Design Changes, Saving Materials and Energy in Food Serving Robot-An application of Topology Optimization

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***Abstract*— This paper explores the use of topology optimization in enhancing the design of an automated guided vehicle, known as Bento-bot. The fear of disease transmission has led to an increased interest in utilizing robots in the food service industry, particularly in indoor food delivery. The Bento-bot is a robot designed to deliver food to the desired table, and this study seeks to optimize its design to improve stability and reduce energy consumption, thereby enhancing battery life. This paper provides a comprehensive review of AGV technology and topology optimization before presenting the Bento-bot design. Using the Bento-bot as a case study, the paper applies topology optimization techniques to enhance the robot's stability and reduce energy consumption. The results indicate that the optimized design enhanced the robot's performance, thus increasing the robot's battery life. This study is expected to benefit researchers, designers, and manufacturers in the food service industry.**

- ***Keywords*— Automated Guided Vehicle (AGV), Food service, Topology optimization, Mass reduction, Energy consumption, Torque, Power***

I. INTRODUCTION

The fear of disease transmission has led to a reluctance among people to have direct contact with others, including restaurant waiters, this combined with labor shortages, has pushed restaurants to consider using robots [1]. The use of robots in restaurants has been suggested globally as a solution to the problem of ensuring food hygiene during delivery, as there is no guarantee of hygiene when food is handled by human waiters [2]. Therefore, there is a pressing need to develop indoor food delivery robots that use Automated Guided Vehicle (AGV) technology [3].

AGVs are self-propelled machines that are commonly utilized in industrial settings to automatically transport materials between pickup points and drop-off points. These mobile devices are primarily utilized for material handling tasks, particularly in facilities such as manufacturing plants, distribution centers, warehouses, and terminals [4]–[7]. AGVs use navigation sensors such as lasers, cameras, and RFID tags to navigate their environment and avoid obstacles [8]–[11]. Control systems manage AGV movements and interactions with other equipment and personnel in the facility [12], while rechargeable batteries power AGVs to operate for extended periods without human intervention[13].

In their study, A. Suryowinoto et al. [14] aim to develop an automated forklift robot prototype that uses AGV technology to collect and place goods in a miniature stacking shelf system, which is remotely monitored via an Android-based device. The robot's navigation system employs photodiodes and proximity sensors, while its control system has two input controllers - one on the robot itself and the other on a handheld device running the Android operating systems. The experimental results demonstrate that the forklift robot can successfully perform the task of picking up and depositing items in the stacking shelf system, with an average processing time of around 43 seconds.

Another study on an AGV with an automatic pick-and-place system based on a scissor lifting platform was proposed for transporting medicines in high-mix low-capacity medicine warehouses to various departments in hospitals. The system utilizes multi-modal control, magnetic stripe navigation, RFID site labels, ultrasonic sensors, and LiDAR for safety. The device was designed and analyzed using Finite-element analysis, and the system met design requirements and specific work tasks according to experimental results [15].

Topology optimization is a design process that uses mathematical algorithms to optimize the shape and layout of a structure or system while meeting specific design criteria and constraints [16]. The objective of topology optimization is to find the optimal material distribution in a given design space, which maximizes the performance of the system while minimizing its weight, cost, or other design metrics [17].

X. Mo et al. [18] used topology optimizations to create a novel cooling plate. The optimized cooling plate's velocity, pressure, and temperature are contrasted with those of the conventional straight cooling plate. Following the comparison, a more in-depth analysis was done to determine how the flow rate and inlet temperature affect the performance of the improved cooling plate. The results indicate that the novel cooling plate created by the topology optimization method could be a workable and highly effective method for managing battery heat.

To reduce weight, P. Yao et al. [16] used ABAQUS to perform structural topological optimization on an upper arm of an industrial welding robot under the harshest operating conditions, both in static and dynamic working scenarios. The results of the repeatability tests revealed that the optimized upper arm's overall performance had been enhanced in comparison to the original one.

Using conventional engineering design concepts and a topology optimization technique, D. J. Munk et al. [19] created a landing gear for a light aircraft. It was determined that a weight reduction of 40% was possible when employing topology optimization techniques. Additionally, they have used the design of an aviation engine mount to illustrate the topology optimization algorithm. A least-weight design was identified, raising the structure's stress level to its maximum value, and preventing individual parts from buckling.

Recent research has focused on multi-scale or hierarchical structural optimization design and topology optimization considering additive manufacturing constraints. A study by J. ZHU et al. [20] emphasizes the importance of integrating material, structure, process, and performance in the pursuit of high-performance, multi-functional, and lightweight production through topology optimization for additive manufacturing.

Elango et al. [21] conducted a topology optimization study on a multi-modal robot with walking and flying capabilities. Using the Solid Isotropic Material with Penalization (SIMP) algorithm, the study focused on reducing the weight of each component of the robot while maintaining its structural integrity and performance requirements. The results had shown that the optimized design led to a maximum weight reduction of 54.4% compared to the initial design.

This paper aims to optimize the Bento-bot design by utilizing Topology Optimization to enhance stability and reduce energy consumption, thus enhancing the battery life.

II. Materials & Methods

A. *Bento-bot Model*

Bento-bot, the designed AGV, has dimensions of (290x480x198) mm as shown in Figure 1. Furthermore, Bento-bot presents a unique and practical solution that encompasses multiple features such as a sound system, locomotion system, overlapping door, and an intelligent navigation system. This AGV has been designed to deliver orders on custom-designed food trays, providing an efficient solution for delivering food to the desired table from its home position. The navigation system, which incorporates a line-following system and QR code readers, utilizes a master-slave network to efficiently manage traffic on the track. The robot is divided into two sections: the food compartment section and the electronics compartment section. Overall, this AGV is a promising design that has the potential to advance food service and delivery cost-effectively.

B. *Topology Optimization*

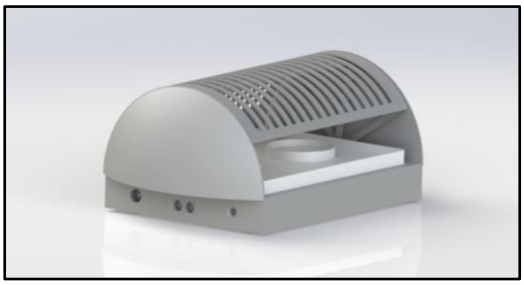
Topology optimization was conducted to enhance the stability and reduce the energy consumption of Bento-bot design, thus enhancing the battery life. Static structural analysis was conducted for the food compartment and electronics compartment to set design requirements for topology optimization, which is used to validate the structural integrity of the optimized one. Loads were defined considering the robot is fully loaded with 7.5 kg. Equivalent stress, total deformation and safety factor were used to compare the new and the old design.

1) *Food Compartment*

The food compartment of Bento-bot consists of two main parts including the food tray and the overlapping doors.

Fixed supports were employed for the food tray as a boundary condition. To retain the layout of the food tray, the plate holders, base, and sides were set as exclusion regions. Furthermore, the objective of the topology optimization was set to minimize the mass by 60% to 75%. Once the retained region obtained, was the food tray was further refined to attain a manufacturable and attractive design. Moreover, static structural analysis was performed to validate the structural integrity of the optimized design. Figure 2 shows the overall topology optimization process for the food tray.

Figure 1. Optimized Bento-bot design.



Cylindrical supports were employed for the overlapping doors, considering their weight as the main load. The overlapping doors were optimized by setting the outline of the doors and the contact region between the motor shaft and the door as exclusion regions. Additionally, the topology optimization was set to minimize the mass by 30% to 40%. The rest of the process was similar to the food tray optimization. Figure 3 shows the doors before and after the optimization.

2) *Electronics Compartment*

The Electronics compartment contains all the electronic parts of the Bento-bot including motors, batteries, ...etc.

Figure 2. Optimization process of food tray.

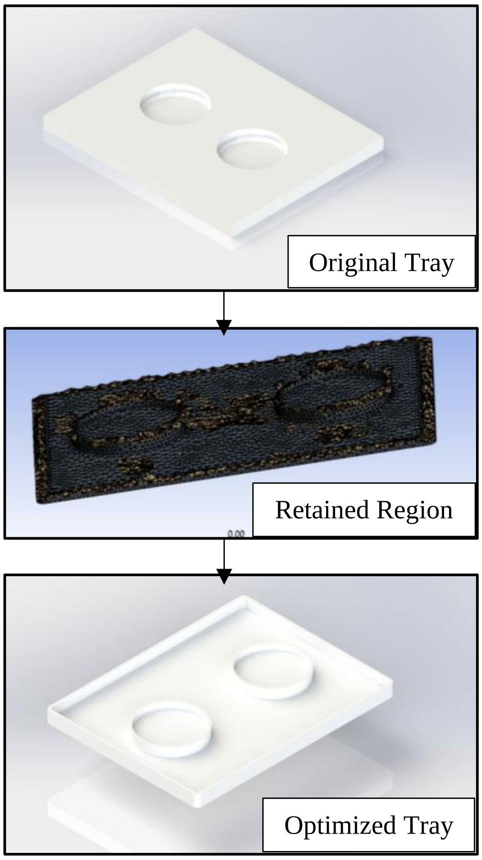
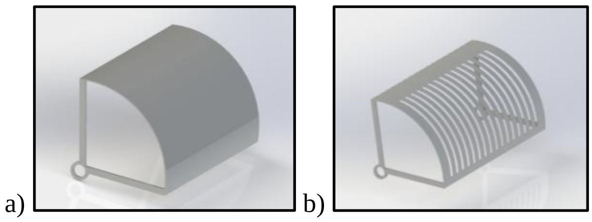


Figure 3. a) Original door; b) Optimized door.



For boundary conditions, fixed supports were employed for the electronics compartment base and the load was the total mass of the AGV excluding the mass of the wheels and the electronics compartment itself. Since the electronics compartment is the most critical part of the AGV, a different mass reduction approach was adopted for the optimization. Thus, a less dense material that can withstand the fixed and variable loads applied on the AGV was required. Hence, several materials were employed and analyzed, such as PEEK, ABS plastic, POM. Consequently, ABS plastic was the material of choice for the electronics compartment, while PEEK was selected as a support material due to its high strength. Static structural analysis was performed to validate the structural integrity of the new material.

3) Parts & Materials

Table I. shows the selected materials for each part of Bento-bot. As part of optimization, the electronics compartment material and support material was changed to achieve lower mass. The selected materials are Polyoxymethylene (POM), Acrylonitrile Butadiene Styrene (ABS), and polyetheretherketone (PEEK).

Table II. shows the material properties of interest. The density, melting point, and tensile strength are crucial parameters of comparison in the current study.

III. RESULTS & DISCUSSION

A. *Mass Reduction*

Upon conducting topology optimization, a total mass reduction of 45.5% was achieved, which is equivalent to 4.55 kg. Further details of mass reduction for all components are shown in Table III.

TABLE I. PARTS AND MATERIALS

Part	**Material**	
	Old	***New***
Tray	POM	POM
Door	POM	POM
Electronics Compartment	Aluminum Alloy	ABS
Support	Aluminum Alloy	PEEK

TABLE II. MATERIAL PROPERTIES

Material list	**Material Properties**		
	Density (kg/mm^3)	***Melting Point (°C)***	***Tensile Strength (MPa)***
POM	1.49×10^{-6}	175	82.75
PEEK	1.455×10^{-6}	350	254.6
ABS	1.05×10^{-6}	200	36.13
Aluminum Alloy	2.77×10^{-6}	660.3	280

TABLE III. MASSES OF PARTS BEFORE AND AFTER OPTIMIZATION

Part	**Old Mass (kg)**	**New Mass (kg)**	**Mass Reduction (kg)**
Tray	3.337	0.9	2.437
Inner door	0.2835	0.18784	0.09566
Outer door	0.31976	0.22003	0.09973
Electronics Compartment	3.5924	1.362	2.2304
Support	0.09993	0.05259	0.04734
Electronics[a]	1.825	1.825	0

a. Electronics include motors, batteries, and sensors.

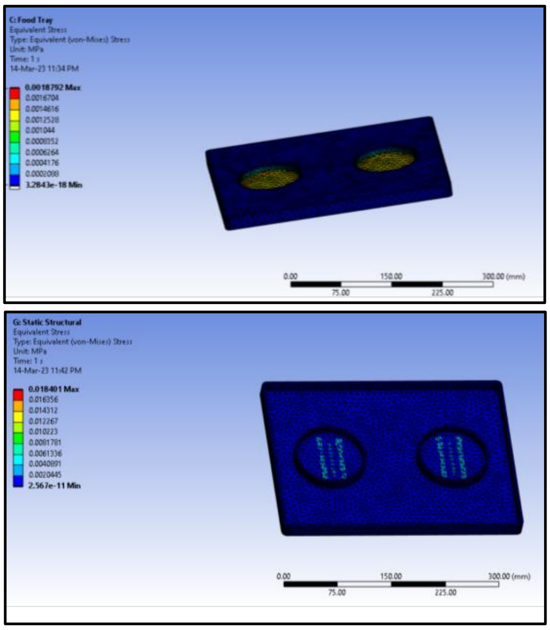
Originally, the rotational moments of inertia values for the outer and inner doors were 18.328 kg.mm^2 and 15.180 kg.mm^2 respectively. The stability of the doors' movement is directly related to their inertia [22]. In addition, the inertia is directly proportional to the mass [23]. Hence, the mass reduction of the door will affect the stability of the movement mechanism. Intuitively, it is desired to increase doors' stability to ensure safety while serving food. With the optimized door design, mass reduction ratios of 33.74% and 31.19% for the inner and outer doors, respectively, were achieved, causing the rotational moment of inertia to drop to 15.18 kg.mm^2 for the outer door and 10.556 kg.mm^2 for the inner door.

The food tray mass was reduced by 73.03% from the original design. As a result, the loads on the driving motors are reduced, causing the required torque to decrease. Thus, improving the motor's efficiency while maintaining the load carrying capacity, the maximum equivalent stress increased by 0.01652 MPa due to the surface area reduction, while the total deformation is negligible, and the safety factor remains at 15 for both designs.

Figure 4. a) Total deformation of original food tray; b) Total deformation of optimized food tray.

a)

b)



Formerly, the electronics compartment was made of aluminum alloy with a total mass of 5.52 kg causing a high load on the driving motors. The total mass of the electronics compartment was reduced by using a less dense materials. PEEK is used for the support, and ABS plastic is deployed for the compartment. Properties of interest for the materials selected are shown in Table II. A mass reduction of 41.28% was achieved upon optimizing the materials for the electronics compartment. The maximum deformation increased from 0.013583 mm to 0.35522 mm and the maximum equivalent stress increased by 2.11 MPa which is due to the fact that plastics have less strength than aluminum alloy. Nevertheless, the safety factor remains constant.

Figure 5. a) Equivalent stress on original electronic compartment; b) Equivalent stress on optimized electronic compartment.

a)

b)

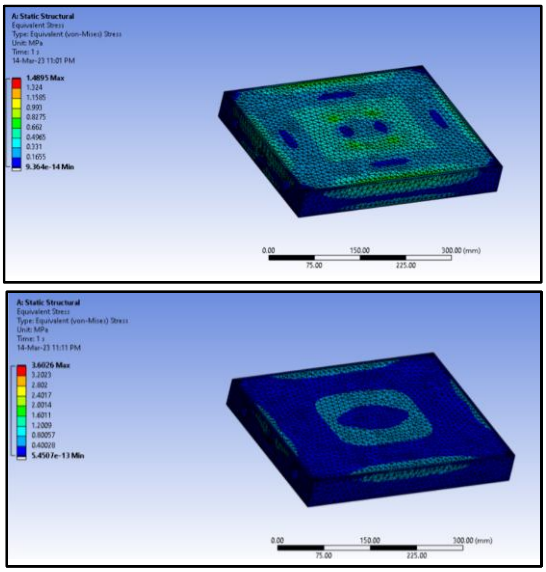


Figure 6. a) Equivalent stress of original electronic compartment; b) Equivalent stress of optimized electronic compartment.

a)

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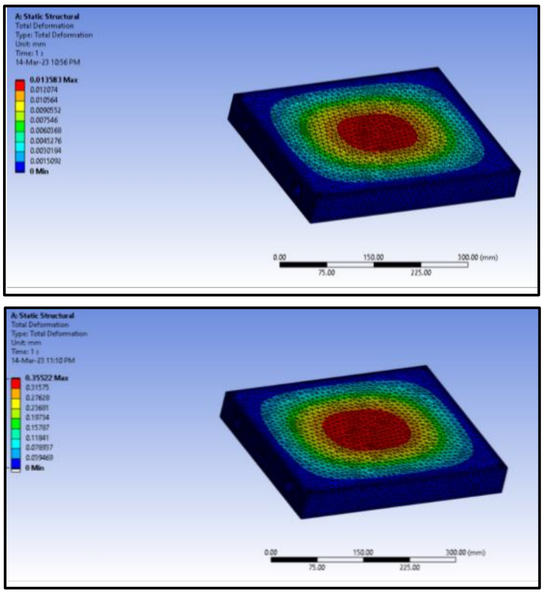


B. Energy Reduction

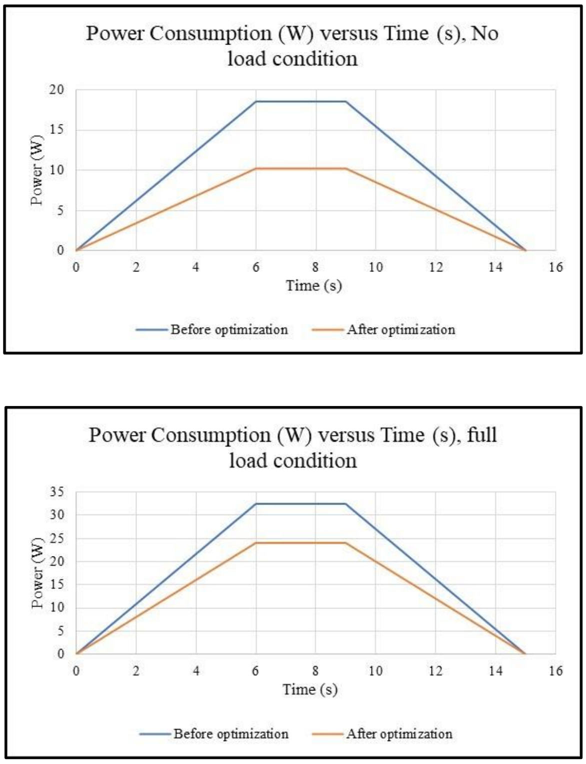
The goal of this analysis was to use topology optimization to reduce the weight of a robot, which it did by making Bento-Bot much lighter. Therefore, it is essential to examine the impact of mass reduction on the energy consumption of the DC motors that are used to locomote the AGV. To demonstrate how mass reduction affects energy consumption, Figure 7 illustrates the power consumption of the AGV both before and after mass reduction, under full load and no-load conditions, assuming the load to be 7.5 kg and different velocities. The graph demonstrates a noticeable decline in power consumption following the reduction in mass, suggesting a decrease in energy consumption as well.

To understand how reducing the mass of Bento-Bot affects its energy consumption, it is needed to consider the force required to move the AGV, which is proportional to its mass according to Newton's second law. Therefore, reducing the mass of Bento-Bot will lead to a decrease in force required to move the robot. In addition, the frictional force acting on the AGV's wheels will also be reduced with the decrease in mass. Therefore, less energy will be needed to overcome the frictional force. Moreover, the total force required to move Bento-Bot must be greater than the sum of the tractive force required to move the AGV, and the force required to overcome friction. With the reduction in mass, the total force required to move the robot will be reduced, leading to a decrease in energy consumption. As a result, the mass is directly proportional to the power. This analysis can be represented by the following equations [24]:

Figure 7. a) Difference in power consumption of two DC motors under different velocities in Full-load condition; b) Difference in power consumption under different velocities in no-load condition.

a)

b)



$$F_i = ma \quad (1)$$

$$F_f = \mu N \quad (2)$$

$$\mathrm{F}_\tau > \mathrm{F}_i + \mathrm{F}_f \quad (3)$$

$$\mathrm{F}_\tau = \frac{T}{r} \Longrightarrow T = \mathrm{F}_T \times r \quad (4)$$

$$\omega = \frac{v}{r} \quad (5)$$

$$P = \tau \times \omega \quad (6)$$

$$\frac{P_1}{P_2} = \frac{m_1}{m_2} \quad (7)$$

where:

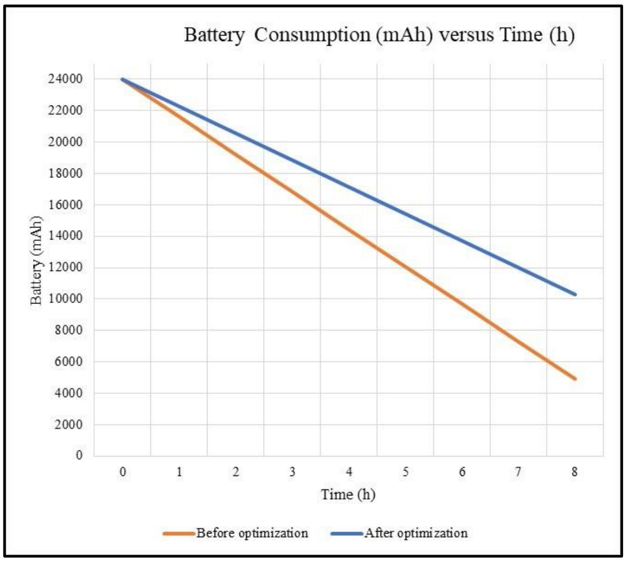
F_i – Force inertia.
m_1 – Mass of Bento-bot before mass reduction.
m_2 – Mass of Bento-bot after mass reduction.
a – Desired acceleration.
F_f – Friction force.
μ – Friction coefficient.
N – Normal force.
F_τ – Torque force.
T – Motor torque.
r – Radius of the wheel.
ω – Angular velocity.
r_{in} – Diameter of the inner door.
r_{out} – Diameter of the outer door.
P – Power.

After analyzing the power consumption of Bento-Bot's motors under full load and no-load conditions, it was determined that the motors consumed 18.52 W and 32.4 W, respectively, before the AGV's mass was reduced. However, after the mass reduction, the power consumption decreased to 10.17 W in no-load conditions and 24.05 W in full-load conditions. This indicates that the mass reduction has a significant effect on the energy efficiency of the robot, resulting in a decrease in power consumption of 45.5% and 25.8% under no-load and full-load conditions, respectively. These results demonstrate the effectiveness of topology optimization in lowering the robot's mass, which can result in significant energy savings in real world applications.

TABLE IV. PARAMETERS OF BENTO-BOT

Parameters	Value	Unit
m_1	10.015	kg
m_2	5.5	kg
v	1.8	m/s
a	0.3	m/s^2
r	0.0254	m
μ	0.05	–
r_{in}	0.145	m
r_{out}	0.139	m

Figure 8. Battery lastness at full load condition.



Similarly, after analyzing the power consumption of the servo motors responsible for rotating the inner and outer doors, it was found that the inner door required 0.309 W of power before the AGV's mass was reduced, but only 0.205 W after the reduction.

After the mass reduction, the outer door motor's power consumption decreased from 1.13 W to 0.78 W. These results illustrate that the reduction in mass has a positive impact on the energy efficiency of the AGV's servo motors, leading to a significant reduction in power consumption. The inner door and outer door motors reduced their energy consumption by 33.3% and 30.1%, respectively.

IV. CONCLUSION

In conclusion, the Bento-bot was redesigned by conducting Topology Optimization and resulted in enhancements in its stability, energy consumption, and improvement in its battery life. The utilization of topology optimization led to a 45.5% reduction in the total mass of the Bento-bot, resulting in a corresponding 45.5% reduction in power usage of the driving motors under no-load conditions. Furthermore, under full-load conditions, the power usage of the driving motors was reduced by 25.8%. Moreover, the reduction of the inner door's mass resulted in a reduction of 33.3% in the power consumption of the corresponding servo motor. while a 30.1% reduction in the outer door servo motor power consumption was achieved. These findings demonstrate the effectiveness of topology optimization in reducing power consumption and increasing energy efficiency in practical applications.

V. DECLARATION

All authors listed contributed equally.

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