Final Report

MIE498Y1: Research Thesis

Development of an Intelligent Assistive Service Robot for Human-Centered Environments

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1.0 Abstract

This thesis explores the development of an intelligent assistive service robot designed for human-centered environments. The research follows a multi-iteration design process, utilizing advanced tools like Fusion 360's generative design to optimize the Unmanned Ground Vehicle (UGV)'s upper body.

Initial iterations focused on creating topologies that balance innovative design with practical manufacturability, addressing challenges in strength, weight, and structural resilience. Subsequent designs explored the potential of lightweight materials, such as PVC, as alternatives to traditional aluminum, demonstrating significant improvements in reducing weight and controlling vibrations, while addressing issues of stress concentration and displacement.

By incorporating a 3D printed base with the PVC design, the design effectively redistributes stress, enhancing structural stability and reducing the robot's susceptibility to vibrations. Graphical analyses and moment calculations further validate the effectiveness of this design, showing a marked improvement in stability and a reduced probablitiy of tipping compared to the aluminum frame.

2.0 Introduction

In an era where technological advancements are increasingly shaping our lives, the integration of intelligent assistive service robots into human-centric environments has become a useful tool for navigational human aid. This thesis aims to test, redesign, build and integrate a functional assistive service robot upper body. The robot design should be robust, aesthetically appealing, and seamlessly integrate into human environments, able to successfully navigate without large vibrations, and interact with users easily through the top screen interface. Some major issues existing in the original system which this new design aims to eliminate includes noise, vibrations, and a seamless user experience in terms of robot accessibility and aesthetics.

2.1 Motivations

The development of intelligent assistive robots, particularly in human-centric environments, is motivated by the rapidly evolving landscape of robotics and its expanding role in various sectors. This thesis is inspired by the escalating demand for such robots.

The field of assistive robotics is an emerging and dynamic area of research and application, with a primary orientation toward healthcare and support for individuals with special needs. The broader definition encompasses robots that provide users of all abilities with physical, cognitive, and social assistance. These robots are increasingly being introduced in workplaces, hospitals, care homes, and private residences, where they interact directly with humans. This trend has been further intensified by the COVID-19 pandemic, highlighting the robots' potential in supporting human professionals, particularly in healthcare sectors [1].

The integration of advanced technologies like Artificial Intelligence (AI) and Machine Learning (ML) in robotics has brought remarkable enhancements in performance and capabilities. AI-powered robots can now optimize tasks, recognize objects, and make decisions with improved accuracy. These robots, through machine learning, adapt to new situations and learn from experiences, which is crucial for assistive applications where adaptability and personalized care are essential [2].

A significant focus in current research is on designing robots that can assist humans on various levels, including social, medical, and biomedical aspects. There is a growing emphasis on understanding what "assistance" means from the user's perspective [1]. For instance, a study by Saille et al. used innovative methods like Community Philosophy and Design Thinking to explore how people with different physical impairments envision a "useful robot" [1]. This research identified 31 relevant themes related to the roles of robots in the lives of people with disabilities, emphasizing the importance of user-centered design in developing assistive robots [1].

In terms of physical assistance, novel orthotic devices and systems are being designed to support individuals with specific needs, such as post-stroke patients. For example, a wearable system combining sensing, haptics, orthotics, and robotics has been developed to assist in daily activities, highlighting the potential of assistive robots in enhancing independent living [1].

This thesis is driven by the need to contribute to these fields where service, guidance, and assistance to humans is needed, with a focus on creating a service robot that is robust and user-friendly. The objective is to design a robot that not only meets the functional requirements of assistive tasks but also aligns with the evolving trends and user expectations in the field of assistive robotics.

2.2 Background and Objectives

This thesis aims to build upon the existing knowledge of service robot hardware to design and test a service robot that showcases both robust mobility and effective user interaction. The objective is to construct a working robot prototype through CAD design, simulation, validation, and rapid prototyping. This prototype, based on an existing mobile base, will serve as the foundation for further developements. Simulation tools such as Fusion 360 will be used for the comprehensive analyses and generative design for the robot's upper body. The final objective of this project is to conduct comprehensive system testing after upper body implementation, ensuring the robot's reliability and effectiveness in real-world settings.

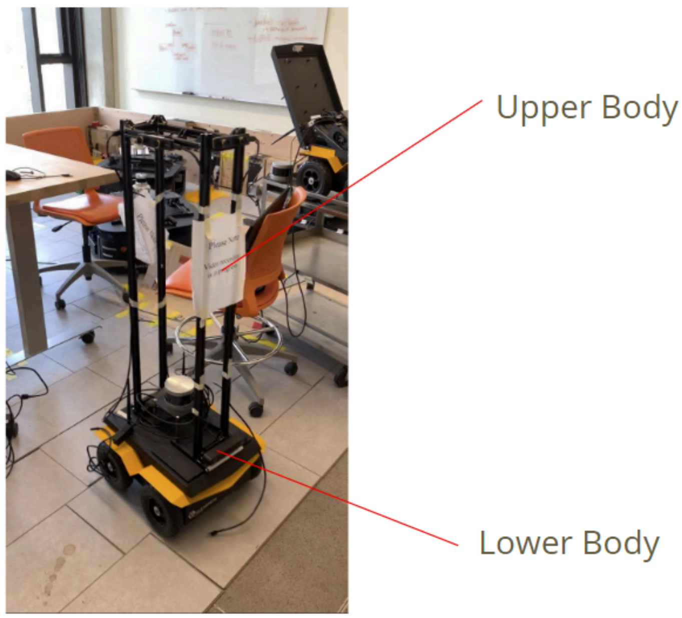


Figure 1. Original Prototype Design with Upper and Lower Body Labeled

2.3 Literature Review

In order to develop important design specifications for the robot upper body, five Autonomous Mobile Robots (AMRs) with various upper body and overall characteristics are compared. Currently, AMRs are commonly used in the manufacturing industry, from which the intended use for these five robots derives; however, there is high adaptability to various other fields such as hospitality and healthcare [3]. Each type of robot offers unique characteristics that can influence the design and functionality of the UGV.

The robots to be compared include the Lowpad S AMR is tailored for automating the transport of roll cages, primarily in food distribution and postal services [4]. On the other hand, the SEIT 100, designed by Milvus Robotics, focuses on safely and efficiently carrying products and materials in warehouses and factories. Its infrastructure-free navigation system, which requires no physical markers, along with its precise and safe operation, highlights the significance of integrating advanced sensory capabilities and safety standards in UGVs [5].

Pickerbots by inVia Robotics are mobile packing robots that demonstrate the importance of adaptability in warehouse operations. Their compact design and extendable lift, capable of reaching up to 8 ft with a payload of up to 40 lbs, showcase how UGVs with upper body that can effectively utilize vertical space in storage facilities [6]. The MoMa from Omron is a mobile cobot with a TM 20 robotic arm manipulator as its upper body, and the LD series as its lower base. This configuration demonstrates the collaborative potential between AMRs and robotic arms in performing complex tasks [7]. Finally, the AMR F602 from ABB Robotics is a stacker AMR known for its maneuverability and efficiency in handling pallets and containers. With a service weight capacity of up to 1600 kg and advanced navigation and safety systems, the AMR F602 illustrates the capabilities required for UGVs in heavy-duty applications [8].

Given the varying characteristics of these five robots, a market benchmarking table is developed to identify the major design specifications.

Table 1. Market Benchmark of Existing

Specifications	Lowpad S [4]	SEIT 100 [5]	Pickerbot [6]	Moma [7]	AMR F602 [8]
Weight (kg)	N/A	N/A	62	95	N/A
Dimensions (mm)	1194 x 700 x 657	820 x 630 x 297	648 x 663 x 300	N/A	2055 x 830 x 2751
Colour	Customizable (Blue or Yellow)	Dark Grey Base, Red Upper Body	Black Base, Red Upper Body	Black Base, Black Upper	White Base, Black Upper Body

				Body	
Payload (kg)	450	100	9.0	60	1600
Lifting Height (mm)	225	N/A	2438.4	N/A	600
Maximum Speed (m/s)	1.2	1.5	2.2	0.9	1.7
Upper Body Material	Aluminum	Plastic	Aluminum	Stainless Steel	Plastic

From Table 1, comparing the design characteristics of the five different robots identifies some common characteristics of the robot upper body. These characteristics include payload capacity, height, overall dimensions, adaptable features, and material choice. Each of these factors will be important in analyzing design performance.

3.0 Research Methodology

This section of the thesis progress report details the methodology used in developing an intelligent assistive service robot designed for human-centered environments. The primary challenges addressed include mitigating vibrations in the robot's upper body, reducing rattling noises during movement, preventing the Jackal unit from tipping off during abrupt stops, and ensuring a clean and aesthetically pleasing design for the finished frame.

3.1 Design Benchmarking

The initial step involved establishing a benchmark design to guide the development process. This was achieved by gathering data on various components of the robot, as detailed in Table 1 and Table 2.

Table 1. Upper Body Robot Components and Corresponding Forces

Component	Weight	Force	Load Location
Camera [11]	0.06kg	0.5886N	Middle of camera
Tablet Clamp [12]	0.68039kg	6.6746N	Centre of Robot and on each clamp location
Tablet [13]	0.52kg	5.1012N	Centre of Robot
Jackal [14]	17 kg	166.77N	Base of Robot

Table 2. Upper Body Frame Maximum Forces and Additional Specifications

Design Specification	Components Considered	Value
Lateral Maximum Force	Max speed (2m/s), Max acceleration(1m/s^2), Jackal weight (17kg)	17 N
Maximum Vertical Force	All components in Table 1	14.1302 N
Jackal Vehicle Motor Frequency [14]	Maximum motor frequency	6.5 Hz

3.2 Design and Simulation Tools

In the design and simulation phase, a combination of software tools and analytical techniques were employed to ensure the development of a robust and functional intelligent assistive service robot. Fusion 360 played a central role in this process, serving as the primary platform for creating comprehensive 3D models of the robot's individual components and its overall structure. In addition to this, several simulations were conducted to refine and optimize the design.

Generative Design was utilized to enhance the robot's structural integrity and overall performance. This approach focused on weight reduction, strength enhancement, and the enhancement of aesthetic qualities in the robot's design.

Modal Analysis was employed to gain insights into the vibrational characteristics of the robot, with particular attention to addressing vibrations in its upper body. This analysis was crucial in mitigating potential issues related to vibrations.

Moment Calculations were performed to ensure the stability and balance of the robot, especially during dynamic movements and abrupt stops. These calculations were instrumental in preventing the robot from tipping over during operation.

Dynamic Simulation was a key aspect of the methodology, involving the consideration of various parameters. An initial velocity of 2 m/s was assumed to simulate the robot's movement. The total lateral force, both in the forward and backward directions, was set at 17 N to assess the robot's ability to handle lateral forces. An assumed maximum acceleration of 1 m/s^2 was used to simulate dynamic movements and abrupt stops, further evaluating the robot's stability and performance under challenging conditions.

Table 3. Simulation Tools and Methods

Tool	Use Case
Fusion 360 Design	Computer Aided Design (CAD)
Fusion 360 Generative Design	Topology Optimization
Fusion 360 Modal Frequencies Analysis	Solve for Natural Frequency
Moment Calculations	Determine tipping force of the upper body
Fusion 360 Dynamic Simulation	Deterime maximum stress and displacement when robot is in motion

3.3 Safety and Performance Criteria

In ensuring the robot's safety and robust performance, a safety factor of 2.5 was incorporated into the design. This factor was crucial in determining the strength and durability requirements of the robot, especially in scenarios involving high dynamic loads and abrupt movements.

4.0 UVG Upper Body Design Candidates

4.1 UVG Upper Body Benchmark Simulation

To establish a standardized architecture for the upper section of the Unmanned Ground Vehicle (UGV), the initial phase involved developing a Computer-Aided Design (CAD) model. This model mirrors the existing upper body structure, as illustrated in Figure 3. The structure is further simplified to represent the major components subjected to acting forces and includes joining brackets to facilitate an accurate and more efficient simulation time, as depicted in Figure 4.

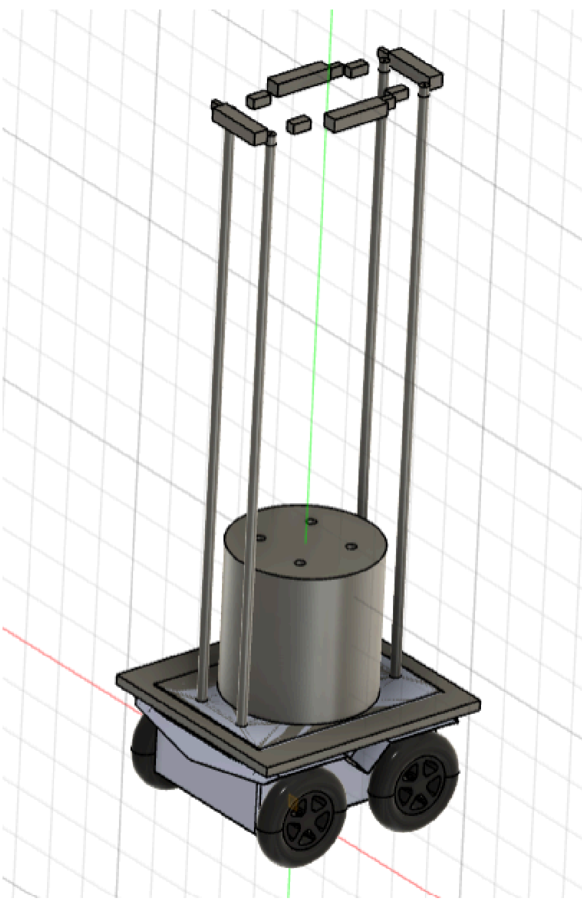


Figure 3. CAD model of UGV structure

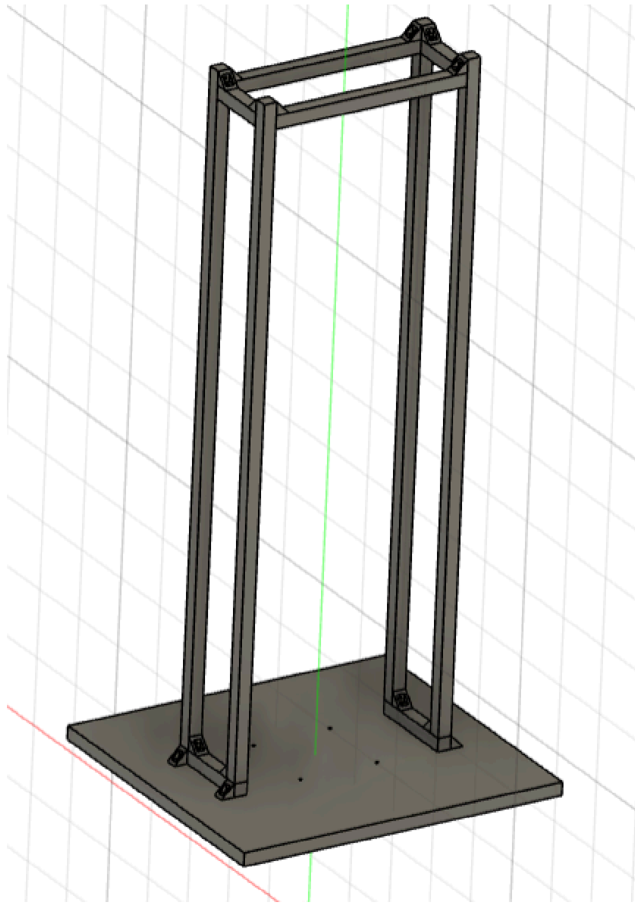


Figure 4. Simplified CAD model for simulation

Following this, a detailed dynamic simulation was conducted to evaluate the kinetic behavior and operational performance of the upper body's design. This simulation, executed at an initial velocity of 2 meters per second, was further enhanced by the incorporation of an acceleration multiplier curve, as depicted in Figure 5. This comprehensive analysis yielded significant insights into the structural resilience and the response of the upper body to dynamic forces. Most notably, the simulation identified the peak stress levels, which were recorded at 2328 megapascals (MPa), and an associated displacement of 2.037 millimeters, predominantly at the critical point of the lower connection from the upper body to the base plate (Figure 6). These empirical findings lay a solid groundwork and the benchmark values for further comparisons.

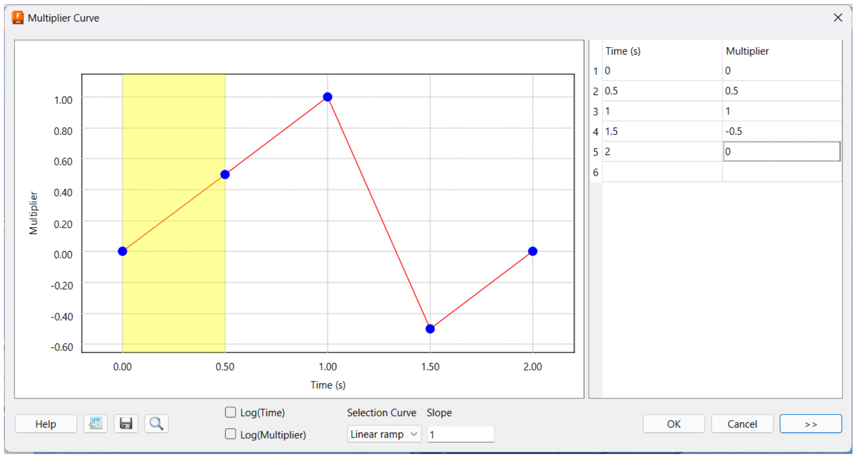


Figure 5. Acceleration Multiplier Curve Applied to Base of Model for Dynamic Simulation

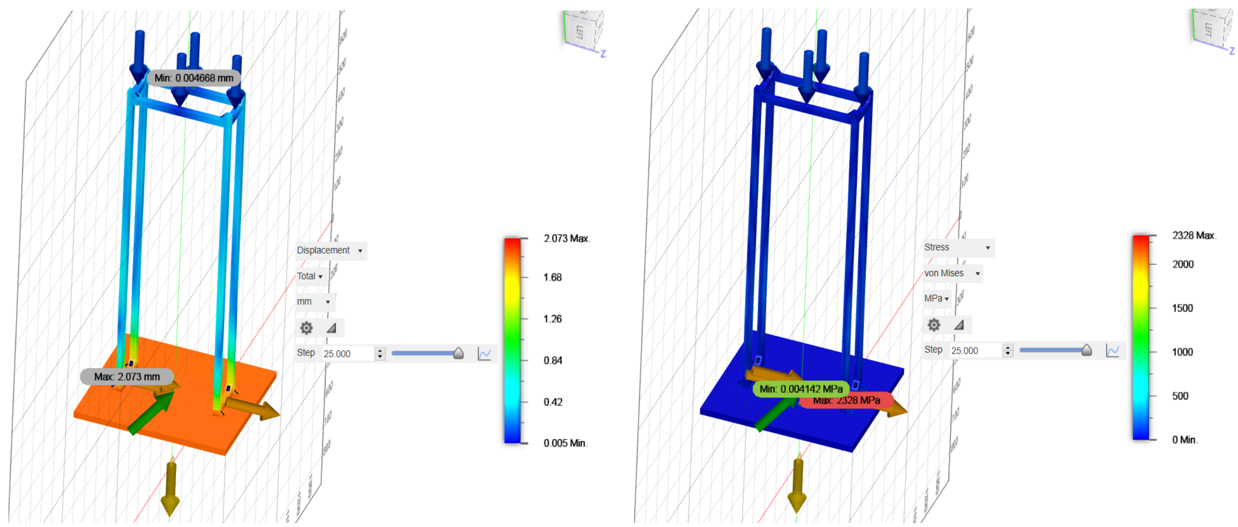


Figure 6. Displacement (Left) and Stress (Right) Dynamic Simulation Results

Modal analysis is also applied to the singular aluminum extrusion using benchmark vertical and lateral forcesand the motor frequency of 6.5 Hz, is shown in Figure 7, where the natural frequency of the aluminum extrusion is found to be 17.94 Hz.

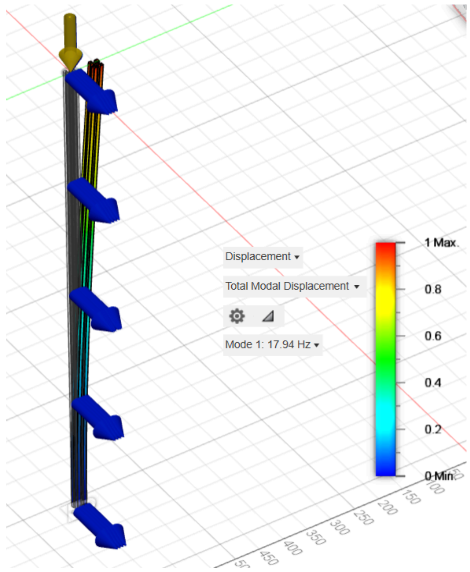


Figure 7. Modal Frequency Analysis of Aluminum Extrusion

4.2 First Design Iteration: Optimizing the Upper Body of Unmanned Ground Vehicle Using Fusion 360 Generative Design

In the initial design iteration, the focus was on optimizing the topology of the upper body of an Unmanned Ground Vehicle (UGV) using Fusion 360's generative design capabilities. The primary objective was to refine the structural design to withstand calculated forces while simultaneously reducing the overall weight.

4.2.1 Design Setup

The setup for the generative design process is detailed in Figure 8. This figure illustrates the application of benchmark forces on the model. Key areas are marked to guide the generative design algorithm: red areas indicate regions that must be avoided due to potential obstructions, while green areas signify critical attachment points. These points include interfaces for tablet clamps, the Jackal UGV, and various joints. The generative design was tasked with creating connections across these points while adhering to the specified force and weight constraints.

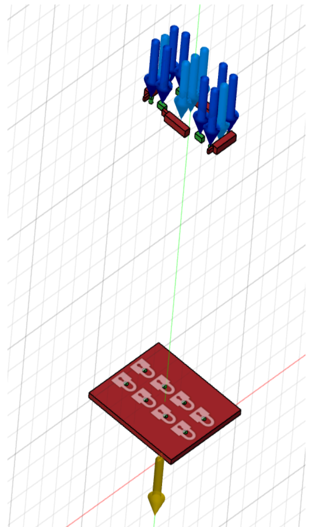


Figure 8. Generative Design Set Up

4.2.2 Design Outcomes

The generative design process yielded several candidate designs that met the benchmark criteria, showcased in Figure 9. To evaluate these designs, a comparative analysis of the minimum factor of safety and mass was conducted, the results of which are presented in Figure 10.

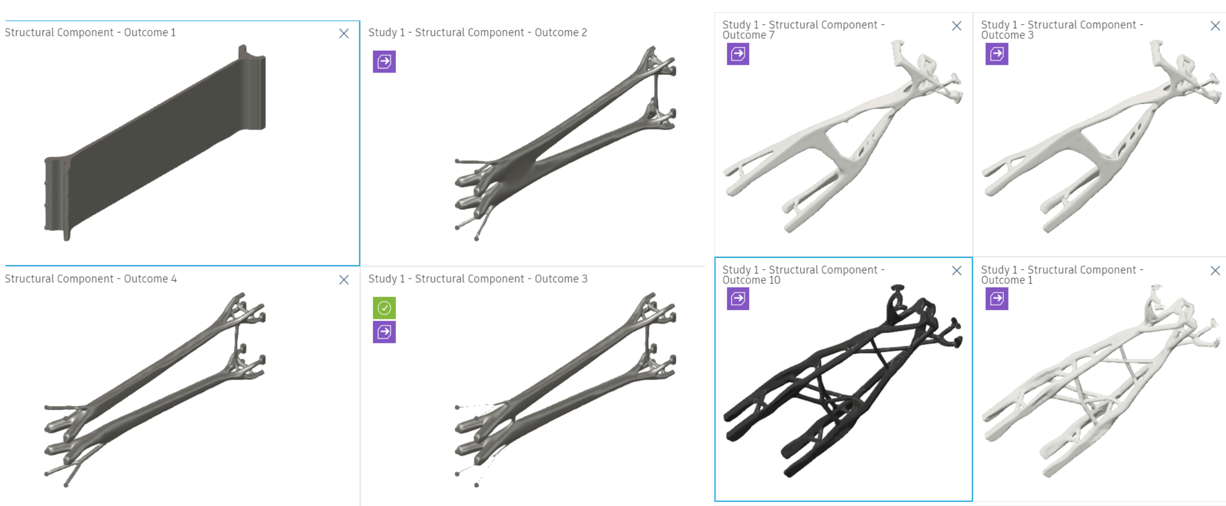


Figure 9. Generative Design Simulation Outcomes

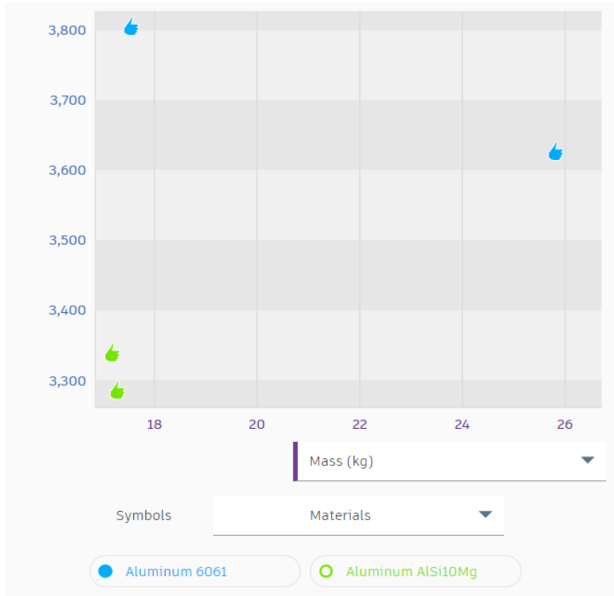


Figure 10. Sample of Minimum Factor of Safety Generative Design Comparisons Based on Material and Mass

4.2.3 Challenges Encountered

Despite the success in meeting the initial design criteria, the iteration faced significant practical challenges:

Organic Shape Complexity: The generative design resulted in shapes that were highly organic, posing manufacturing challenges. The complexity of these designs necessitated the use of a 3-axis CNC machine, which was not only costly but also impractical given the resources available.

Machine Shop Limitations: The largest CNC machine at the University of Toronto Machine Shop, the Haas™-1, was incapable of accommodating the size of the designed part. This limitation implied that the part would need to be divided into two segments for manufacturing. However, this division contradicted one of the primary benefits of CNC machining - enhancing structural strength through unibody construction.

Due to these challenges, it is determined that this design will not be feasible for prototyping.

4.3 Second Iteration: Enhanced Support Structure for Base of Aluminum Extrusion Attachment Points

The benchmark simulations outlined in Section 4.1 identified a critical issue: a high concentration of stress at the base of the aluminum extrusion attachment points. Addressing this problem was imperative to improve the structural integrity of the design.

4.3.1 Design Set Up

In response, a design modification was proposed, focusing on the reinforcement of the attachment points. The revised design incorporates a more robust support structure at the base, aiming to distribute the stress more evenly across the attachment area. This design iteration is illustrated in Figure 11.

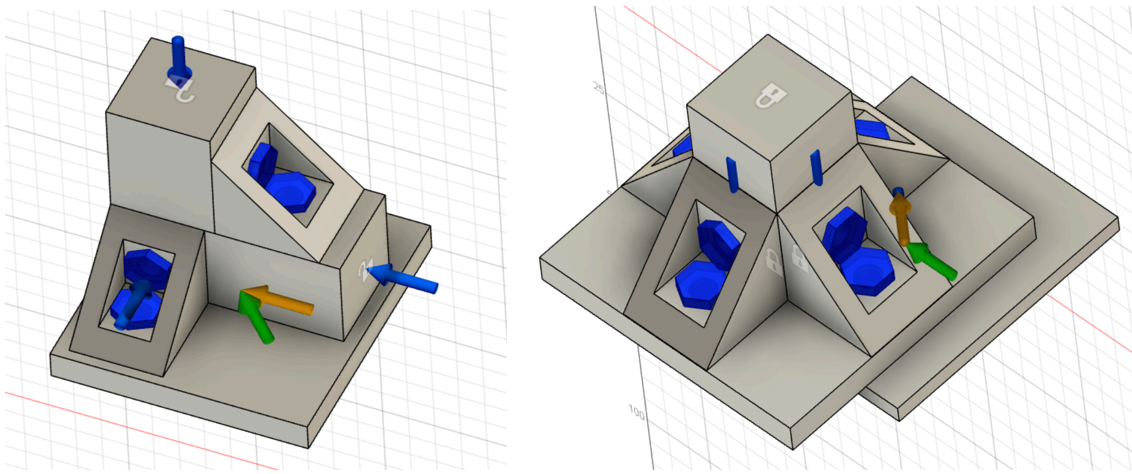


Figure 11. Simulation Set Up of Original Support (Left) and Enhanced Support Structure (Right)

4.3.2 Design Outcomes

The redesigned attachment point offers significant benefits including stress reduction and enhanced stability. By enlarging and reinforcing the support structure, the design effectively minimizes the stress concentration at these critical points. The modifications contribute to the overall stability of the upper body, ensuring better performance under operational conditions.

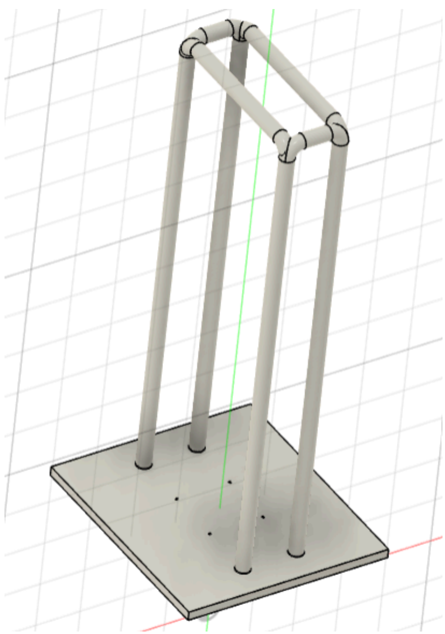
However, the design modification also presents certain drawbacks, mainly increased weight, and additional stress acting on Jackal attachment points. The addition of a reinforced support inevitably adds extra weight to the overall design, potentially impacting the UGV's agility and energy efficiency. The modification also transfers additional stress to the Jackal attachment points, which may necessitate further design considerations to ensure overall structural integrity.

4.4 Iteration Three: Lightweight PVC Design

The third iteration of the design process addresses the critical issues identified with the aluminum extrusions in the benchmark design. The primary concerns were the instability of the Unmanned Ground Vehicle (UGV), particularly when the Jackal tips over during abrupt stops due to the upper body's weight, and the vibrations caused by the unstable attachment of the upper body to the Jackal UGV. To resolve these issues, this iteration explores the use of Polyvinyl Chloride (PVC) as an alternative material, aiming to reduce weight and dampen vibrations**.**

4.4.1 Design Set Up

The PVC model was conceptualized using the same dimensions as the benchmark design detailed in Section 4.1. In this setup, the aluminum extrusions and their connections were substituted with ½ inch PVC pipes and connectors, as depicted in Figure 12. The design maintained the same load and design specifications as the benchmark during the dynamic simulation. Additionally, a modal analysis was performed considering the Jackal motor's frequency of 6.5Hz. This analysis was critical in determining the natural frequency of the PVC structure, thereby aiding in minimizing vibrations. The setup for this modal analysis, which applied the benchmark forces and the motor frequency of 6.5 Hz to a singular PVC pipe, is shown in Figure 13.



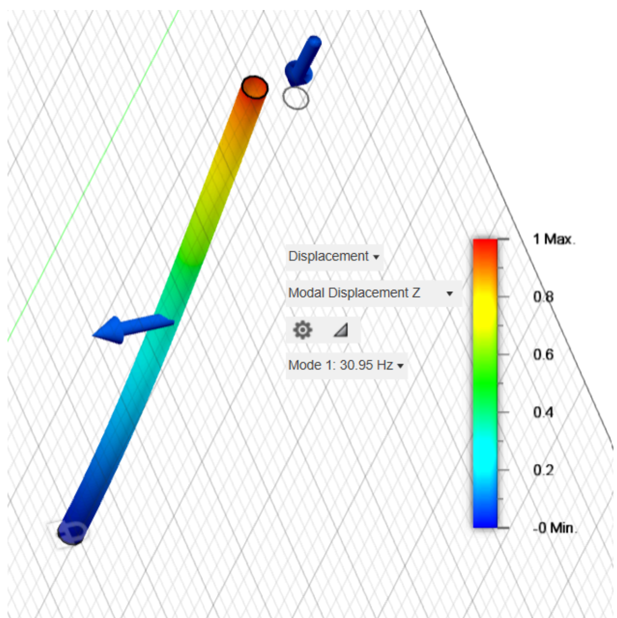


Figure 12. CAD of the PVC Design **Figure 13.** Modal Frequency Analysis of PVC Pipe

4.4.2 Design Outcomes

The dynamic simulation of the PVC design yielded promising results. The maximum displacement observed was 1.476 mm, and the maximum stress recorded was 262 MPa (Figure 14). Notably, the natural frequency of the PVC structure was determined to be 30.95 Hz. These findings indicate a higher performance level compared to the aluminum benchmark design, particularly in terms of weight reduction and vibration control. However, a notable concern was identified: the stress concentration at the base of the upper body still required mitigation to reduce vibrations effectively.

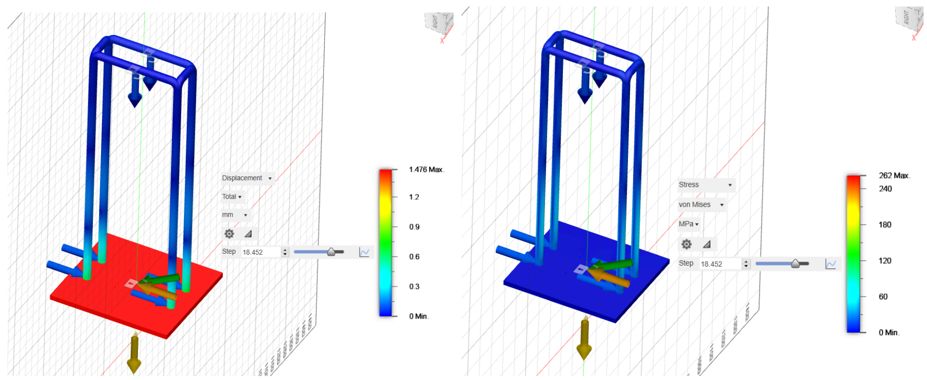


Figure 14. Displacement (Left) and Stress (Right) Dynamic Simulation Results

4.5 Iteration Four: 3D Printed Base for PVC Design

The fourth iteration of the design process builds upon the successful outcomes of the lightweight PVC design discussed in Section 4.4. This iteration introduces a novel component: a 3D printed base fixture. The primary objective of this enhancement is to address and mitigate the stress concentration observed at the base of the lightweight PVC design, aiming to enhance the overall structural integrity and stability of the system.

4.5.1 Design Set Up

In this iteration, a 3D printed baseplate was designed and integrated into the PVC structure. The baseplate material selected was additive ABS plastic, known for its strength and durability. This baseplate was then incorporated into the existing PVC design. Rather than directly mounting the PVC pipes onto the Jackal UGV, these pipes were now affixed to the 3D printed base using a press-fit method, further reinforced with PVC pipe cement for enhanced attachment security, as shown in . Additionally, the 3D printed base was secured to the Jackal using screws and rubber washers. The inclusion of rubber washers was a strategic choice aimed at absorbing and reducing vibrations (Figure 15).

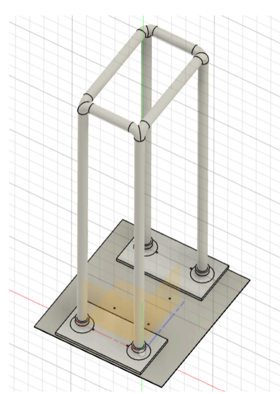


Figure 15. CAD of 3D Printed ABS Base with PVC Upper Body Design

4.5.2 Design Outcomes

The dynamic simulation of this newly configured design yielded significant results. The maximum stress was recorded at 1586 MPa, and the maximum displacement was measured at 2.002 mm (Figure 16). Notably, both the highest stress and displacement concentrations were localized at the attachment point between the 3D printed base and the Jackal UGV. This finding indicates a successful redistribution of stress away from the robot's upper body, effectively addressing the previous iteration's primary concern.

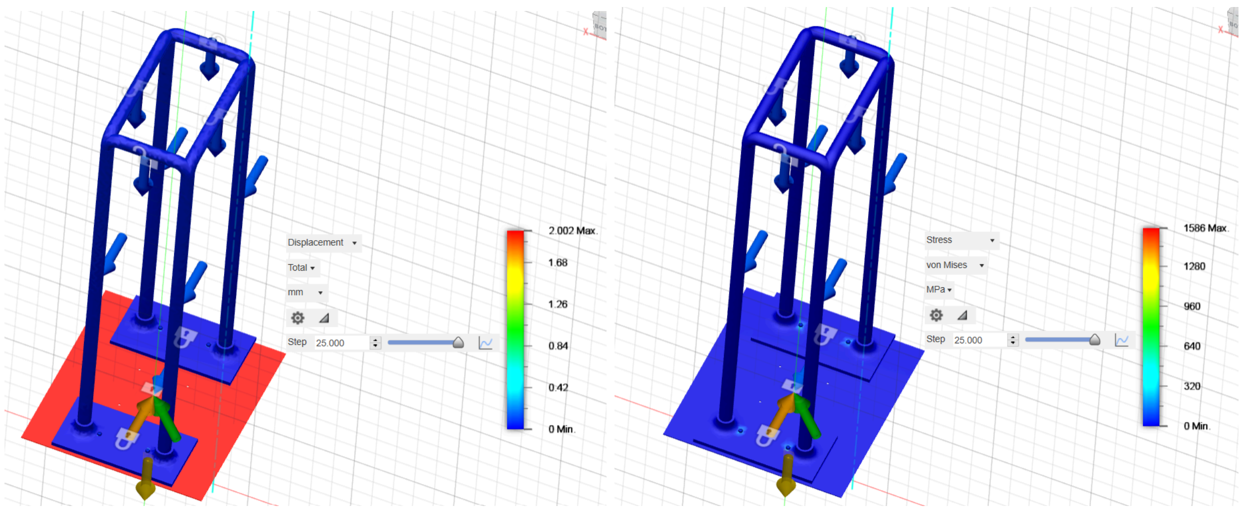


Figure 16. Displacement (Left) and Stress (Right) Dynamic Simulation Results

4.6 Results Discussion

4.6.1 Simulation Results

This section presents a comparative analysis of the simulation results obtained from the feasible design iterations discussed in Section 3. Specifically, the focus is on evaluating the performance of the lightweight PVC design and the 3D printed base design against the benchmark aluminum extrusion design.

The comparative data, as detailed in Table 4, reveals several key insights. Firstly, the PVC design demonstrates an ability to maintain a similar maximum displacement as the benchmark design, which is a significant achievement considering the material differences. More importantly, the PVC design excels in minimizing both the weight and stress of the upper body. This reduction is not just numerically significant but also crucial from a practical standpoint, as it contributes to an overall more efficient and sustainable upper body design for the Unmanned Ground Vehicle (UGV).

A critical aspect of the evaluation is the natural frequency of the materials used. The motor frequency of the UGV is 6.5 Hz. In this context, the PVC plastic shows a higher natural frequency of 30.95 Hz. This frequency is substantially higher than the motor's operating frequency, thereby effectively reducing the likelihood of modal resonance. Modal resonance is a known cause of stronger vibrations, and its avoidance is key to enhancing the structural integrity and operational stability of the UGV. In contrast, the benchmark aluminum extrusion material exhibits a lower natural frequency of 17.94 Hz, making it more susceptible to vibrations and potentially less stable under operational conditions.

However, the results also indicate a challenge with the 3D printed base combined with the PVC design. Numerically, this configuration shows an increase in both the maximum stress and the total weight compared to the PVC design alone. This increase necessitates further graphical analysis to fully understand and interpret the implications of these results.

Table 4. Simulation Results Comparison of Candidate Designs and Benchmark Design

Model	Material	Total Weight (g)	Max stress (MPA)	Max Displacement (mm)	Natural Frequency (Hz)
Benchmark Design	Aluminum	16281.405	253.3	2.078	17.94
PVC Design	PVC Plastic	3879.399	266.9	2.003	30.95
3D Printed Base with PVC Design	PVC Plastic, ABS Plastic	5477.577	1586	2.002	-

4.6.2 Graphical Comparison

In this section, a detailed graphical comparison is conducted between the two leading design candidates: the PVC Design and the 3D printed base with PVC design. This analysis is crucial in further evaluating and contrasting the maximum stress and displacement characteristics of each model, as derived from dynamic simulations.

4.6.2.1 Stress Distribution Analysis

Figure 17 presents a comparative visualization of the stress distribution in both models. A critical observation from this figure is the location and intensity of maximum stress in each design. For the PVC design, the peak stress, recorded at 251.6 MPa, is predominantly located near the bottom of the four legs of the robot's upper body. This indicates a significant concentration of stress in these areas.

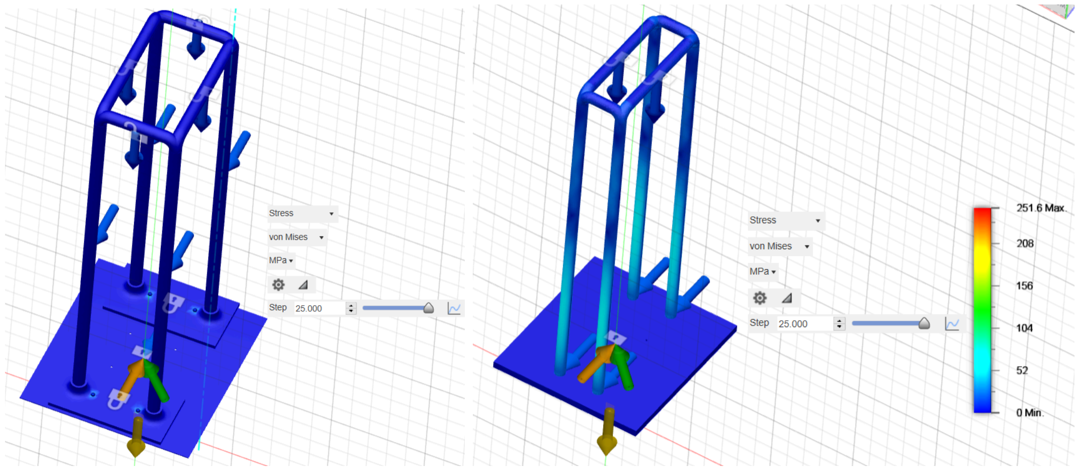


Figure 17. PVC Design with Base (Left) and Without Base (Right) Stress Simulation Results

Conversely, the 3D printed base design exhibits a distinctly different stress profile. The maximum stress for this model, which is considerably higher at 1586 MPa, is centralized at the attachment point of the 3D printed base. Notably, this design effectively redirects stress away from the upper body and the four legs. Although this results in an increased overall stress level, it aligns with our design criteria by eliminating stress distribution across the robot's upper body. This characteristic is particularly advantageous as it enhances the structural integrity and operational stability of the design.

4.6.2.2 Displacement Distribution Analysis

The displacement distribution for both models is depicted in Figure 18. The maximum displacement values for the two designs are closely comparable, with the 3D printed base showing a maximum of 2.001mm and the PVC design displaying a slightly higher value of 2.003mm. However, the distribution pattern of this displacement varies significantly between the two designs.

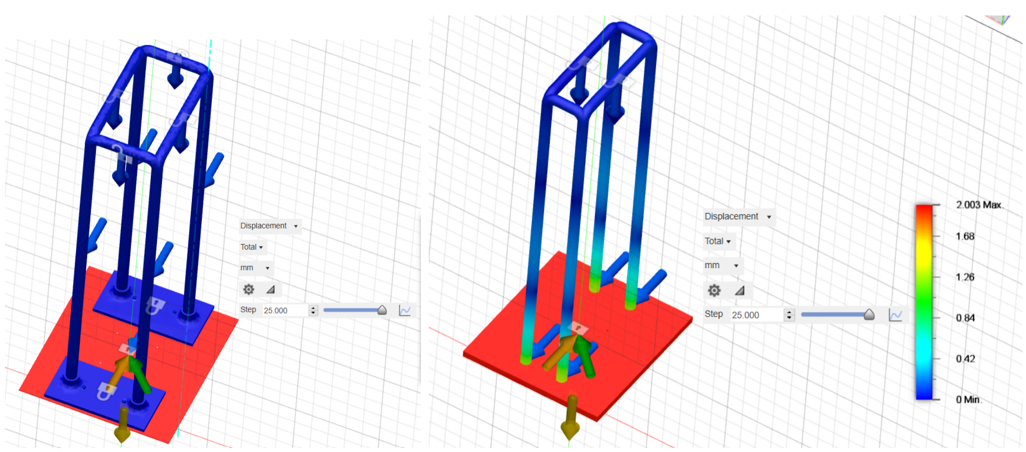


Figure 18. PVC Design with Base (Left) and Without Base (Right) Displacement Simulation

For the PVC design, a considerable amount of displacement is observed at the base of the four legs of the robot's upper body. This finding suggests a potential vulnerability in these areas under operational conditions. In contrast, the 3D printed base design exhibits a more favorable displacement pattern, with negligible displacement evident in the upper body. This outcome is aligned with our design objectives, as it effectively minimizes vibrations and the associated rattling noises that could arise during operation.

4.6.3 Moment Calculations

This section details the moment calculations performed to assess the risk of tipping during abrupt maneuvers for the robot designs. The analysis compares the tipping forces between the benchmark aluminum design and the PVC design, with the tipping point defined at the wheel-ground contact point at the corner of the robot.

4.6.3.1 Gravitational Moment Calculation

The gravitational moment (Mg) around the tipping point is calculated using the formula:

$$\mathbf{Mg = W \times dg} \quad \text{(Equation 1)}$$

where:
Mg is the gravitational moment,
W is the weight of the robot, calculated as mass M times gravitational acceleration g,
dg is the perpendicular distance from the line of action of the weight force to the tipping point.

For the metal frame:

$$\mathbf{Mg\ (metal) = (51.581743\ kg*9.81\ m/s^2) \times 0.5\ m = 253.01\ Nm}$$

For the PVC frame:

$$\mathbf{Mg\ (PVC) = (8.646069\ kg*9.81\ m/s^2) \times 0.5m = 42.409\ Nm}$$

4.6.3.2 Applied Force Moment Calculation

The moment generated by the applied force (Mf) around the tipping point is calculated as:

$$\mathbf{Mf = F \times df}$$

where:
Mf is the moment due to the applied force,
F is the applied force of the upper body on the base of the robot,
df is the perpendicular distance from the line of action of the applied force to the tipping point (in this case, df = 1m.

4.6.3.3 Equilibrium Condition for Tipping

The tipping point is reached when the moment due to the applied force equals the gravitational moment:

$$\mathbf{Mf = Mg}$$

Solving for F yields the tipping force as shown in Table 5.

Table 5. Tipping Force Calculation Results for Various Designs

Design	Tipping Force (N)
Jackal UGV	166.77
Aluminum Upper Body Frame	253.01
PVC Upper Body Frame	42.409

For the metal frame, the tipping force is 253.01 N, whereas, for the PVC frame, it is substantially lower at 42.409 N. Comparing these with the counteracting force from the Jackal (166.77N), we find, for the Metal Frame, 253.01 N > 166.77 N, indicating a risk of tipping over at approximately 0.659 times gravity (6.466 m/s^2). For the PVC Frame, 42.409 N < 166.77 N, suggesting it would require nearly 3.9 times gravity (38.26 m/s^2) to tip over.

5.0 Upcoming Work

As the project transitions from the design phase to the practical implementation of the finalized design, a detailed plan for prototyping and software development is outlined. This phase is critical in transforming theoretical designs into a tangible, functional robot, ensuring that the design objectives are met in real-world applications.

5.1 Upper Body Prototyping

The immediate step involves the construction of the robot's upper body, a task that requires specific components listed in Table 6.

Table 6. Prototyping Componenets, Quantity, and Cost

Part	Qty Needed	Cost
90 degree ½ inch 3 way connectors [15]	1 (we only need 4 but this is a 10 pack)	$22.99
½ inch x 10' PVC pipe [16]	2	$12.49 ea

PVC Pipe Cement [17]	1	$8.81
PVC Lock Cap [18]	4	2.38 ea
Rubber Washer [19]	4	$0.58 / 5 washers
3D Print [20]	2	$5/hr printing time plus material cost
Estimated Total Cost		$68.88

The acquisition of these parts is crucial for the assembly process. Once all parts are procured, the following steps will be undertaken:
Assembly of Upper Body: The components will be methodically assembled to form the upper body of the robot. This process must adhere to the design specifications and blueprints developed in the previous phases.
Mounting to Jackal UGV: After assembly, the upper body will be securely mounted to the Jackal Unmanned Ground Vehicle. This step is pivotal in integrating the upper body with the mobility platform, forming a cohesive unit.
Testing: Post-assembly, a series of tests will be conducted to ensure the structural integrity and functional performance of the assembled upper body in conjunction with the Jackal UGV.

5.2 Software Implementation for Tablet Interface

Parallel to the hardware assembly, the development of the tablet interface software is scheduled. This process encompasses several key components:
User Interface Design: Development of an intuitive and user-friendly interface is paramount. The focus will be on creating an interface that is easy to navigate and understand, ensuring seamless interaction between the user and the robot.
Integration of Advanced Features: This step involves incorporating voice commands, a virtual robotic face, and visual feedback mechanisms into the interface. These features are aimed at enhancing user interaction and making the interface more engaging and responsive.
Software and Hardware Systems Testing: The final phase in software development involves rigorous testing in specified environments. This step is critical to ensure that both software and hardware components work harmoniously and are resilient under various operational conditions.

6.0 References

[1] L. Alboul, M. Dimitrova, A. Lekova, V. G. Kaburlasos, and P. Mitrouchev, “Editorial: Emerging technologies for assistive robotics: Current challenges and perspectives,” Frontiers, https://www.frontiersin.org/articles/10.3389/frobt.2023.1288360/full (accessed Nov. 29, 2023).

[2] Charles, “10 Robotics Trends & Predictions for 2023,” Into Robotics, https://intorobotics.com/10-robotics-trends-predictions-for-2023/ (accessed Nov. 29, 2023).

[3] D. Norman, "The Design of Everyday Things: Revised and Expanded Edition," Basic Books, Nov. 5, 2013.

[4] M. J. Mataric, "The Robotics Primer," MIT Press, Aug. 17, 2007.

[5] O. Khatib and B. Siciliano, Eds., "Springer Handbook of Robotics," Springer International Publishing, 2016.

[6] L. W. Tsai, "Robot Analysis: The Mechanics of Serial and Parallel Manipulators," John Wiley & Sons, Feb. 22, 1999.

[7] S. Thrun, "Toward a framework for human-robot interaction," Human–Computer Interaction, vol. 19, no. 1-2, pp. 9-24, Jun. 1, 2004.

[8] R. R. Murphy, "Introduction to AI Robotics," MIT Press, Oct. 1, 2019.

[9] R. A. Brooks, "Intelligence without representation," Artificial Intelligence, vol. 47, no. 1-3, pp. 139-59, Jan. 1, 1991.

[10] A. Weiss, R. Bernhaupt, M. Lankes, and M. Tscheligi, "The USUS evaluation framework for human-robot interaction," in Proceedings of the Symposium on New Frontiers in Human-Robot Interaction, AISB2009, Apr. 8, 2009, vol. 4, no. 1, pp. 11-26.

[11] “Zed Mini - mixed-reality camera,” STEREOLABS, https://www.stereolabs.com/zed-mini/ (accessed Nov. 29, 2023).

[12] “Arkon TAB086-12 heavy duty tablet clamp mount with 12 inch neck for iPad Pro iPad Air Galaxy Note 10.1 retail black,” Amazon.ca: Electronics, https://www.amazon.ca/ARKON-Wheelchair-Tablet-12-Inch-TAB086-12/dp/B00BCSYZVY?th=1 (accessed Nov. 29, 2023).

[13] S. Khan, “Acer iconia one 10 B3-A30 - full specification,” Gizmochina, https://www.gizmochina.com/product/acer-iconia-one-10-b3-a30/ (accessed Nov. 29, 2023).

[14] “Jackal UGV - small weatherproof robot - clearpath,” Clearpath Robotics, https://clearpathrobotics.com/jackal-small-unmanned-ground-vehicle/ (accessed Nov. 29, 2023).

[15] “PVC fittings 1/2 inch, 3-way PVC connectors for SCH40 1/2" PVC pipe - build heavy duty PVC furniture and plumbing projects available, white [pack of 10], pipe fittings - Amazon Canada,” , Pipe Fittings - Amazon Canada, https://www.amazon.ca/Fittings-3-Way-4-Way-5-Way-Connectors/dp/B081SGMZM6/ref=asc_df_B081SGMZM6/?tag=googleshopc0c-20&linkCode=df0&hvadid=335485183877&hvpos=&hvnetw=g&hvrand=14348681142649108925&hvpone=&hvptwo=&hvqmt=&hvdev=c&hvdvcmdl=&hvlocint=&hvlocphy=9061009&hvtargid=pla-869954990134&th=1 (accessed Nov. 29, 2023).

[16] 1/2" x 10’ schedule 40 PVC pressure pipe | home hardware, https://www.homehardware.ca/en/12-x-10-pvc-schedule-40-pressure-pipe/p/3262123 (accessed Nov. 30, 2023).

[17] “Pipe Cements & Primer - Plumbing Accessories,” Pipe Cements & Primer - Plumbing Accessories - Homedepot.ca, https://www.homedepot.ca/en/home/categories/building-materials/plumbing/plumbing-accessories/pipe-cements-and-primer.html (accessed Nov. 29, 2023).

[18] “Orbit 1/2inch PVC-lock cap,” The Home Depot Canada, https://www.homedepot.ca/product/orbit-12inch-pvc-lock-cap/1000832878?eid=PS_GOOGLE_D00+-+E-Comm_GGL_Shopping_PLA_EN_All+Products_All+Products__PRODUCT_GROUP_pla-488082539672&gclid=Cj0KCQjwpc-oBhCGARIsAH6ote9uYQ4H1F9VFxkLfCfje_RLsCLg7rJ7ZuJkT46kFw1_UyWCmvufd9IaAgg1EALw_wcB&gclsrc=aw.ds (accessed Nov. 29, 2023).

[19] DigiKey - electronic components distributor, https://www.digikey.com/ (accessed Nov. 30, 2023).

[20] “Mie home,” Department of Mechanical & Industrial Engineering, https://www.mie.utoronto.ca/ (accessed Nov. 29, 2023).