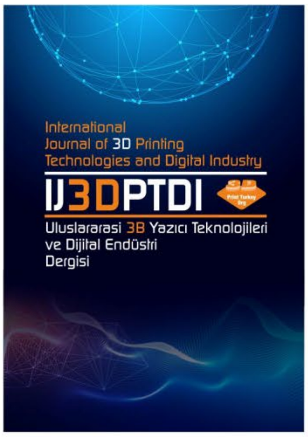

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FINITE ELEMENT ANALYSIS AND PRODUCTION OF A BALANCE ROBOT DESIGNED TO BE USED IN THE FIELD OF ADVERTISING

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ABSTRACT

This study presents the finite element analysis and prototype development of a self-balancing robot designed for applications in the advertising sector. The structural behavior and dynamic properties of the robot were analyzed using static, modal, and rigid body simulations in ANSYS software. Static analysis confirmed the mechanical durability of the robot by evaluating the forces acting on the motors and body, while modal analysis identified potential resonance conditions. Notably, in the third vibration mode, a deformation of 330.24 mm at 52.169 Hz was observed, indicating a critical resonance issue. To enhance structural efficiency, topology optimization was applied to the outer casing, resulting in a 14% reduction in mass (from 0.45392 kg to 0.39069 kg) while maintaining structural integrity. During the experimental phase, the prototype successfully demonstrated autonomous movement using integrated distance sensors. However, initial tests revealed a wobbling motion due to insufficient motor power, which will be addressed in future iterations by incorporating higher-torque motors. The proposed robot has the potential to serve as an interactive advertising tool, capable of attracting attention through dynamic motion and engaging promotional content display. Future work will focus on enhancing stability and refining control algorithms to improve performance in real-world advertising environments.

Keywords: Self-Balancing Robot, Finite Element Analysis, Topology Optimization, Advertising.

1. INTRODUCTION

Balance robots stand out as a significant advancement in the field of robotics. These robots have the ability to balance on two wheels and typically maintain stability and movement using PID control algorithms. These algorithms regulate the speed and direction of the motors to ensure the robot remains in equilibrium [1].

Self-balancing robots, a subset of mobile robots, are designed to maintain dynamic balance using control theory principles, often modeled as an inverted pendulum. Their ability to remain upright while navigating various terrains makes them ideal for applications requiring both balance and mobility, such as personal transporters and service robots. Among the different configurations, two-wheeled models are the most common, utilizing horizontally positioned wheels and control algorithms like PID controllers to ensure stability [2,3].

Spherical self-balancing robots, which operate on a single sphere, provide exceptional maneuverability and dynamic balance adjustments. These robots are classified not only by their physical structure but also by their control strategies, incorporating advanced techniques such as fuzzy logic and reinforcement learning [4]. Beyond mobility and service applications, their autonomous navigation and balancing capabilities open new possibilities in the advertising industry, enabling dynamic and interactive promotional strategies. [5].

Robotic applications in advertising are expanding, particularly with the integration of service robots into marketing strategies. A notable example is the deployment of multiple robots for distributed questionnaire services at tourist sites and exhibitions, enhancing visitor engagement while simultaneously collecting valuable consumer data to optimize marketing strategies [6].

Moreover, the development of marketing systems that integrate robots with smartphones has been explored, highlighting the synergy between mobile technology and robotics in creating interactive advertising experiences. These systems enable real-time customer engagement and feedback, further enhancing the effectiveness of marketing campaigns [7]. This technological integration allows for a more personalized advertising approach, tailored to individual consumer preferences and behaviors.

In the hospitality sector, consumer acceptance of service robots is influenced by factors such as innovativeness and personal norms, underscoring the importance of marketing strategies that address psychological and social dynamics. Likewise, the adoption of service robots in advertising aligns with broader robotics trends, particularly the rise of collaborative robots ("cobots"), which enhance efficiency by working alongside humans in marketing operations [8,9].

Recent studies indicate that social robots in public spaces, such as shopping malls, function as effective advertising tools by engaging users and distributing promotional materials. Research suggests that adapting their communication styles enhances their effectiveness, making them more engaging and impactful than traditional advertising methods [10,11]. Self-balancing robots are expanding beyond conventional roles, evolving from interactive kiosks into dynamic promotional tools in marketing and retail. Their ability to enhance customer engagement, personalize experiences, and simulate human-like interactions makes them increasingly valuable in advertising applications [12].

Additionally, their autonomous navigation enables direct product delivery, optimizing the shopping experience and efficiency [13]. The marketing potential of self-balancing robots goes beyond mobility, offering creative branding opportunities. They can be customized with brand colors and logos, transforming into mobile advertisements that attract consumer attention [14]. Their interactive capabilities, such as voice and visual engagement, enhance brand recall and create memorable experiences. Utilizing these robots in promotional events and experiential marketing campaigns can significantly boost consumer engagement and drive sales [15].

Self-balancing robots, traditionally used for mobility and personal transportation, are now emerging as dynamic tools in advertising. Their ability to navigate autonomously, engage users interactively, and serve as mobile promotional platforms offers a significant advantage over static advertising methods. By integrating robotics with marketing strategies, these robots enhance consumer engagement, brand visibility, and personalized advertising experiences. This study highlights the potential of self-balancing robots to transform conventional advertising approaches, making them a valuable asset in modern marketing.

2. MATERIAL AND METHODS

This study presents the design and fabrication of a two-wheeled self-balancing robot optimized for advertising applications. Stability and durability were ensured through a 3D model, followed by static, modal, and rigid body dynamics analyses in ANSYS. Static analysis assessed mechanical strength, modal analysis identified natural frequencies to prevent vibrations, and rigid body dynamics simulated real-world motion for smooth indoor operation. Topology optimization reduced the robot's mass by 14%, enhancing mobility while preserving structural strength. Polylactic Acid (PLA) was chosen for its lightweight, cost-effectiveness, and aesthetic appeal, as well as its biodegradable nature, supporting sustainable marketing solutions. Designed as an interactive advertising platform, the robot features dynamic mobility and customizable content display. Manufacturing utilized FDM 3D printing for high-quality, rapid production. Optimized printing parameters included a 0.4 mm nozzle diameter, 0.2 mm layer height, and 30% infill density. A print speed of up to 600 mm/sec significantly reduced production time, while an extrusion temperature of 200°C and a print bed temperature of 60°C ensured dimensional stability and minimized errors.

2.1. Design

The mechanical design of the robot was modeled using Autodesk Inventor software. The main body was carefully designed with a balanced structure, ensuring that the center of gravity remains between the wheels to enhance stability and maneuverability during movement. To ensure robustness, studs and mounting elements were meticulously selected to keep all components securely in place.

PLA was specifically selected for this application as it offers sufficient mechanical strength while remaining lightweight, thereby reducing the load on the motors and improving energy efficiency. Additionally, its smooth surface finish enhances the aesthetic appeal, making it particularly suitable for advertising applications. Since the robot is intended for indoor use, PLA's moderate thermal resistance and biodegradability further support its suitability for this project. The image of the designed model is presented in Figure 1 with enhanced resolution for improved clarity.

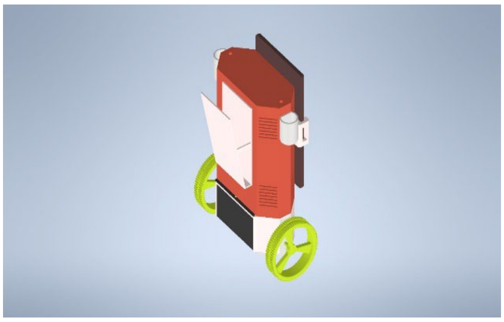

Figure 1. Designed model of the self-balancing robot

2.2. Static Analysis

The forces applied to the motors and the body in the motion joint of the robot and the forces that may occur during the movement are discussed in detail within the scope of static analysis. Stress, strain and deformation results were carefully calculated in line with the effects of these forces. This study is a basic reference for ensuring the mechanical durability of the snake robot and optimizing the design. In line with the calculations performed using PLA material during the analysis process, the physical prototype will also be built using PLA material during the production phase of the design. Table 1 presents the main properties of PLA material.

Table 1. The properties of PLA [16].

Properties	Units	Values
Density	*g/cm*^{3}	1.24
Tensile Strength	*MPa*	45-65
Elongation at Break	*%*	5-10
Young's Modulus	*GPa*	2.7-16
Coefficient of Thermal Expansion	*µm/m·K*	68-72

The boundary conditions applied to the robot model are given in Figure 2.

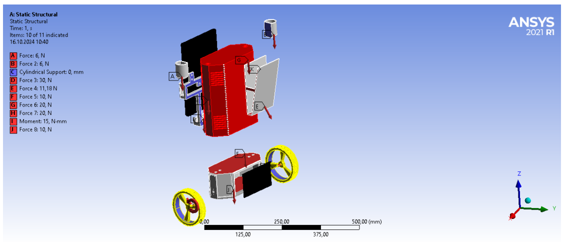

Figure 2. Boundary conditions defining constraints and external forces on the robot model

After applying these boundary conditions, total deformation, strain and stress results were obtained. These results are presented in Figures 3, 4 and 5, respectively.

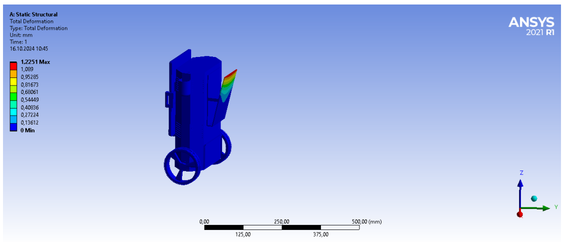

Figure 3. Total deformation results of the robot model

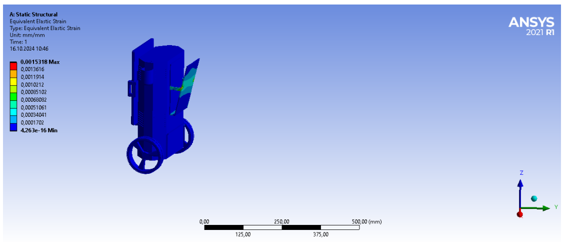

Figure 4. Strain distribution in the robot model

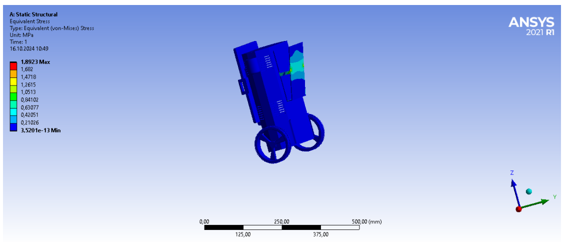

Figure 5. Stress distribution in the robot model

The total deformation, stress and strain values obtained as the output of the analysis results are presented in Table 2.

Table 2. Results of static analysis

Results	Units	Values
Total Deformation	*mm*	1.2251
Elastic Strain	*Mm*	0.0015
Stress	*MPa*	1.8923

2.3. Modal Analysis

A modal analysis was performed to evaluate the dynamic vibration characteristics and structural integrity of the robot. This analysis aims to examine the possible vibration effects on the structure by determining the natural vibration modes and frequencies of each component. The forces due to the motors and other forces that may occur during motion were evaluated. In this way, an important guide is provided to secure and optimize the mechanical stability of the robot. The analysis results obtained provide a better understanding of the flexibility and dynamic behavior of the robot and provide a basic reference for improvements to be made in the design process. The total deformation result for the first mode value are presented in Figure 6.

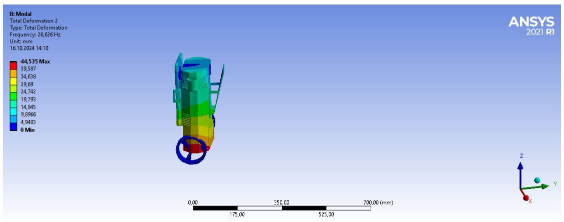

Figure 6. First mode shape and corresponding natural frequency of the robot model

As a result, a total of 6 mode values were obtained. Each mode has different frequency values and different deformation values depending on these frequencies. The results are presented in Table 3.

Table 3. Modal analysis results with natural frequencies and deformations.

Mode	Frequency(Hz)	Deformation(mm)
1	0,03	23,701
2	26,626	44,535
3	52,169	330,24
4	98,793	514,93
5	101,39	145,98
6	118,09	271,92

2.4. Rigid Analysis

A rigid analysis was performed to predict the motion of the robot. This analysis was performed to simulate the joint motion of the robot under certain moment values, to understand how the robot will react under real-world conditions and to determine the necessary measures to stabilize the motion. Furthermore, this analysis, performed before prototype production, helps to identify potential errors and opportunities for performance improvement that may arise during the design process. The result of a 600 mm movement on a flat surface is shown in Figure 7.

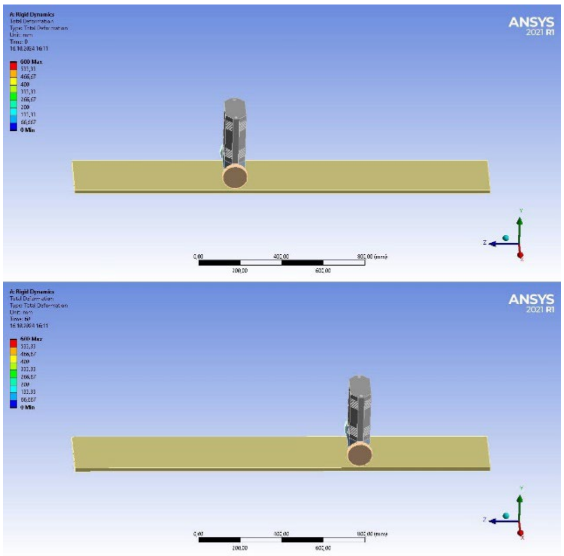

Figure 7. Rigid body analysis simulation of the robot model

2.5. Topology Optimization

Topology optimization (TO) is a computational design technique that seeks to optimize the material layout within a given design space, subject to specified loads and boundary conditions. This method allows for significant flexibility in structural design, enabling both topological and geometrical changes to achieve high-performance structures [17]. The foundational concept of TO was introduced by Bendsøe and Kikuchi in 1988, and since then, it has evolved into a robust field of study with numerous applications across various engineering disciplines [18,19].

In the outer mold of the robot, topology optimization was performed for mass and volume reduction. In the optimization process, PLA (Polylactic Acid) was selected as the material used and these material properties were assigned to the part to be optimized. In this study, the initial part mass of 0.45392 kg was reduced to 0.39069 kg at the end of the optimization process. This optimization, which was achieved after 27 iterations in total, resulted in a mass reduction of approximately 14%.

Topology optimization is based on the principle of using only the necessary material and reducing unnecessary masses by improving the part geometry. In this process, the mechanical properties and strength of the part are preserved, increasing productivity, especially in the production process, and improving the overall performance of the robot. The results obtained show that a lighter and more optimized structure can also contribute to a reduction in production costs and energy savings. The appearance of the part before the topology optimisation is presented in Figure 8 and the final version after the optimisation process is presented in Figure 9. These two figures provide an opportunity to visually compare the mass reduction and structural improvements in the part as a result of the optimisation process.

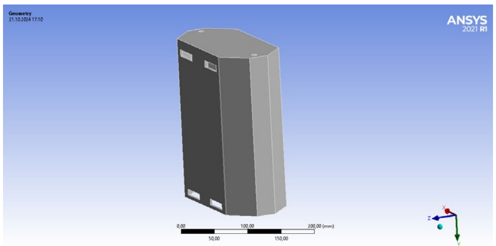

Figure 8. Robot model before topology optimization

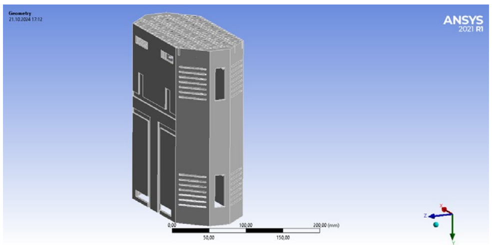

Figure 9. Robot model after topology optimization

The total deformation, stress and strain values obtained as a result of the optimisation are compared in a table for the pre- and post-optimisation cases. This table was created in order to analyse in detail the mechanical effects of structural changes on the part. The differences between the deformation, stress and strain values show the contribution of the optimisation to the performance and the improvements in part strength. These results are given in Table 4.

Table 4 (A: Elastic Strain (mm), B: Stress (MPa), C: Total Deformation (mm), D: Weight (Kg) shows the comparison table of the model before and after optimization.

Table 4. Comparison Table

Target Variable	A	B	C	D
Before Optimization	0,0007	1,064	0,007	0.45
After Optimization	0,0014	2,299	0,021	0,39

The total deformation image of the model obtained as a result of topology optimisation is presented in Figure 10, stress distribution image in Figure 11 and strain distribution image in Figure 12. These images clearly show the effects of the optimisation process on the mechanical performance of the model and provide the opportunity to visually analyse how critical parameters such as deformation, stress and strain are distributed on the part.

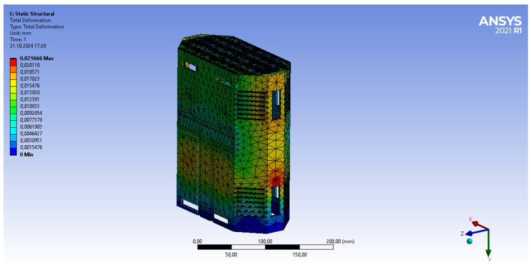

Figure 10. Total deformation results after topology optimization

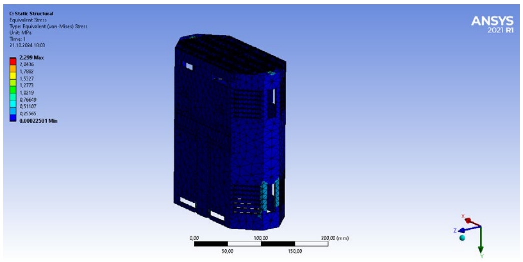

Figure 11. Stress distribution after topology optimization

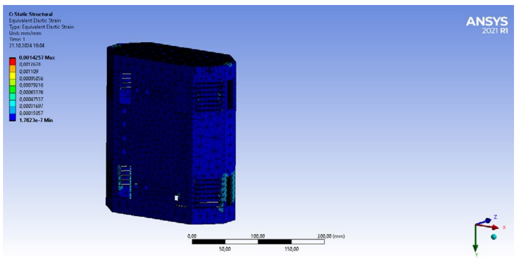

Figure 12. Strain distribution after topology optimization

3. EXPERIMENTAL FINDINGS

3.1. Mechanical Design

Various robotic configurations, such as four-wheeled and spherical robots, are widely used in different applications. However, a two-wheeled self-balancing design was chosen for its compact structure, high maneuverability, and dynamic interaction potential. While four-wheeled robots offer stability but require larger turning radii, spherical robots allow omnidirectional movement but face stability and control challenges. In contrast, the two-wheeled configuration enables agile and engaging movement, making it ideal for promotional settings.

The prototype was fabricated using 3D-printed PLA material and designed for advertising applications. It includes pen holders on the sides, a brochure pocket at the back, and a front-mounted screen for promotional displays. A sensor slot allows obstacle detection during autonomous movement, while rubber strips on the wheels enhance traction. These features collectively enhance the robot's effectiveness as an interactive and attention-grabbing promotional tool.The front view of the prototype is shown in Figure 13 and the rear view is shown in Figure 14.

Figure 13. Front view of the manufactured prototype

Figure 14. Rear view of the manufactured prototype

3.2. Electronic Design

Two motors, a Bluetooth module, a motor driver board, distance sensors, an Arduino and MPU67 integration were used in the electronics of the prototype. The motors are used to provide the mobility of the robot and the two motors control the movement direction and speed of the robot. The Bluetooth module is used to provide wireless communication between the robot and external devices so that the user can remotely control the robot or perform data transfer. The motor driver board regulates the current and voltage required for the control of the motors, ensuring the correct operation of the motors. Distance sensors are used to prevent collisions during autonomous movement by detecting obstacles around the robot, and the sensors provide data to guide the robot's movement. The Arduino acts as the robot's control unit, integrating all components and controlling the movement of the motors by processing data from the sensors. The MPU67 is used to track the robot's position and movement, and this integration supports the robot's balance and guidance systems, increasing its autonomous movement capabilities. These components are integrated to enhance the robot's autonomous movement capabilities and to enable it to detect environmental obstacles and steer effectively. The electronic connections of the robot are given in Figure 15.

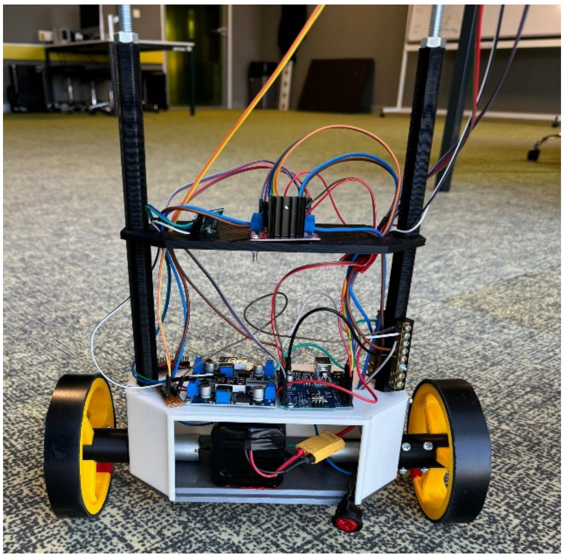

Figure 15. Electronic assembly

4. RESULTS

This study presents the finite element analysis and prototype fabrication of a two-wheeled self-balancing robot for advertising applications. Structural evaluations using static, modal, and rigid body analyses confirmed mechanical integrity, though modal analysis identified a resonance deformation of 330.24 mm at 52.169 Hz, highlighting the need for improved stability. Topology optimization reduced mass by 14% without compromising strength, enhancing material efficiency.

Experimental tests revealed significant yawing motion due to insufficient motor torque and suboptimal PID control parameters. Future improvements will focus on optimizing PID gains, integrating higher-torque motors, and exploring adaptive control strategies for enhanced stability. While the prototype demonstrated autonomous functionality, further studies are needed to assess performance in real-world environments, such as outdoor or crowded spaces, and to improve sensor integration for better maneuverability.

Unlike conventional self-balancing robots designed for mobility or industrial use, this study introduces a novel application in advertising. The robot features a digital display, brochure compartments, and interactive elements, making it a dynamic promotional tool. Additionally, topology optimization has improved energy efficiency. Future advancements, including AI-driven balance algorithms and adaptive control, will further enhance functionality and commercial viability, contributing to both engineering analysis and practical applications.

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