



Integrated Design Improvements in a PLA-Based Service Robot: Focus on Sensor Placement, Motor Selection, and Load Distribution

Final Project Proposal

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Abstrak

Inovasi teknologi modern terus berkembang, khususnya di sektor layanan restoran, di mana robot pelayan berperan sebagai pengganti pelayan manusia. Robot ini meningkatkan efisiensi operasional dengan memungkinkan pelanggan melakukan pemesanan dan menerima makanan secara langsung melalui antarmuka otonom yang menggunakan teknologi line following dengan sensor inframerah dan ultrasonik untuk mendeteksi hambatan .

Penelitian ini berfokus pada perancangan dan pembuatan robot pelayan menggunakan metode pencetakan 3D (3D printing) dengan filamen PLA (Polylactic Acid) sebagai material utama. Pendekatan ini menawarkan proses produksi yang lebih presisi, efisien, dan ekonomis. PLA merupakan termoplastik biodegradable yang umum digunakan dalam metode fused deposition modeling (FDM) karena kemudahan proses serta kekuatan mekaniknya .

Robot ini dirancang untuk membantu operasional restoran dalam pengantaran makanan dan proses pemesanan, sehingga berkontribusi pada otomatisasi layanan . Pada akhirnya, penelitian ini diharapkan dapat memberikan solusi praktis dalam modernisasi layanan restoran serta menjadi model penerapan serupa di berbagai bidang industri .

Kata kunci: Robot Pelayan, 3D Printing, Filamen PLA, Line Following, Sensor Ultrasonik, Otomatisasi Restoran

Abstract

Modern technological innovations continue to evolve, notably in the restaurant service sector, where robot waiters serve as substitutes for human servers. These robots enhance operational efficiency by allowing customers to place orders and receive food directly through an autonomous interface using line-following technology with infrared and ultrasonic sensors to detect obstacles.

This research focuses on the design and manufacturing of a servant robot using a 3D printing method with PLA (Polylactic Acid) filament as the primary material. This approach offers a more precise, efficient, and cost-effective production process. PLA is a biodegradable thermoplastic used in fused deposition modeling (FDM) due to its ease of processing and mechanical strength .

The robot aims to assist restaurant operations in food delivery and order placement, contributing to service automation. Ultimately, this study seeks to provide practical solutions for modernizing restaurant services and serve as a model for similar implementations in various industrial fields.

Keywords: Servant Robot, 3D Printing, PLA Filament, Line Following, Ultrasonic Sensor, Restaurant Automation

I. INTRODUCTION

The development of robotics and automation technology continues to expand across various industries, including the restaurant service sector. One of the significant advancements is the implementation of servant robots or robot waiters designed to automate customer service functions. These robots not only bring a modern and futuristic impression but also help reduce labor dependency,

increase service efficiency, and enhance customer satisfaction[7].

Servant robots are designed to assist in delivering food, drinks, or goods to customers, following a pre-determined path autonomously. The utilization of line-following systems using infrared sensors, coupled with obstacle detection capabilities via ultrasonic sensors, ensures that the robot can navigate restaurant environments accurately and safely[2]. The integration of such features allows

robots to operate effectively even in narrow and crowded pathways, which are common in restaurant layouts[6].

This study focuses on the design and manufacturing of a servant robot using 3D printing technology. By employing PLA filament, the robot's structural components can be produced with precision, affordability, and speed. In addition to reducing the manufacturing cost, the use of 3D printing also enables rapid prototyping and customization according to different needs and applications[8]

Ultimately, this research aims to contribute to the modernization of restaurant services through the integration of robotics, and potentially serve as a model for implementing similar technologies in other service-oriented industries[9].

II. METHODE

A. Redesign Justification

Despite the structural components of the prototype having been individually validated through Static Simulation (FEA), functional testing of the assembled prototype showed a significant dynamic performance failure, where the robot failed to move when loaded with a specific weight. This failure demonstrated a critical imbalance between the initial design weight and the motor's thrust capability.

To identify the root causes of this failure and to provide justification for subsequent design changes, a Cause-and-Effect Analysis using a Fishbone Diagram was conducted. Figure1, presents the results of this analysis, which categorized the main problems into five categories:

1. Machine / Sensor: Suboptimal initial sensor positioning and the Motor Driver's inability to handle the load.
2. Measurement / Accuracy: Inaccurate sensor readings.
3. Method / Process: Excessive initial printing density (Infill Density), which triggered the overweight condition.
4. Material / Design: Excessive robot weight and necessary changes to mechanical components (wheel size).
5. Ergonomics / Interface: The requirement to integrate a new digital menu feature (phone holder).

The redesign carried out on the prototype focused on solving the problems identified above, primarily through revision of slicing parameters (such as setting the Infill Density to 5.0%) and adjustment of the Base Body dimensions.

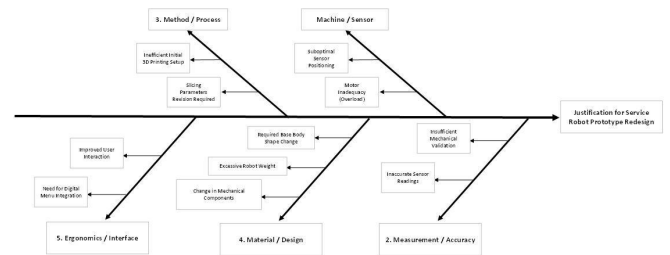


Figure 1. Cause and Effect Diagram

B. Robot Body



Figure 2 . Servant Robot CAD Design

The robot body, as shown in Figure 2, is designed with three trays to hold the ordered food. The top tray includes a tablet that functions as a digital menu, allowing customers to place orders directly from their table. A pushbutton is also provided on the robot, enabling customers to indicate when their food has been removed from the trays. Once pressed, the robot can return to serve other customers.

The lower section of the robot body houses the battery and microcontroller. The robot is equipped with two motors and two freewheels for mobility. Two ultrasonic sensors are mounted at the front, which detect obstacles within a 20 cm range, prompting the robot to stop when necessary. Additionally, two infrared sensors are installed to guide the robot along its designated path. This design, illustrated in Figure 1, ensures efficient navigation and functionality in restaurant environments.

C. Phone Holder

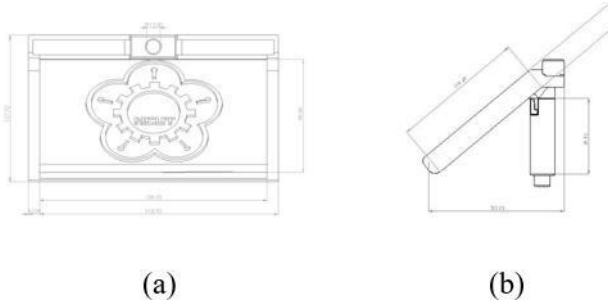


Figure 3. (a) Drawing top view (b) Drawing Side View

The phone holder, as illustrated in Figure 2, is designed to securely hold a handheld tablet used as a menu for placing orders. Additionally, the phone holder features a button that can be pressed once all the orders have been delivered to the customer's table. By pressing this button, the robot is prompted to resume its tasks. The phone holder, shown in the top and side views in Figure 3, has a length of 198.93 mm, a width of 91.56 mm, and a height of 68.34 mm from the tray surface, ensuring a practical and ergonomic design.

D. Tray

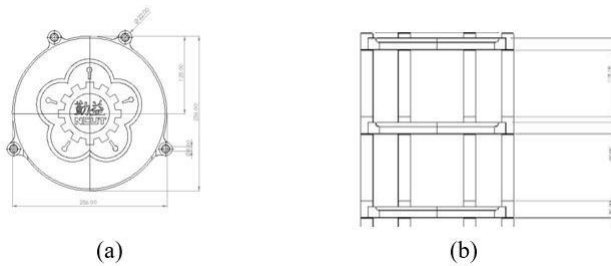


Figure 4. (a) Drawing Top View (b) Drawing side view

Figure 4, shows the detailed design of the tray. The tray has a circular shape with a diameter of 128 mm and is divided into three levels. As illustrated in the side view, the distance between each level is 130 mm, measured from the surface of one tray to the bottom of the tray above it. This design ensures that items with a maximum height of 130 mm can be placed securely on each tray level without interfering with the other levels.

E. Based Body

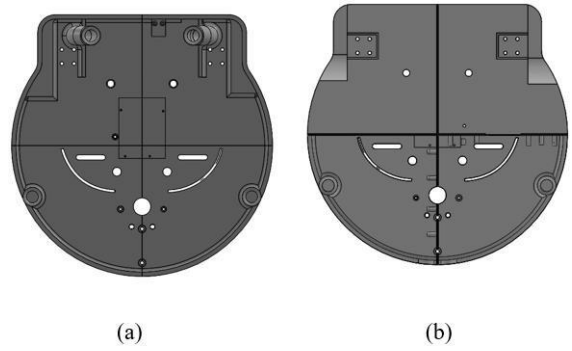


Figure 5. (a) Top view (b) Bottom View

The base body, shown in Figure 4, is designed to house the microcontroller and serve as a compartment for the battery and other driving components. As illustrated in the top and bottom views in Figure 5, this design ensures efficient organization and protection of essential electronics while maintaining a compact and functional structure to support the overall system operation.

F. Manufacturing

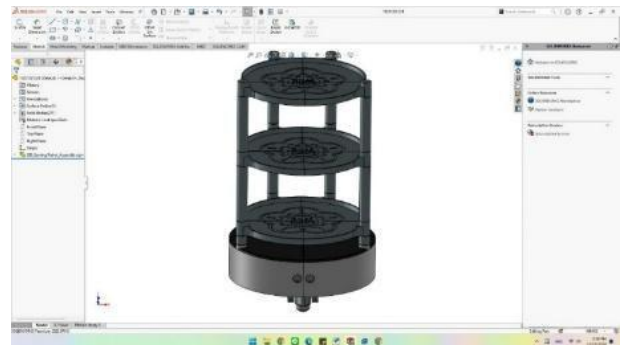


Figure 6. Design servant robot in Solidworks

The design process, as shown in Figure 6, was conducted using SOLIDWORKS, where the entire structure of the servant robot was modeled and verified using the comparison test feature to ensure its reliability. After the design phase was completed, the model was exported in STL format to prepare it for 3D printing. The exported file was then opened in Ultimaker Cura, a slicing application, to configure the printing parameters such as layer height, infill density, and printing speed. This integrated workflow ensured high precision and efficiency during the transition from digital

G. Manufacturing Process

In the manufacturing process, a 3D printer, the UltiMaker 2+ Connect, is used along with PLA filament from Ultimaker with a diameter of 2.85 mm. This material is selected for its compatibility with the printer and its reliability in producing precise and detailed components. Additionally, PLA's biodegradable nature makes it an environmentally friendly choice, aligning with sustainable manufacturing practices.

1) Parameters

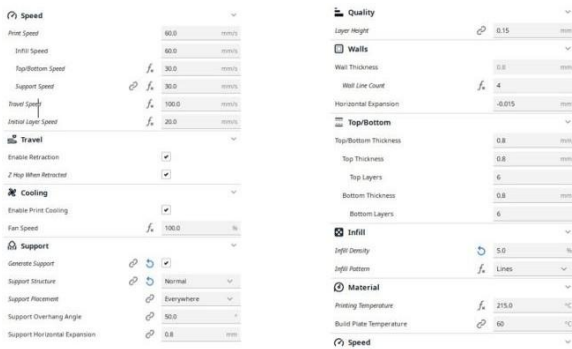


Figure 7. Setting Parameters

Before starting the printing process, it is essential to adjust the parameters to achieve optimal print quality and strength, as shown in Figure 7. During this step, various settings such as printing speed, layer height, infill density, and nozzle temperature are configured according to the specific requirements of the design. These parameters ensure that the final print maintains high precision and structural integrity while optimizing material usage and printing time.

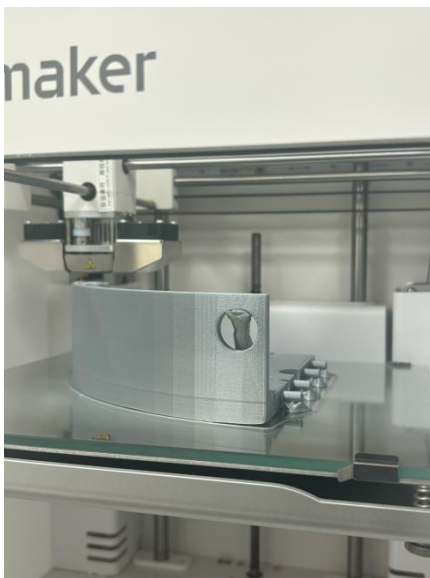


Figure 8 Manufacture process

The manufacturing process, as illustrated in Figure 8, employed an Ultimaker 3D printer with PLA filament as the primary material for producing the robot's components. Once the design file was prepared and opened in Ultimaker Cura, the slicing software, the printing process began with carefully adjusted parameters to ensure the desired part quality. Specific settings, such as infill density and printing speed, were fine-tuned to balance material efficiency with structural strength. This step ensured that the printed parts met the required specifications while minimizing material usage and printing time.

III. RESULT

A. Phone Holder



Figure 9. Phone Holder 3D Printing Result

The phone holder, as shown in Figure 9, was printed using an Ultimaker 3D printer with PLA filament as the primary material. The printed phone holder has dimensions of 198.93 mm in length, 91.56 mm in width, 68.34 mm in height, and a thickness of 5 mm. This printing result demonstrates high detail quality and accuracy according to the original design, ensuring that the phone holder is practical and sturdy for supporting the robot's functions.

B. Tray



Figure 10. Tray 3D Printing Result Tray 3D Printing Result

The tray, as shown in Figure 10, was printed separately for each part, consisting of four individual components during the printing process. The support poles were also printed separately and then assembled with the tray levels. The tray has a radius of 128 mm and a thickness of 6 mm, providing sufficient strength to hold items securely. After printing, each part was carefully cleaned and finished to ensure smooth surfaces and precise fitting during assembly. This modular printing and assembly approach makes it easier to replace or repair specific parts if needed, enhancing the overall practicality and durability of the robot's design.

C. Based Body



Figure 11 Based 3D Printing Result

The base body, as shown in Figure 11, was printed separately and divided into four parts: two rear sections for the wheels and two front sections for the sensors. Each component was individually

manufactured to ensure precise fitting and ease of assembly. The base was printed with a thickness of 6 mm, providing adequate strength and stability to support the mechanical and electronic components mounted on it. After printing, all parts were carefully cleaned and finished to achieve smooth surfaces and proper alignment during the assembly process. This modular approach not only simplifies the manufacturing and assembly process but also enhances the flexibility, maintainability, and overall durability of the robot's structural design.

D. Simulation Result

1) Phone Holder

i. Contact Information

Type : Bonded
 Components : 1 component(s)
 Options : Independent mesh



Figure 12. (a) Phone Holder Isometric View (b) Phone Holder Side View. The simulation uses a bonded contact with independent mesh. View (a) shows mesh and constraints; view (b) shows structure under load. This setup confirms the structural stability of the phone holder.

ii. Resultan Force

The following tables present the reaction forces, moments, and free body forces resulting from the finite element analysis (FEA) of the Phone Holder component under different loading conditions. The simulation evaluates the structural response of the holder to applied weights of 0.5 kg, 1 kg, and 1.5 kg, respectively. These results are crucial for validating the structural integrity of the component under real-world conditions.

a. 0.5 Kg

Table 1. Resultan Force 0.5 Kg

Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-0.00126808	11.3098	9.41045	14.7128

Reaction Moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-0.0104279	-0.0647358	-0.0515262	0.0833931

Free body moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

b. 1.0 kg

Table 2. Resultan Force 1 Kg

Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	0,000228821	12,241	-0,000230956	12,241
Reaction Moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0
Free body forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-0,00304998	1,73097	-0,00637316	1,73099
Free body moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

c. 1,5 kg

Table 3. Resultan Force 1.5 Kg

Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-0,00126808	11,3098	9,41045	14,7128
Reaction Moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0
Free body forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-0,0104279	-0,0647358	-0,0515262	0,0833931
Free body moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

iii. Study Result

Figures 14-16 illustrate the stress distribution, strain behavior, and displacement contours of the Phone Holder under respective loads. The results show how the structure responds to increased loading and help identify critical stress areas.

a. 0.5 kg

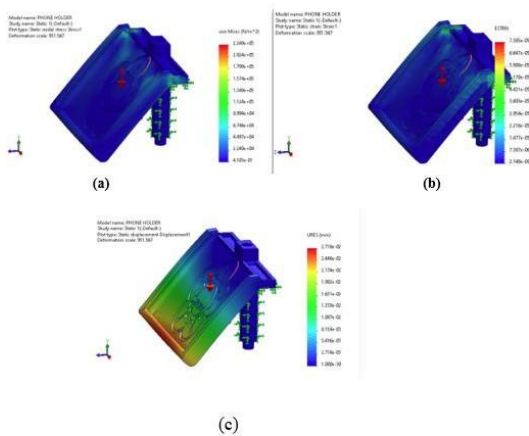


Figure 13. (a) Stress (b)Strain (c) Displacement

b. 1,0 kg

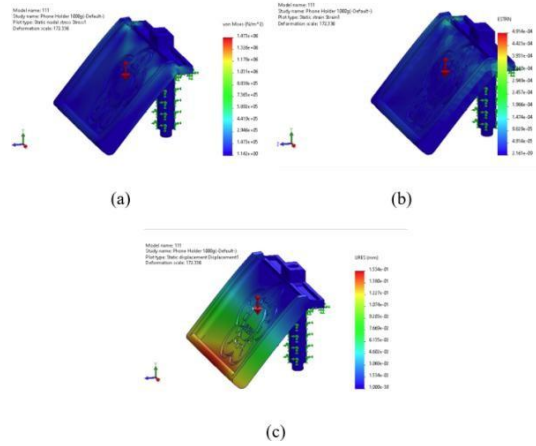


Figure 14. (a) Stress (b)Strain (c) Displacement

c. 1,5 kg

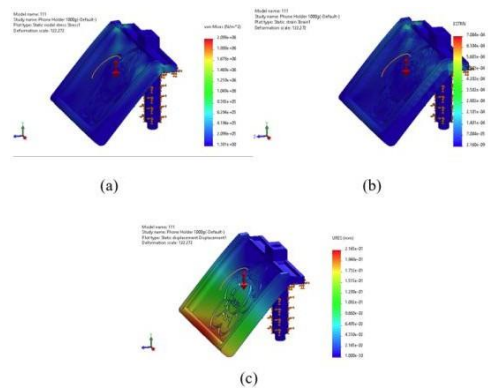


Figure 15. (a) Stress (b)Strain (c) Displacement

2) Tray

i. Contact Information

Type : Bonded
 Components : 1 component(s)
 Options : Independent mesh

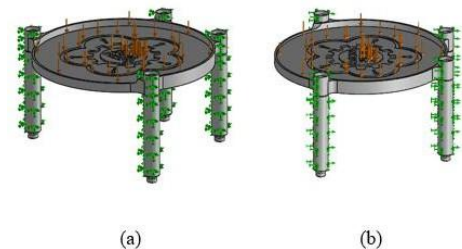


Figure 16. (a)Tray (b) Tray

The simulation uses bonded contact with one component and independent mesh. View (a) shows mesh and constraints; view (b) illustrates structural

configuration under load. This confirms the tray's structural reliability in the design.

ii. Resultan Force

A resultant force analysis was conducted to evaluate the structural response of the tray component under vertical loads of 1 kg, 1.5 kg, and 2 kg. The simulation results demonstrate an increase in reaction forces proportional to the applied load, while maintaining structural stability. No significant reaction moments were observed, indicating reliable mechanical performance. The detailed force distribution is presented in Table 4 for 1 kg, Table 5 for 1.5 kg, and Table 6 for 2 kg loading conditions.

a. 1 Kg

Table 4. Resultan force 1 kg

Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-3.19059e-06	3.41691e-06	16.3197	16.3197

Reaction Moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-9.83477e-07	6.82101e-06	4.66858	4.66858

Free body moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

b. 1.5 Kg

Table 5. Resultan force 1.5 kg

Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-8.40071e-07	3.8102e-06	14.71	14.71

Reaction Moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-6.14906e-07	2.92435e-06	5.84871e-07	3.045e-06

Free body moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

c. 2 Kg

Table 6. Resultan force 2 kg

Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-9.10263e-06	-3.44496e-06	26.1297	26.1297

Reaction Moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-1.58884e-06	-7.77468e-06	4.66864	4.66864

Free body moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

iii. Study Result

Figures 16-18 illustrate the stress distribution, strain behavior, and displacement contours of the Tray under respective loads. The results show how the structure responds to increased loading and help identify critical stress areas.

a. 1 Kg

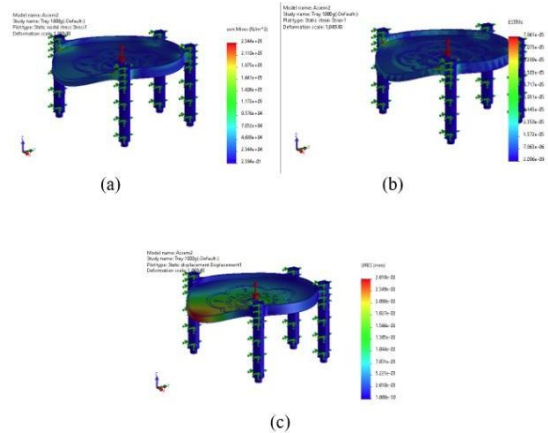


Figure 17. (a) Stress (b) Strain (c) Displacement

b. 1.5 Kg

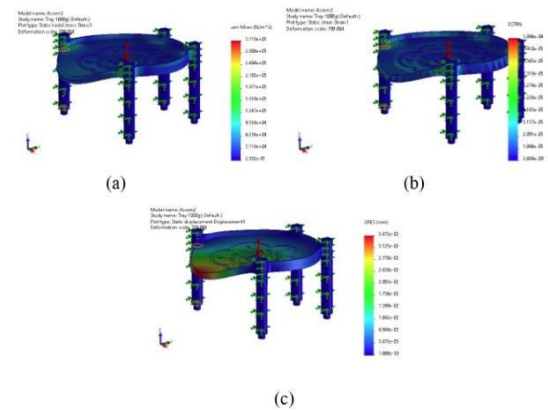


Figure 18. (a) Stress (b) Strain (c) Displacement

c. 2 Kg

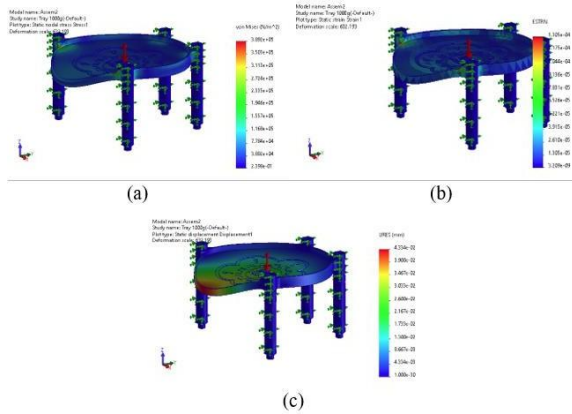


Figure 19. (a) Stress (b) Strain (c) Displacement

3) Based Body

i. Contact Information

Type : Bonded
 Components : 1 component(s)
 Options : Independent mesh

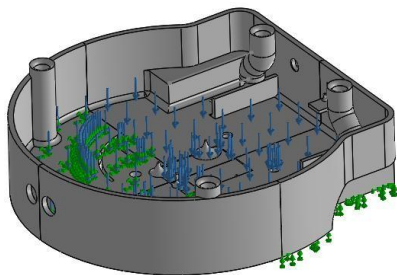


Figure 20. Based Body

The simulation uses a bonded contact with one component and independent mesh. View (a) shows mesh and constraints applied to the Based Body. This setup demonstrates the structural setup of the Based Body component under simulated conditions

ii. Resultan Force

A resultant force analysis was conducted to evaluate the structural response of the tray component under vertical loads of 1 kg, 1.5 kg, and 2 kg. The simulation results show a progressive increase in reaction forces as the applied load increases, while maintaining structural integrity. Reaction moments remained negligible across all load cases, reflecting stable mechanical behavior. Detailed force distributions are provided in Table 7 for the 1 kg load,

Table 8 for the 1.5 kg load, and Table 9 for the 2 kg load conditions.

a. 1 Kg

Table 7. Resultan force 1 kg

Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	3.33937e-06	1.76358e-06	20.5337	20.5337

Reaction Moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-9.48829e-05	2.70248e-05	7.77	7.77

Free body moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

b. 1.5 Kg

Table 8. Resultan force 1.5 kg

Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	-8.28644e-06	5.13799e-07	25.4386	25.4386

Reaction Moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	7.28738e-05	7.41456e-06	7.77001	7.77001

Free body moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

c. 2 Kg

Table 9. Resultan force 2 kg

Reaction forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	5.80619e-06	3.88839e-06	30.3437	30.3437

Reaction Moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	0

Free body forces					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N	0.000214211	-7.06588e-05	7.76983	7.76983

Free body moments					
Selection set	Units	Sum X	Sum Y	Sum Z	Resultant
Entire Model	N.m	0	0	0	1e-33

iii. Study Result

Figures 22–24 illustrate the stress distribution, strain behavior, and displacement contours of the component under vertical loads of 1 kg, 1.5 kg, and 2 kg. The analysis demonstrates how the structure reacts to increased loading and highlights critical stress and deformation zones. The results help in identifying performance limits and validating design integrity.

a. 1 Kg

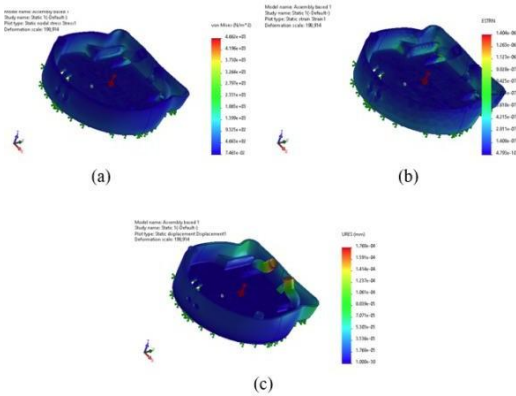


Figure 21. (a) Stress (b) Strain (c) Displacement

b. 1.5 Kg

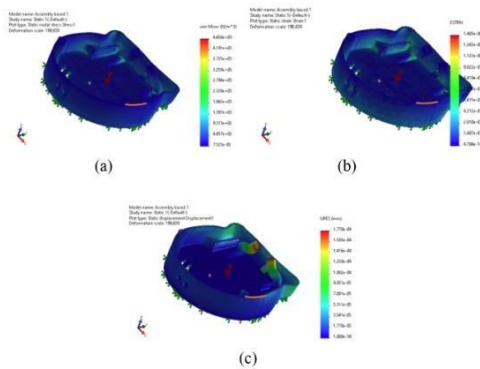


Figure 22. (a) Stress (b) Strain (c) Displacement

c. 2 Kg

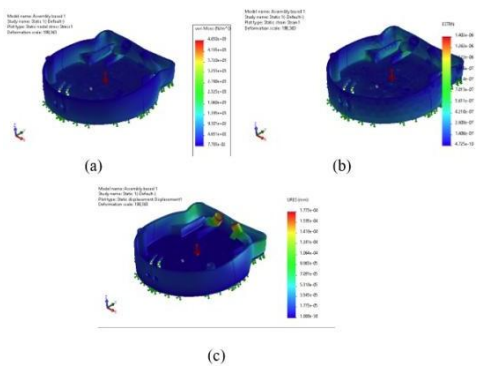


Figure 23. (a) Stress (b) Strain (c) Displacement

IV. CONCLUSION

This research successfully developed a prototype of an autonomous servant robot using a 3D printing approach with PLA filament as the primary material.

The design process involved CAD software (SolidWorks), slicing in Ultimaker Cura, and subsequent printing with the Ultimaker 2+ Connect. Components like the phone holder, tray, and base body were printed separately and validated through stress and deformation simulations.

Material Success and Excellence

- The utilization of PLA as the printing material demonstrated several advantages:
- Ease of printing due to low temperature requirements and a high success rate.
- High precision, suitable for complex geometric shapes.
- Environmentally friendly, being bio-based and biodegradable.
- Lightweight, while offering sufficient strength for static loads on individual components.

Based on the simulation tests, the structural components were able to withstand loads of up to 2 kg without exhibiting structural deformation, confirming PLA's reliability for light- to medium-scale robotics applications in the prototyping stage.

Limitations and Justification of Redesign

Despite the demonstrated structural integrity under static loads, functional testing of the assembled prototype revealed a significant dynamic performance failure: the robot was unable to move when subjected to specific loads. This failure indicated a critical imbalance between the prototype's total weight and the motor's thrust capability.

This necessitated a critical redesign, justified by the Cause-and-Effect Analysis (Figure 1), which identified key issues including:

- Suboptimal sensor positioning, leading to inaccurate navigation.
- Excessive robot weight caused by high initial *Infill Density* during the first printing process (Method/Process).
- The need to accommodate changes in mechanical specifications (tire size) and functionality (digital menu integration via the phone holder).

Final Conclusion

In conclusion, while the use of PLA is structurally reliable for static loading in prototyping, achieving optimal functional performance requires careful balancing of the overall mechanical system and precise adjustment of manufacturing parameters. The successful implementation of the *redesign*, specifically through revising the slicing parameters (e.g., setting the *Infill Density* to 5.0%) and adjusting the *Base Body*, ensured the structural strength met the dynamic performance demands.

The main limitations of PLA remain its low heat resistance and brittleness under dynamic loading. Future work should focus on long-term testing and potential material upgrades for applications in challenging environments.

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