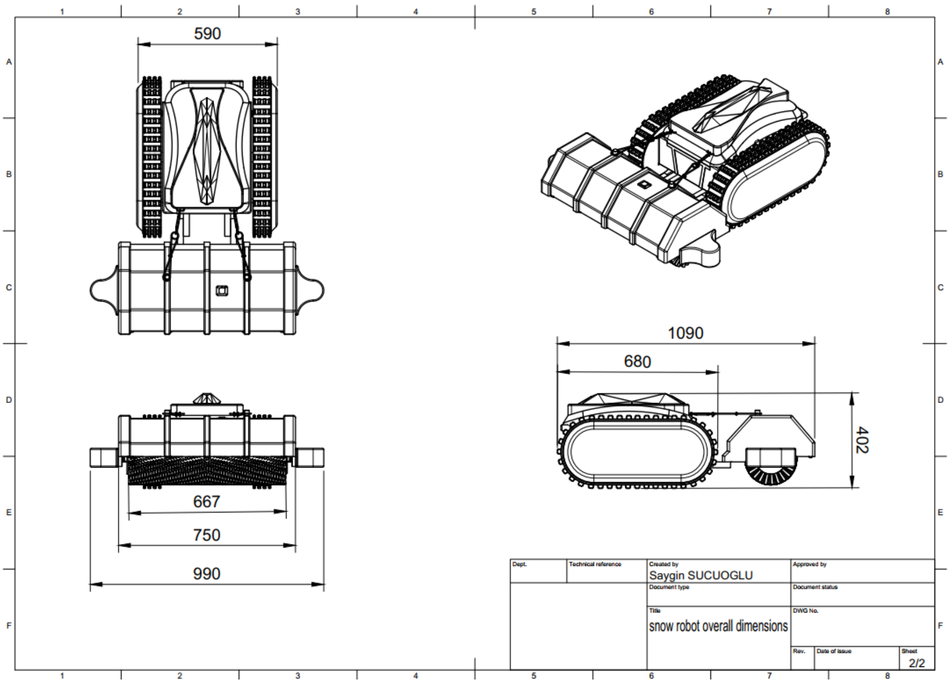

Figure 4. Overall dimensions.

2.2. Engineering Analysis of Preliminary Structure

Engineering analyses were performed using finite element analysis (FEA) to ascertain the structural integrity and stability of the mechanical structure. A significant rationale underlying this approach pertains to the necessity of ascertaining the viability of the topology optimization process. In the case of these models, the materials assigned to the brush cover and chassis cover were aluminum 6061. The application of loads served to verify the resulting safety factor and stress values. The creation of engineering analysis sets was facilitated within the Ansys Workbench 2024 Static Structural Environment. These analyses were applied separately to the brush and chassis covers. The applied loads are presented in Figures 5 and 6, respectively. The loads were calculated as the sum of the forces due to the actuators, the weights of the structure and the snow load. For the chassis cover, 150 and 750 N forces resulting from the movement of the entire structure and weights were applied. For the brush cover, 720,200 and 400 N forces and 22Nm moment loads caused from the rotation of the brush rotary motors and snow brush and weights were applied.

The finite element models of both components were discretized using tetrahedral elements with a target mesh size of approximately 2 mm. The brush cover model contained nearly 180,000 elements, while the chassis cover model comprised approximately 250,000 elements. A mesh sensitivity analysis was performed to ensure that further refinement had no significant effect on the stress or safety factor results.

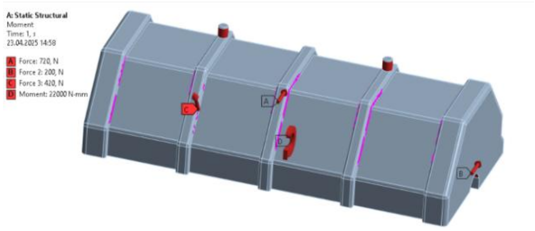

Figure 5. Loads of brush cover.

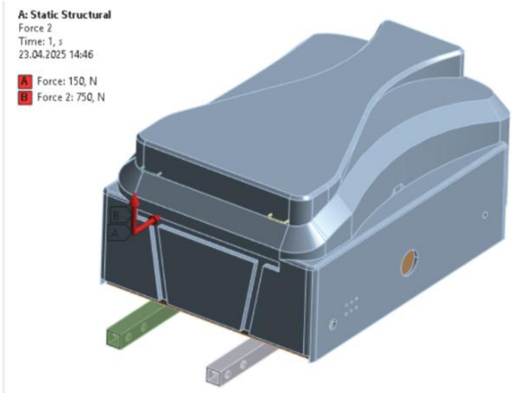

Figure 6. Loads of the chassis cover.

2.3. Topology Optimization

The topology optimization processes were executed utilizing the Ansys Structural Optimization tool. The load conditions employed in this study were consistent with those utilized in preliminary structural engineering analyses. The optimization definitions were selected as topology density, with a threshold value of 60%. Connection zones were designated as preserved areas, which excluded from the optimization processes. The objective function was defined to minimize structural compliance (maximize stiffness) under the applied loads. A total of 30 optimization iterations were performed, with convergence assessed based on density change across the mesh. Manufacturing constraints such as minimum member size were applied to ensure fabrication feasibility. New, optimized structure proposals were obtained through multiple iterations. Utilizing the collated data and the design file output, new optimized structures were created. These newly generated models are demonstrated in Figures 7 and 8, respectively.

Figure 7. Optimized brush cover.

Figure 8. Optimized chassis cover.

2.4. Power Analysis Tool

The tool has been developed for the purpose of facilitating energy consumption and weight analysis for a snow removal robot system, by means of creating an intuitive graphical user interface (GUI) using Python's tkinter library. The application was utilized for the purpose of conducting comparative power analysis of two robotic de-signs, a process which involves the processing of parts lists detailing components such as motors, batteries, sensors, and coating materials (Figure 9). The tool is utilized by users through the entry of component properties, including voltage, current, quantity, and weight. These properties directly reflect the data present in the parts list. The component entries are added to a cumulative list in a systematic manner, thereby facilitating an iterative and comprehensive analysis. The tool facilitates real-time design evaluation and optimization through the dynamic calculation of total power consumption and total weight. It is notable that the tool incorporates a significant feature in the form of its image visualization capability, which enables users to load and subsequently view component images directly within the GUI. This enhancement in clarity facilitates a more integrated approach to system design, correlating visual representations with numerical analysis.

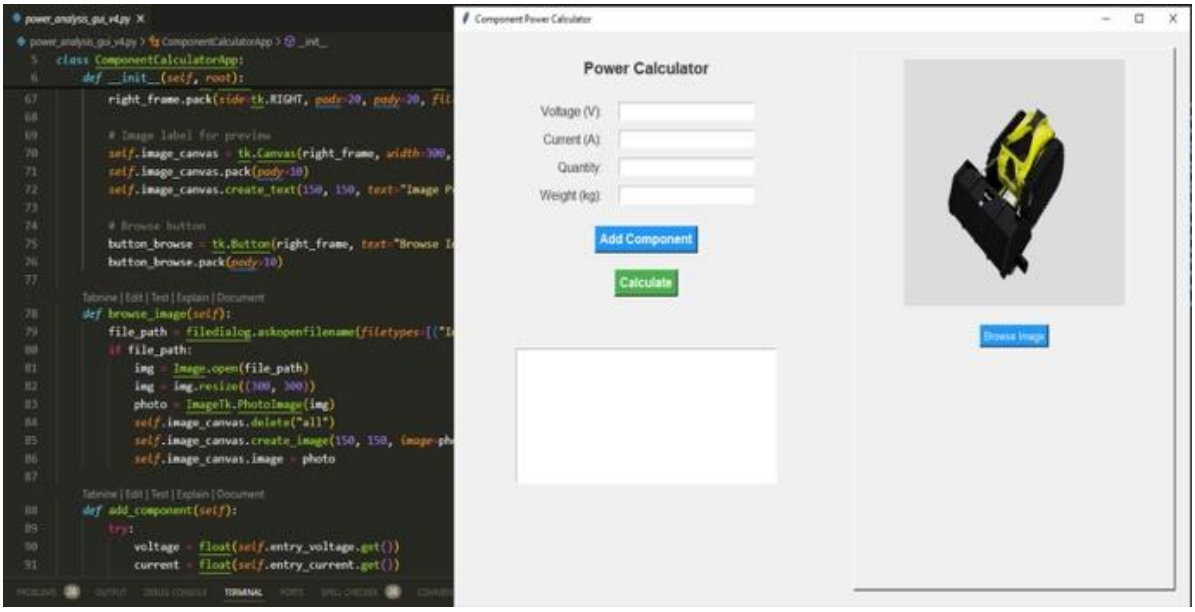

Figure 9. Design of power analysis tool.

In the analysis of the two robotic structures (preliminary and optimized), the tool facilitated the calculation of the total energy requirements and weight distribution based on the parts lists provided. This approach contributed to the identification of design efficiencies, including reduced power consumption and the adoption of lighter chassis configurations. The tool's capacity to execute critical calculations and to visualize components was conducive to the iterative design process and to the improvement of documentation for engineering reports (Figure 10). Although formal experimental validation of the tool has not yet been completed, the outputs were manually cross-checked with conventional electrical formulas and verified component specifications. This ensured consistency and reliability within the scope of the study. For future work, hardware-based power measurements are planned to further validate and calibrate the tool under actual operating conditions.

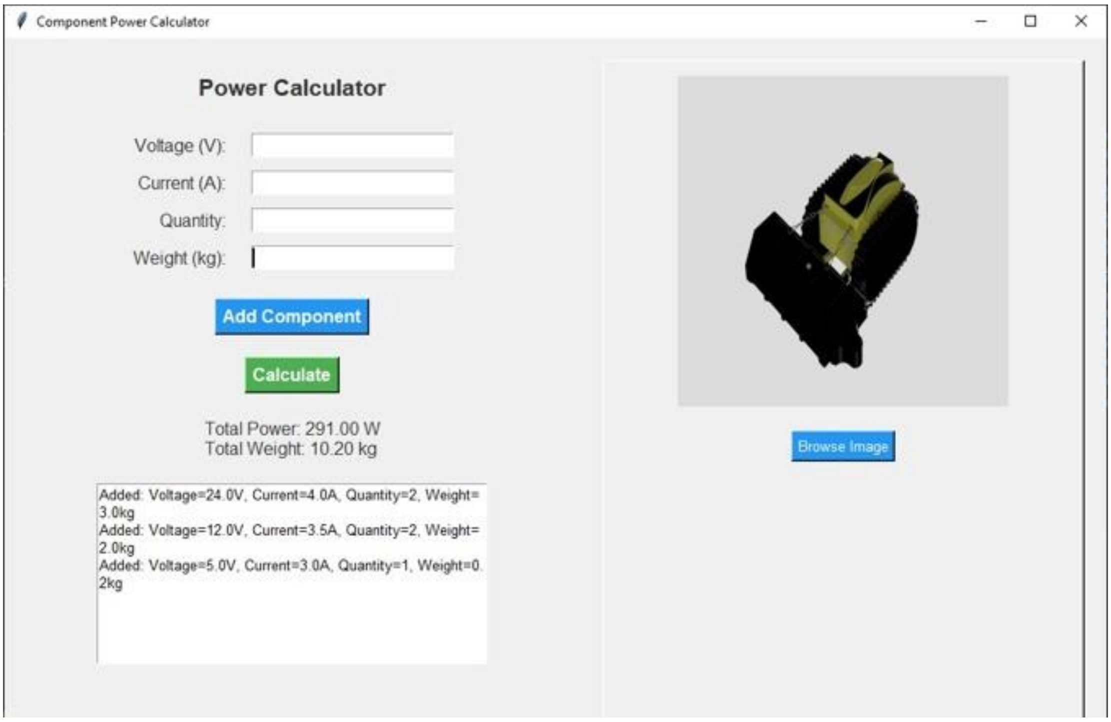

Figure 10. Calculations with power analysis tool.

2.5. Optimized Snow Robotic System

In this section of the study, a new assembly model was devised through the utilization of the optimized covers (Figure 11). The integration of all parts and hardware has been achieved, and the new, optimized structure has been prepared for power analysis.

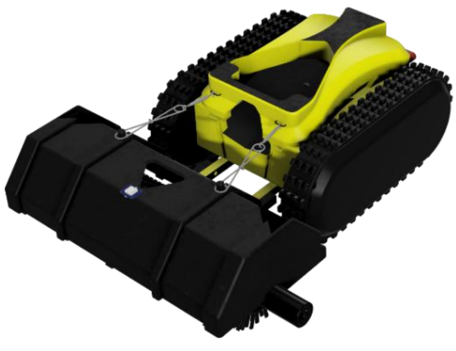

Figure 11. Optimized snow robotic system.

3. RESULTS AND DISCUSSION

The results of the analysis studies are examined to verify the necessity of the topology optimization study. Preliminary structure calculations indicated that the weights of the brush and chassis covers were approximately 9.5 and 16 kilograms, respectively. The safety factors have been calculated to be in the range of approximately 13.5 and 5.7, which was more than sufficient. The resulting von Mises stresses were also observed to be approximately 7.5 and 15 MPa. The findings of this study indicated that the implementation of topology optimization was viable in terms of reducing both the weight and energy consumption of the snow removal robot system. The obtained factor of safety and von Mises stresses values of the brush cover are represented in Figures 12 and 13.

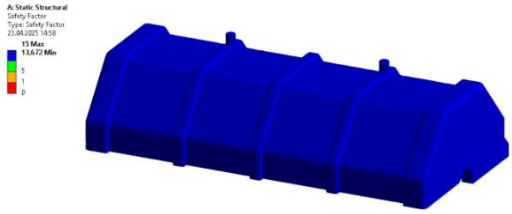

Figure 12. Factor of safety distribution in the preliminary design of the brush cover.

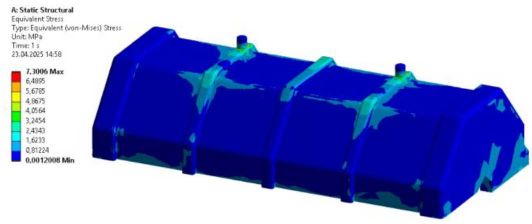

Figure 13. von Mises stress distribution in the preliminary brush cover design.

As demonstrated by the engineering analysis of the optimized structures, the safety factor values for the brush and chassis covers were approximately 2.2 and 5.4, respectively. Furthermore, von Mises stresses were approximately 16 and 47 MPa. The analysis results of the optimized brush cover are presented in Figures 14 and 15. The ensuing results demonstrated that the safety factor values remain valid, and the von Mises stresses continue to be within safe limits. Consequently, it is hypothesized that snow robotic system structure can be established using new optimized structures to ensure reduced energy consumption and long-term use.

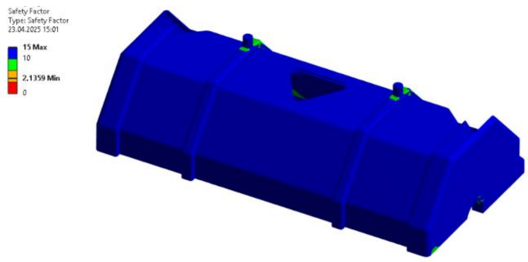

Figure 14. Factor of safety distribution in the optimized brush cover design. The minimum safety factor remains above 2, confirming structural integrity after material reduction.

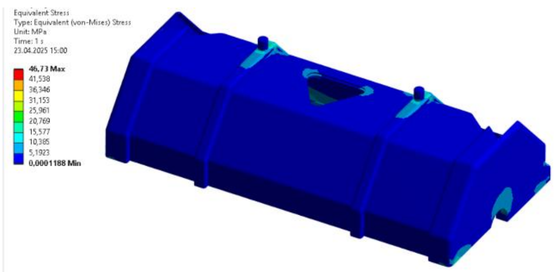

Figure 15. von Mises stress distribution in the optimized brush cover design, with peak stresses reaching 47 MPa. Stress remains within the allowable limits for aluminum 6061.

The power analysis of the snow robotic system was performed to evaluate the energy efficiency and overall performance of the optimized structure in comparison to the preliminary version. The objective of this analysis was to quantify the improvements achieved through topology optimization, with a particular focus on reductions in weight, power consumption and energy requirements.

In power analysis standard electrical and energy calculation formulas were used, including:
a. Power (P) = Voltage (V) × Current (I)
b. Total Energy (E) = Power (P) × Time (t)
c. Total Power Consumption = ∑ (Power consumption of individual components)
d. Weight comparison = ∑ (weights of all components in each design)
Comparison between the optimized and preliminary structures are given in Table 1.

Table 1. Comparison table between preliminary and optimized structure.

Results	Preliminary Structure	Optimized Structure
von Mises stresses of brush cover (MPa)	7.5	16
von Mises stresses of chassis cover (MPa)	15	47
Weight of the brush cover (kg)	9.5	7.5
Weight of the chassis cover (kg)	16	10
Weight of the entire system (kg)	116	108
Energy consumption (Wh)	446	405

The results showed that the optimized design achieved a 7% reduction in weight, which directly contributed to a decrease in energy consumption and an increase in efficiency. The total energy consumption of the optimized robot was almost 41 Wh lower than that of the preliminary structure, corresponding to a 9% reduction. This enhancement supported longer operational duration without increasing battery capacity. Furthermore, the optimized design's reduced energy consumption indicated the possibility of utilizing smaller or fewer battery modules, which could lead to a reduction in overall system cost and weight. This emphasized the pivotal function of design optimization in the advancement of energy-efficient robotic systems.

Although the safety factors in the optimized components decreased compared to the preliminary design, the values remained within acceptable engineering limits (2.2 for the brush cover and 5.4 for the chassis cover), indicating sufficient strength for operational loading conditions.

When compared with similar studies, our results are in line with reported trends. For example, Sreeramoju and Rao [20] reported a 35% weight reduction in drone chassis, while Sobocki et al. [21] achieved structural improvement using the SIMP method. Our 7% and 9% energy reductions are considered effective outcomes for a full-scale mobile robotic system.

4. CONCLUSION

In this study, a comprehensive design and analysis workflow was presented for a mobile snow removal robotic system, integrating CAD modeling, finite element analysis, topology optimization, and a Python-based power evaluation tool. The results showed that the proposed optimization strategy successfully reduced the structural weight of the robot by 7% and its energy consumption by 9%, without compromising mechanical safety. These outcomes confirm the relevance of topology optimization in enhancing the energy efficiency and structural performance of robotic systems operating in snow-covered environments. This study also introduced a practical power analysis interface that enables designers to assess and compare energy usage during early-stage development. In future work, we aim to construct a physical prototype of the optimized system and conduct experimental validation of the power consumption predictions under real-world operating conditions.

Author Contributions
The percentages of the author(s) contributions are presented below. The author(s) reviewed and approved the final version of the manuscript.

	H. S. S
C	100
D	100
S	100
DCP	100
DAI	100
L	100
W	100
CR	100
SR	100
PM	100
FA	100

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest
The author(s) declared that there is no conflict of interest.

Ethical Consideration
Ethics committee approval was not required for this study because there was no study on animals or humans.

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