INNOVATIVE APPROACHES TO ENGINEERING PROBLEMS

DESIGN and DEVELOPMENT of ROVER MOBILE ROBOT with TOPOLOGY OPTIMIZATION and POWER ANALYSIS

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***Abstract*— In this study, comprehensive design, development, topology optimization and power analysis studies of rover mobile robot were conducted. All the elements and assembly model were created using Computer Aided Design tools. The electronic hardware (Rgb - camera, raspberry pi, motor drivers etc.) were selected and integrated into the structure with proper mounting elements. FEA (finite element analyses) were conducted to check the structural strength and stability of the system. Topology optimization process was applied to decrease the weight and energy consumption of the robotic system. Specific power analysis tool was developed for calculation and comparison of the energy consumption of the non-optimized and optimized structures. The FEA and power analyses results showed that optimization of the rover mobile robot structure was provided worthy decreases in the weight and energy consumption with the percentages of 33% and 21%, respectively.**

***Index Terms*— Computer Aided Design, Computer Aided Engineering, Finite Element Analysis, Rover Mobile Robot, Power Analysis, Topology Optimization**

I. INTRODUCTION

There is no universally accepted definition of a robot. However, there are some characteristics and features that can be used to determine whether a device or machine can be considered as a robotic system. Firstly, a robot must be aware of its environment, able to move and powered by an energy source. If necessary, it must also be intelligent enough to meet the required requirements.

Robotic systems can be used in a wide variety of fields. The robot manipulator, also known as the robot arm, is used to perform tasks in industry such as welding, painting and palletizing, due to its power, rigidity, speed and accuracy. It is also worth noting that the usage area of robots has recently shifted from classical industrial manufacturing robots to service robots. Medical robotics has made significant inroads into the medical field, though it has not yet displaced medical professionals. Numerous robotic applications have emerged in medical settings, such as laboratory robots, surgical robots and training simulators. Rehabilitation robotics have also found applications in assisting people with disabilities. Mobile robots are the systems that able to perform tasks in changing conditions and different places using a platform and locomotive elements. The locomotive system is adapted to suit the specific requirements of the operational environment. The locomotive system varies according to the operation environment. In the aquatic and aerial environments, propellers, screws and legs are generally used, while wheels, pallets and legs are used in terrestrial environments [1-4].

The operation environment is the key factor in determining the locomotion systems of the robots. The environment can be categorized as either aerial, aquatic or terrestrial [5, 6]. In mechanical aspects, propellers and screws are used in aquatic and aerial operation environments. But the motion requirements of a terrestrial environment are more intricate than those in other environments. So, the selection of suitable elements for terrestrial motion necessitates a distinct approach. These elements may include wheels, tracks, legs, or combinations thereof, depending on the specific requirements of the task. [7-9].

Besides those types of general locomotion some more systems have been studied and developed. Legged robots and hybrid tractions can be given as the samples. Also some mechanism such as “rocker bogie” have been proposed for improved adaptability for unknown environments. The rocker-bogie suspension system has been demonstrated to ensure that all six wheels of the robot remain in contact with the ground, even when traversing uneven surfaces. This property engenders excellent traction and maneuverability. Notably, the rocker-bogie suspension mechanism has been designated as the prevailing design for wheeled mobile robots by NASA, primarily due to its capacity to withstand obstacles and its uniform distribution of the payload across all six wheels. The rocker-bogie suspension system has been found to be effective in a range of applications, including navigation on uneven terrain and the ascent of steps [10-12]. The rocker bogie mechanism has been commonly used for rover type robotic systems. Rover type robotic systems have numbers of usage advantages as environment adaptability, obstacle pass and climbing. With those advantages, rover style robotic systems can be designed and developed for different type of operations.

Kiran (et al. [13]) designed a 4 wheeled independent driver rover system. They designed the suspension system to operate in adverse environment conditions. In their structure they also developed a robotic arm with 6 degrees of freedom for multipurpose usage of the system.

Jun (et al. [14]) studied; design, control and application of a novel 4 legged rover for planetary exploration. They proposed an active-passive leg mechanism for terrain adaptability. They designed a wheel-legged hybrid type locomotion with proper actuator. They also presented; kinematic model for the structure, kinematic based control strategy and steering modules.

Murad (et al. [15]) designed and used a rover style tank robot for fire detection and extinguishing for closed area applications. The robot was equipped with small water tank, servo motor, flame sensor, arduino controller and required motor driver.

Islam (et al. [16]) introduced a mars exploration robotic system. Their robotic system was a semi-autonomous structure and had capability to complete the human assistant tasks and also collecting resource from planet mars, giving a feedback of soils condition such as temperature and.

Venkatnikhil (et al. [17]) designed and developed a rover robotic system for cleaning and monitoring of the solar panels. Their system could be controlled wirelessly via Bluetooth module with the range of 10 m.

Nowadays computer-based tools are crucial for the design and analysis of structures. Solid modelling using CAD (Computer Aided Design) methods allows designers to define parts and assemblies and utilize geometry for simulations, analysis and prototyping. CAE methods [18-20] enable virtual prototype simulations and static, kinematic and dynamic analysis.

Topology optimization is a useful tool for product design. It is used in many industries, like the car and plane industries. Additive manufacturing technologies have also increased how often topology optimization is used. Topology optimization and additive manufacturing work well together to make prototypes more quickly. Topology optimization is a way of organizing materials in a design so that specific loads, boundary conditions and constraints are met. The plan is to make the structure lighter, but still as strong and stable as before [21, 22].

In this study, a rover mobile robotic structure was designed and developed. All the parts and assembly model were created using Computer Aided Design tools. The electronic hardware (Rgb - camera, raspberry pi, motor drivers etc.) were selected and integrated into the structure with proper mounting elements. FEA (finite element analyses) were conducted to confirm the strength and stability. Topology optimization was applied to decrease the weight and energy consumption of the system. Special power analyses tool was developed to calculate and to compare the energy consumption of the non-optimized and optimized structures. When compared to the literature, a useful power analysis tool was designed to validate the results of the topology optimization studies with the aspects of energy consumption and power requirement. This tool was developed as a GUI (graphical user interface), the researchers can consider their results and optimized structure outputs with the parameters of power requirements and energy consumption. By this way the efficiency of the optimization studies can be improved.

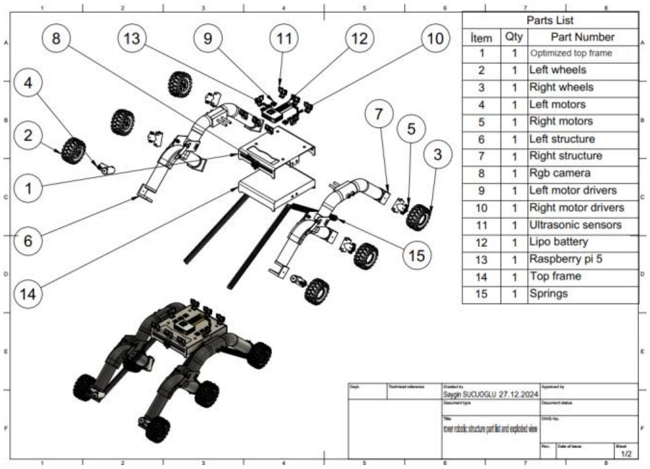
II. MATERIAL AND METHOD

A. Design of the Robotic Structure

In this part of the project, rover robotic structure was designed using Fusion 360 software. All the parts such as right-left structures, top frame, motor holders, sensor holders and raspberry pi case were created and assembled. The electronic hardware; rgb camera, distance measurement sensors, etc. selected properly and integrated into the robotic structure. The hardware mounting parts were designed. For the suspension and terrain adaptability, parts of the “rocker bogie” elements and springs were designed and assembled. The top frame material used as aluminum 6061. The right and left structure elements were selected as abs plastic material. The assembled structure of the rover robotic system was shown in Figure 1.

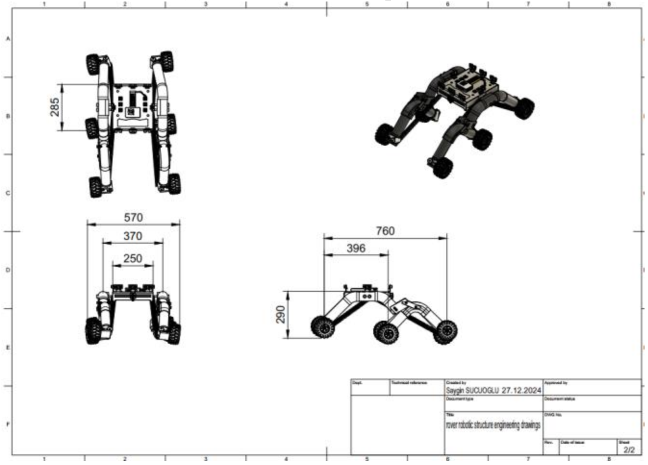
Fig. 1. Assembled structure of rover robotic system

After the 3d design process, the part list and exploded view and engineering drawings were created. Those documents were useful to determine the required parts and hardware. 6 pieces of DC motors and wheels placed into the system as motion elements. The robotic system was equipped with 8 pieces of HCSR-04 ultrasonic sensors to develop path planning and obstacle avoidance algorithms. Rgb camera was integrated for operation and algorithm development. Li-po battery, raspberry pi 5 and motor drivers were selected and integrated into the structure as energy source, main and motor controller, respectively. The part list and exploded view and engineering drawings documents were represented in Figure 2.



Parts List		
İtem	Qty	Part Number
1	1	Optimized top frame
2	1	Left wheels
3	1	Right wheels
4	1	Left motors
5	1	Right motors
6	1	Left structure
7	1	Right structure
8	1	Rgb camera
9	1	Left motor drivers
10	1	Right motor drivers
11	1	Ultrasonic sensors
12	1	Lipo battery
13	1	Raspberry pi 5
14	1	Top frame
15	1	Springs

(a) Part list and exploded view



(b) Engineering drawings

Fig. 2. Part list and exploded view and engineering drawings of rover robotic system

B. Engineering Analyses of Non-Optimized Structure

Engineering analyses with the methods of FEA were conducted to check the structural strength and stability of mechanical structure. One significant reason of the process of the FEA was to confirm the feasibility of the application of the topology optimization. For those, the top frame was assigned as aluminum 6061, loads were applied to calculate the factor of safety and stress values. The engineering analyses were conducted in Ansys Workbench 2024 Static Structural Environment. The loads (3, 10 and 25 N) caused from the weights of the components and motion of the robotic system were applied to the structure. Those load sets were shown in Figure 3.

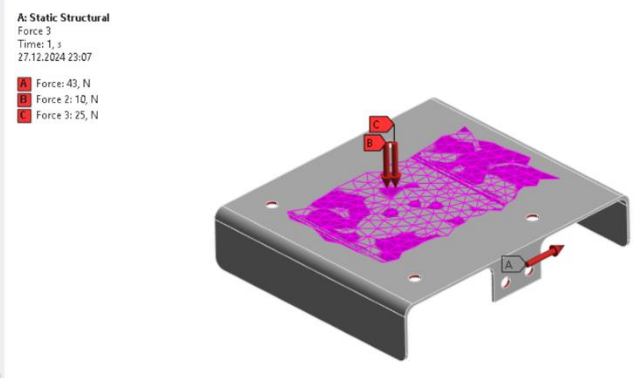


Fig. 3. Load cases of top frame

C. Topology Optimization Process

Topology optimization is a technique for optimizing material distribution within a design space, taking into account specific loads, boundary conditions and constraints. The objective is to reduce the weight of the structure while keeping or improving its strength and natural frequencies. The main aim of optimization is to determine the most appropriate material usage within the specified design area to achieve the desired structural performance. The process involves dividing the designed volume into smaller elements, creating a finite element analysis (FEA) model, and applying boundary conditions. During the analysis, the elements exhibit intermediate density values that approach 1 or 0 by employing penalization techniques such as the power law to penalize higher-density elements. This process ensures convergence towards solid and void regions to build the final structure. The material density is updated iteratively by the optimization algorithm to converge on a solution, achieving optimal performance and design volume. The final structure is determined by ensuring a smooth transition between solid and void regions. Two commonly preferred methods for determining the distribution of elements in topology optimization are Solid Isotropic Material Penalization (SIMP) and the Evolutionary Structural Optimization Technique (ESO). The stress based ESO method, typically employs von Mises stress for removal process. Firstly, a piece of material large enough to cover the area of the final design is divided into a fine mesh of finite elements. Loads and boundary conditions are applied, and a stress analysis is carried out using a finite element program. Since the structure has been divided into many small elements, the removal of material can conveniently be represented by any method. The stress level at each point can be measured by calculating an average of all the stress components. One of the most frequently used criteria for isotropic materials in this regard is von Mises stress. For plane stress problems, the von Mises stress is defined as;

$$\sigma^{vm} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_x\sigma_y} + 3\tau_{xy}^2 \quad (1)$$

Where σ_x and σ_y are normal stresses in x and y directions, respectively, and τ_{xy} is the shear stress. The stress level of each element is determined by comparing the von Mises stress of the element σ_e^{vm} to the maximum von Mises stress of the entire structure σ_{max}^{vm}. At the end of each finite element analysis, all elements that satisfy the following condition are removed from the model;

$$\frac{\sigma_e^{vm}}{\sigma_{max}^{vm}} < RR_i \qquad (2)$$

Where RRi is the current rejection ratio (RR). This limit value for RR is commonly used 25%. The cycle of finite element analysis and element removal is repeated using the same RRi value until a steady state is reached. This means that no further elements are deleted at the current iteration. At this stage, the evolutionary rate (ER) is introduced and added to the rejection ratio. It is evident that as the rejection ratio is increased, the cycle of finite element analysis and element removal is reinitiated until a new steady state is achieved [23-25].

Topology optimization processes were conducted using ESO method in Ansys Structural Optimization environment. The same load conditions with the engineering analyses were used. The type of optimization definitions was selected as topology density, the threshold value was selected as 40%. The new optimized structure recommendations with numerous iterations were found with the optimization calculations. Using info and design file output, a new optimized top frame was created (Figure 4).

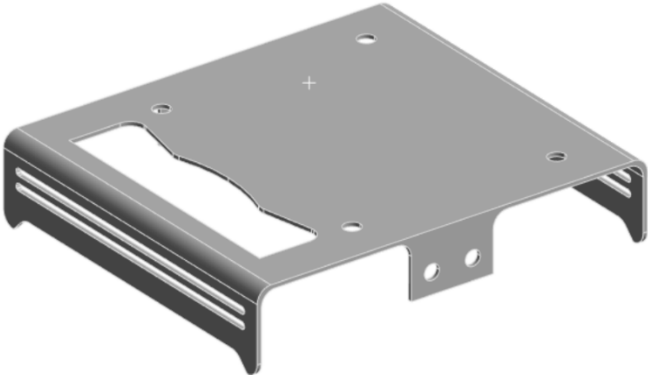


Fig. 4. Optimized structure

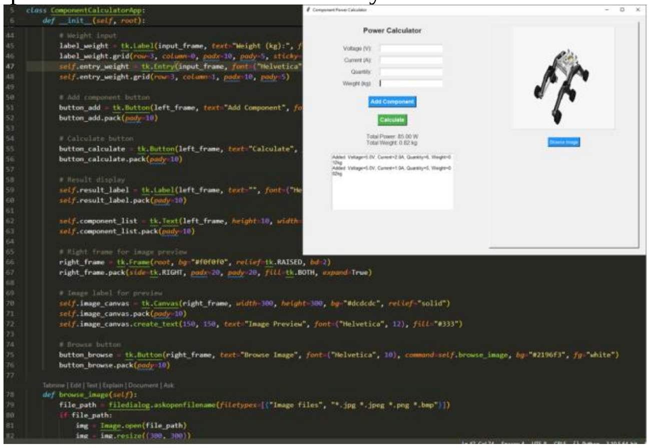
The weights of top frame decreased from 0.9 to 0.6 kg. This lightening was considered as promising for lower energy consumption. The structural engineering analyses were conducted with the same load cases of non-optimized structure to validate the structural strength of the new top frame.

D. Power Analysis Tool

Power analysis tool was created to facilitate energy consumption and weight analysis for robotic systems, utilizing Python’s tkinter library to create an useful graphical user interface (GUI). The application was employed to conduct a comparative power analysis of rover robotic structure by processing part lists that detailed components such as dc motors, battery, ultrasonic sensors, and chassis material. (Figure 5).

Users can use GUI by inputting component specifications, including voltage, current, quantity, and weight directly reflecting the part list data. Each component entry is added to a cumulative list to enable iterative and comprehensive analyses. Tool can dynamically calculate the total energy consumption and aggregate weight, supporting real-time design evaluation and optimization.

A core feature of the tool is its image visualization capability allows users to upload and display component images directly within the GUI. This property enhances the clarity of component selection and aids in correlating visual representations with numerical analysis.



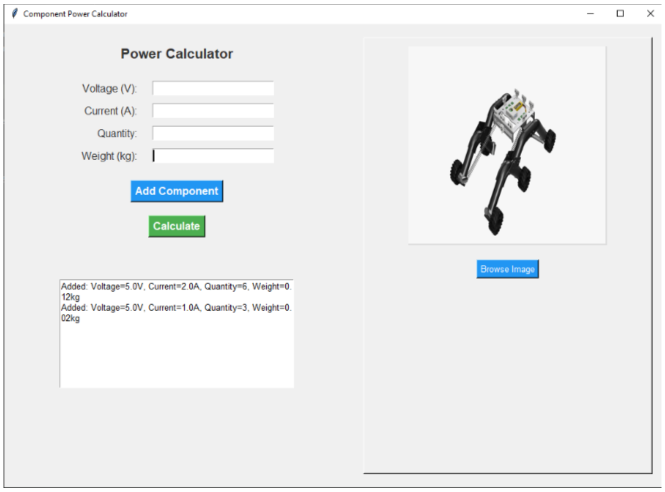
```
class ComponentCalculatorApp:
    def __init__(self, root):
        # Weight input
        label_weight = tk.Label(input_frame, text="Weight (kg):", f
        label_weight.grid(row=3, column=0, padx=10, pady=5, sticky=
        self.entry_weight = tk.Entry(input_frame, font=("Helvetica"
        self.entry_weight.grid(row=3, column=1, padx=10, pady=5)

        # Add component button
        button_add = tk.Button(left_frame, text="Add Component", fo
        button_add.pack(pady=10)

        # Calculate button
        button_calculate = tk.Button(left_frame, text="Calculate",
        button_calculate.pack(pady=10)

        # Result display
        self.result_label = tk.Label(left_frame, text="", font=("He
        self.result_label.pack(pady=10)

        self.component_list = tk.Text(left_frame, height=10, width=
        self.component_list.pack(pady=10)

        # Right frame for image preview
        right_frame = tk.Frame(root, bg="#f0f0f0", relief=tk.RAISED, bd=2)
        right_frame.pack(side=tk.RIGHT, padx=20, pady=20, fill=tk.BOTH, expand=True)

        # Image label for preview
        self.image_canvas = tk.Canvas(right_frame, width=300, height=300, bg="#dcdcdc", relief="solid")
        self.image_canvas.pack(pady=10)
        self.image_canvas.create_text(150, 150, text="Image Preview", font=("Helvetica", 12), fill="#333")

        # Browse button
        button_browse = tk.Button(right_frame, text="Browse Image", font=("Helvetica", 10), command=self.browse_image, bg="#2196f3", fg="white")
        button_browse.pack(pady=10)

    Tabnine | Edit | Test | Explain | Document | Ask
    def browse_image(self):
        file_path = filedialog.askopenfilename(filetypes=[("Image files", "*.jpg *.jpeg *.png *.bmp")])
        if file_path:
            img = Image.open(file_path)
            img = img.resize((300, 300))
```

```
Total Power: 85.00 W
Total Weight: 0.82 kg
```

Fig. 5. Design and development of power analysis tool

In the analysis of robotic structure designs, the tool enabled the calculation of total power requirements, energy consumption and weight distribution based on the provided part lists. This contributed to identifying design efficiencies, such as reduced power requirement, energy consumption and lighter frame configuration. The tool's ability to visualize components alongside performing critical calculations streamlines the iterative design process and improves documentation for engineering reports.

This tool is particularly valuable for early-stage design, prototyping, and comparative analysis of mechanical and electronic systems, where rapid assessment of power and weight characteristics is essential for informed decision-making and performance optimization (Figure 6).



```
Added: Voltage=5.0V, Current=2.0A, Quantity=6, Weight=0.
12kg
Added: Voltage=5.0V, Current=1.0A, Quantity=3, Weight=0.
02kg
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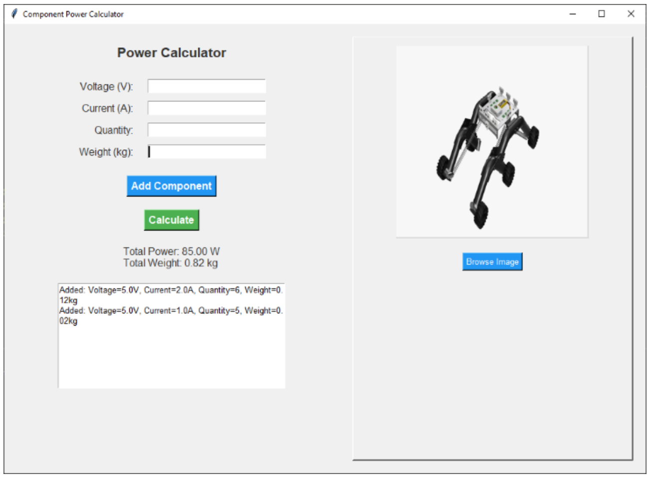

Total Power: 85.00 W
Total Weight: 0.82 kg

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Added: Voltage=5.0V, Current=2.0A, Quantity=6, Weight=0.
12kg
Added: Voltage=5.0V, Current=1.0A, Quantity=5, Weight=0.
02kg
```

Fig. 6. Calculations with power analysis tool

D. New Optimized Robotic Rover Structure

A new assembly model of rover robotic structure was created using optimized frame (Figure 7). The battery, controllers, sensors, camera and dc motors could be integrated into the new frame properly. The structure was constructed perfectly and prepared for power analyses.

Fig. 7. New optimized structure

III. RESULTS AND DISCUSSION

A. Engineering Analyses Results of Non-Optimized Structure

The results of the analyses were investigated to check the necessity of topology optimization. With the non-optimize structure, the weights of the top frame and entire structure were about 0.9 and 1.75 kg with the 3 mm of aluminum plate and 5 mm abs pipe thicknesses, respectively. The factor of safety was calculated at about 15, which was much more than required. The occurred von Mises stresses were also observed as about 2.6 MPa (Figure 8). With all those results, the application of topology optimization was considered as feasible to decrease the weight and energy consumption of the robotic system.

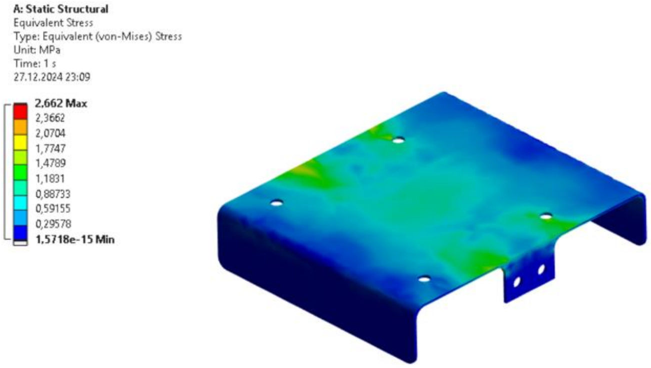
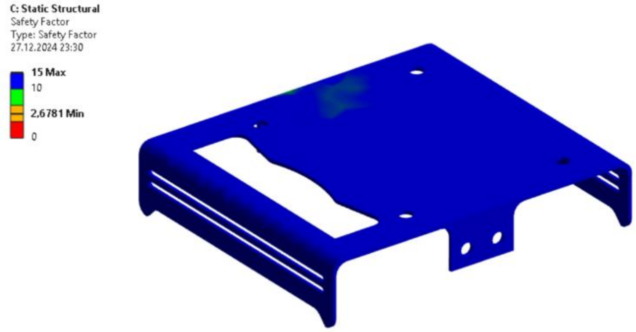


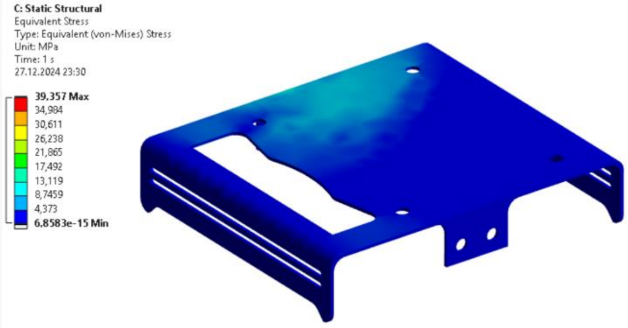
Fig. 8. Results from engineering analyses

B. Engineering Analyses Results of Optimized Structure

Engineering analyses results of the new optimized top frame were presented in Figure 9. It was observed from the engineering analyses of the optimized structure that the factor of safety values were about 2.6 and von Mises stresses were around 40 MPa. From those results, it was considered that robotic system could be established using a new optimized top frame to provide lower energy consumption and long-term usage.



(a) Factor of safety



(b) von Misses stresses

Fig. 9. Obtained results from engineering analyses

C. Power Analysis Results

Power analysis of the rover robot was conducted to evaluate the energy efficiency and overall performance of the optimized structure compared to the non-optimized version. This analysis aimed to quantify the improvements achieved through topology optimization, particularly focusing on reductions in weight, energy consumption, and power requirements.

The power analysis utilized standard electrical and energy calculation formulas, 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)

Key assumptions made during the analysis were as follows:

a. The standard lipo battery voltage was set at 11.1V (3S configuration).
b. DC motors were assumed to operate at 12V with a nominal current of 2A per motor.
c. Ultrasonic sensors drew 30mA at 5V.
d. RGB camera consumed 500mA at 5V.
e. The Raspberry Pi and motor controllers required 1A at 5V.

The comparison between the non-optimized and optimized robotic structures revealed significant improvements in energy efficiency. The data is given in Table 1.

TABLE I
DATA SUMMARIZATION OF POWER ANALYSIS

Component	Non-optimized	Optimized	Remarks
Frame weight (gr)	900	600	Optimized frame is lighter.
Total structure weight (gr)	1,750	1,450	Structure is lighter.
Total power requirement (W)	160	125	Optimized design requires less power.
Energy consumption per Hour (Wh)	160	125	Lower energy demands for same duration.

The obtained results indicated that the optimized design achieved a 33% reduction in frame weight, contributing directly to reduced energy consumption and increased operational efficiency. The total power consumption of the optimized robot was 35 W lower than the non-optimized structure.

The reduced weight achieved through topology optimization, resulted in decreased load on the drive motors, consequently lowering power requirement. This improvement extends the operational duration of the robot.

Additionally, the optimized design's lower energy consumption suggested a potential for using smaller or fewer battery modules without compromising operational time, thereby reducing overall system cost and weight further.

The power analysis results validate the effectiveness of topology optimization in enhancing energy efficiency and operational capacity. The optimized design not only achieved a 33% weight reduction but also demonstrated a 21% decrease in energy consumption.

IV. CONCLUSION

In this study, comprehensive design, development, topology optimization and power analysis studies of rover style robotic structure were conducted. All the parts and entire assemblies were created using CAD tools, all the required engineering analyses were applied to confirm the necessity of the topology optimization and structural strength of both non-optimized and optimize structures. A power analysis tool was also created to compare the energy consumptions of those optimized and non-optimized structures. It can be concluded from all analyses results:

a. The frame of the structure was lightened with 33% ratio,
b. The new designed frame structure was structurally strong with the factor of safety value of 2.6
c. The power requirement of the rover robotic structure was decreased as 21%,
d. A useful power analysis tool was designed and developed. The designers and researchers can use this tool to validate their structural and topology optimization studies,
e. Proper "rocker bogie" mechanism was designed and integrated into the rover mobile robotic system for terrain adaptation,
f. The required hardware such as main controller, dc motor controllers, and ultrasonic sensors were selected and integrated into the structure properly,
g. A mobile rover robotic structure was designed and developed.

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