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DESIGN & DEVELOPMENT OF SEMI-AUTONOMOUS STREET-CLEANING VEHICLE

Khouloud Safa AZOUD

Master's Thesis

Supervisor

Assoc. Prof. Dr. Süleyman BAŞTÜRK

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The thesis titled DESIGN & DEVELOPMENT OF SEMI AUTONOMOUS STREET CLEANING VEHICLE prepared by KHOULOUD SAFA AZOUD and submitted on 11/10/2024 has been **accepted unanimously** for the degree of Master of Science in Mechanical Engineering.

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Khouloud Safa AZOUD

Signature

DEDICATION

I dedicate this work.

To my parents Mohamed and Yasmina, for the love they always gave me, their encouragement, and all the help they gave me during my studies.

To my husband Mahdi, for his invaluable moral support and his noble advice, for my success.

To my sisters Achouak, Maroua, Serine, and my adorable brother Yahya, thank you for pushing me to move forward when sometimes I didn't want to at all.

There probably won't be enough words to describe how truly supportive they were on every level.

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I would like to express my thanks to the people with whom I was able to interact and who helped me write this thesis.

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ABSTRACT

DESIGN & DEVELOPMENT OF SEMI-AUTONOMOUS STREET CLEANING VEHICLE

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This thesis introduces two pioneering innovations in automated cleaning machines, each targeting unique challenges to enhance urban sanitation systems. The first innovation presents a semi-automatic road surface cleaning machine that combines human labor with solar energy. This integration of manual operation and solar panel utilization enhances environmental sustainability and adaptability, particularly in areas with limited access to electricity. By reducing carbon emissions and improving operational efficiency, this approach shows promise for advancing urban sanitation systems.

The second innovation is a multifunctional semi-automatic floor-cleaning machine designed to address challenges in developing countries. This machine features an automatic system comprising a camera, Arduino programming, and GPS, enabling autonomous operation to overcome cost barriers prevalent in these regions. Emphasizing low energy consumption and cost savings, the machine offers a versatile solution effective in various environmental conditions.

The study involves market sampling for Semi-automatic Street cleaning machines with specific parameters to meet the needs of target markets. It includes creating detailed drawings and explanations for each component, employing mathematical equations to design the solar panel, and optimizing the machine's motor considering the specific operating environment.

SOLIDWORKS software is utilized to execute comprehensive die designs for the machines, ensuring precision and functional performance. Furthermore, simulation within SOLIDWORKS is employed to test and validate the designs, ensuring optimal performance across diverse conditions. This process aids in evaluating the machine's efficiency, safety, and overall functionality.

These innovations contribute to sustainable urban sanitation by providing advanced cleaning solutions that are energy-efficient and cost-effective, particularly in developing regions. By integrating solar energy, diverse cleaning capabilities, and meticulous design and analysis, this thesis represents a significant step forward in urban sanitation.

Keywords: Automated Cleaning Machines, Solar Energy Integration, Solid Works, Simulation, Developing Countries, Operational Efficiency, Urban Sanitation Systems.

ÖZET

YARI OTONOM SOKAK TEMIZLEME ARACININ TASARIMI VE GELIŞTIRILMESI

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Bu tez, kentsel temizlik sistemlerini geliştirmeye yönelik benzersiz zorlukları hedefleyen iki yenilikçi otomatik temizlik makinesini tanıtmaktadır. İlk yenilik, güneş enerjisini insan emeği ile birleştiren yarı otomatik bir yol yüzeyi temizleme makinesidir. Manuel operasyon ve güneş paneli kullanımının entegrasyonu, özellikle elektriğe erişimin sınırlı olduğu alanlarda çevresel sürdürülebilirliği ve uyum yeteneğini artırmaktadır. Karbon emisyonlarını azaltarak ve operasyonel verimliliği artırarak, bu yaklaşım kentsel temizlik sistemlerini geliştirme potansiyeli taşımaktadır.

İkinci yenilik ise gelişmekte olan ülkelerdeki zorlukları ele almak için tasarlanmış çok fonksiyonlu bir yarı otomatik zemin temizleme makinesidir. Bu makine, maliyet engellerini aşmak için kamera, Arduino programlama ve GPS içeren bir otomatik sistem ile donatılmıştır. Düşük enerji tüketimi ve maliyet tasarrufunu vurgulayan bu makine, çeşitli çevresel koşullarda etkili, çok yönlü bir çözüm sunmaktadır.

Çalışma, hedef pazarlara uygun belirli parametreler doğrultusunda yarı otomatik sokak temizleme makineleri için pazar örneklemesini içermektedir. Her bir bileşenin ayrıntılı çizimlerinin ve açıklamalarının oluşturulmasının yanı sıra, güneş panelini tasarlamak için matematiksel denklemler kullanılmakta ve makinenin çalışma ortamına uygun motorun optimizasyonu yapılmaktadır.

SOLIDWORKS yazılımı, makinelerin hassasiyet ve işlevsel performansını sağlamak amacıyla kapsamlı kalıp tasarımlarını gerçekleştirmek için kullanılmaktadır. Ayrıca, tasarımları test etmek ve doğrulamak amacıyla SOLIDWORKS içinde simülasyon yapılmakta, böylece çeşitli koşullarda optimum performans sağlanmaktadır. Bu süreç, makinenin verimliliğini, güvenliğini ve genel işlevselliğini değerlendirmeye yardımcı olmaktadır.

Bu yenilikler, enerji verimliliği ve maliyet etkinliği sağlayan gelişmiş temizlik çözümleri sunarak kentsel temizlikte sürdürülebilirliğe katkıda bulunmaktadır. Güneş enerjisinin entegrasyonu, çeşitli temizlik yetenekleri ve titiz tasarım ve analiz çalışmaları ile bu tez, kentsel temizlik sistemlerinde önemli bir adımı temsil etmektedir.

Anahtar Kelimeler: Otomatik Temizlik Makineleri, Güneş Enerjisi Entegrasyonu, SolidWorks, Simülasyon, Gelişmekte Olan Ülkeler, Operasyonel Verimlilik, Kentsel Temizlik Sistemleri.

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1. INTRODUCTION

1.1 GENERAL OVERVIEW ABOUT SEMI-AUTOMATIC STREET CLEANING MACHINES

In the ever-evolving landscape of urban development, the imperative of maintaining cleanliness in city streets stands as a paramount concern. Beyond mere aesthetics, cleanliness is foundational to public health, environmental well-being, and the overall quality of urban life. Traditional Manual Street cleaning, although effective to a certain degree, grapples with the burgeoning demands of modern urban environments. The advent of semi-automatic street cleaning machines signifies a paradigm shift, not just in addressing these challenges but also in redefining the trajectory of urban sanitation [1].

Cleanliness in urban spaces is more than a visual necessity; it is intricately woven into the fabric of a thriving and healthy community. As cities burgeon and populations soar, the demand for efficient and sustainable cleaning solutions becomes paramount. A clean urban environment fosters public well-being, contributes to the aesthetic appeal of neighborhoods, and mitigates environmental risks. The need for innovation in street cleaning practices is evident, paving the way for advancements that transcend the limitations of manual methods [2] as illustrated in Figure 1.1.

Figure 1.1: Historical Streetscape: Manual Street Sweeping in the Early 20th Century [2].

The conceptualization of semi-automatic street cleaning machines evolved from a confluence of technological breakthroughs and a recognition of the pressing need for greater efficiency in urban maintenance. The realization that automation could alleviate the laborintensive nature of traditional cleaning methods while enhancing precision sparked the genesis of these machines.

Countries at the forefront of this innovation, including but not limited to the United States, Germany, Japan, and China, embarked on collaborative efforts to develop semi-autonomous capabilities [3,4].

Creating semi-automatic street cleaning machines is a testament to international collaboration and the fusion of diverse expertise. Engineers from various disciplines, including mechanical engineering, robotics, and artificial intelligence, collaborated to design machines that could operate semi-autonomously. These collaborative efforts addressed challenges related to the robustness and efficiency of cleaning mechanisms, the development of advanced navigation systems, and the integration of cutting-edge sensor technologies for obstacle detection [5].

The development of these machines was not without challenges. Countries involved in this innovative venture faced obstacles such as navigating complex urban terrains, optimizing energy efficiency, and addressing economic constraints. Overcoming these challenges required a concerted effort to refine and iterate on the design, incorporating feedback from real-world testing scenarios. The collaborative spirit extended beyond borders, with shared insights contributing to the evolution of semi-automatic street cleaning machines.

The integration of renewable solar energy into semi-automatic street cleaning machines is crucial, aligning with the broader sustainability agenda and offering a multitude of benefits. This strategy shift enhances environmental responsibility, reducing dependence on traditional energy sources and contributing to a cleaner and greener urban landscape. Moreover, it improves operational efficiency, increases worker well-being, and signals a forward-looking approach to sustainable urban maintenance [6].

1.2 THESIS OVERVIEW

This thesis outlines the design process of a semi-automatic street cleaning machine powered by solar energy. Chapter 1 introduces the street cleaning machine powered by solar energy, providing an overview of its design and highlighting its efficiency and sustainability.

Additionally, it outlines the thesis structure and briefly reviews relevant literature on solar-powered cleaning technologies.

Chapter 2 covers the methodology, detailing the installation of a solar panel with specified characteristics and measurements on the machine. Additionally, two electric motors and a battery will be incorporated for electricity storage. It also discusses the essential components that manage motors, correct GPS drift, and provide a user interface. The software integrates sensor data and controls motors via Arduino Mega.

Chapter 3 conducts Finite Element Analysis (FEA) simulations on key components of the street cleaning machine: the basket, chassis, and handle. Results confirm structural durability and performance under operational loads.

Moving to Chapter 4, explores the manufacturing of a semi-autonomous street cleaning vehicle, focusing on key components like the metal framework, sweeper brushes, and avionics enclosure. It emphasizes precision engineering, durable materials, and meticulous assembly for high-quality construction.

Chapter 5 assesses the performance of a solar-powered street cleaning vehicle in Algeria and Morocco, leveraging MATLAB to analyze energy output. It demonstrates the vehicle's viability in various regions, emphasizing its sustainability, environmental benefits, and cost-effectiveness compared to traditional methods.

Finally, in Chapter 6, the thesis concludes with a discussion of the final findings, detailing any remaining business and proposing future work to further develop or complete this type of machine.

1.3 THESIS CONTRIBUTIONS

a. Innovation: The introduction of a semi-automatic road floor-cleaning machine that integrates human labor with solar energy efficiency.
b. Applicability to Developing Regions: Extends applicability to areas with limited electricity access, particularly in developing regions like Africa, the Middle East, and the Gulf.

c. Environmental Friendliness: Utilization of solar energy reduces reliance on fossil fuels, significantly lowering the carbon footprint.
d. Operational Efficiency: Semi-automatic functionality enhances operational efficiency, enabling extensive area coverage with minimal effort.
e. Holistic Solution: The combination of human guidance and solar-powered functionality offers a sustainable and efficient approach to street cleaning, contributing to advancements in urban sanitation systems.
f. Versatility: Capable of garbage collection, scrubbing, mopping, drying, and wiping, with the option to operate on solar energy, battery, or electricity.
g. Cost-Effective Design: Designed to overcome cost-related barriers, making it viable in regions with lower labor costs.
h. Energy Efficiency: Significantly reduces energy consumption, contributing to operational cost savings and environmental friendliness.
i. Utilization of Renewable Energy: Harnesses renewable energy sources, particularly solar energy, abundant in many developing countries, contributing to reduced environmental impact.

1.4 LITERATURE REVIEW

The evolution of street sweepers can be traced back to concerns about cleanliness and pollution, prompting innovations that eventually gave rise to the modern street sweeper. Initially, manual labor was employed to roam streets and collect debris from newly paved roadways. The mechanized street sweeper emerged in the 1910s, marked by innovators like John Murphy from Elgin, Illinois, whose design laid the foundation for Elgin, a prominent sweeping manufacturing company still operational today. Murphy's creation was a highly maneuverable three-wheeled sweeper, emphasizing ease of maintenance, as seen in Figure 1.2. With a focus on aesthetics and sanitation, street sweeping, whether manual or mechanical, has been a municipal practice for centuries. Recent investigations into street sweeper efficiency prioritize minimizing pollutant transport to receiving waters, with current types categorized as mechanical broom, vacuum-assisted broom, and regenerative-air units. Schilling offers insights into US sweeper manufacturers, models, and specifications, highlighting the superior performance of vacuum-assisted and regenerative air sweepers in handling finer sediments, while mechanical sweepers excel in clearing larger debris (FHWA) [1, 2, 7, 8].

Figure 1.2: John Murphy's Three-Wheeled Sweeper [7].

In 1901, Hubert of England is credited with inventing the vacuum cleaner. Decades later, Booth attended a demonstration at the Empire Music Hall in London, where an American machine's inventor showcased its capabilities. Although the inventor remained unnamed, Booth's description aligned closely with Thurman's modified design. Witnessing a demonstration of the device blowing dust off chairs, Booth envisioned a reversed system with a filter to hygienically retain dust in a receptacle. Testing his idea by suctioning dust onto a handkerchief placed on a restaurant chair, Booth confirmed its potential effectiveness upon seeing collected dust and dirt. A hand-powered pneumatic vacuum cleaner was designed in 1910. An early electric-powered model is also depicted in Figure 1.3 [9, 5].

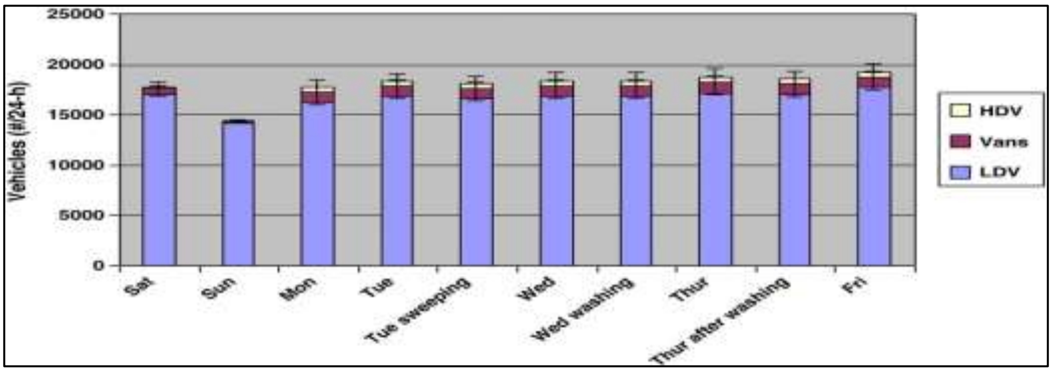


Figure 1.3: Daily Average Traffic Intensity (and Standard Deviation) in the Jan van Galenstraat: Tuesday (Without and With Sweeping), Wednesday (Without and With Washing), and Thursday (after a Wednesday Without and With Washing). N=9 (Without Sweeping/Washing) and N=14 (With Sweeping/Washing) [5].

Walter Griffiths, a Birmingham-based manufacturer, introduced the first portable vacuum cleaner for the domestic market in 1905. His creation, named Griffith's Improved Vacuum Apparatus for Removing Dust from Carpets, shared striking similarities with contemporary cleaners. Notably portable and easily storable, it operated through a bellows-like contraption, enabling anyone to suction dust using a removable, flexible pipe. Various shaped nozzles could be attached, enhancing their versatility and utility for household cleaning tasks as shown in Figure 1.4 [10].

In 1906, James Kirby introduced his inaugural vacuum, the "Domestic Cyclone," utilizing water for dirt separation. Around 1908, the Electric Suction Sweeper Company launched an electric vacuum cleaner. In 1907, James Murray Spangler, a department store janitor, patented the Electric Suction Sweeper, marking the inception of the first portable electric vacuum. Spangler's innovative design incorporated an electric fan for suction, directing dirt into a soapbox through his wife's pillowcase, while a rotating brush aided in debris removal. Lacking funds to produce the design, Spangler sold the patent in 1908 to Henry Hoover, a local leather goods manufacturer. Hoover's redesigned machine, introduced as the 1908 Model O, marked the inception of the Hoover Company, known for subsequent innovations like the beater bar in disposal filter bags in the 1920s and the upright vacuum cleaner in 1926 [10].

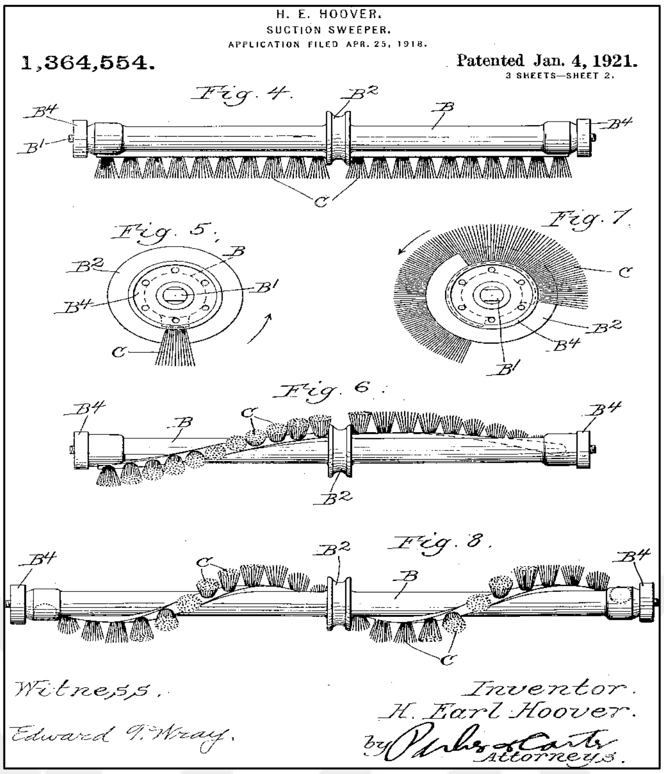


Figure 1.4: Adjustable Parts and Operational Features of Suction-Sweeper [10].

The review by Brunekreef and Forsberg underscores the potential mortality implications linked to coarse particulate matter (PM) [11], particularly in arid regions. Epidemiological studies, exemplified by L. Perez et al. [12] establish a correlation between elevated levels of anthropogenic coarse particles and daily mortality. Furthermore, transition metals present in road dust contribute to particle oxidative capacity and are associated with toxicity, as evidenced by Valavanidis et al. [13] and Schlesinger et al. [14] Notably, studies by Schins et al. [15] and Schwarze et al. [16] highlight the inflammatory effects induced by coarse particles, emphasizing the health consequences of particulate pollution. This comprehensive understanding sets the stage for exploring the efficacy of cleaning machines in mitigating these health challenges, as discussed in subsequent paragraphs by Minton et al. and Duncan et al. [17, 18].

In the subsequent studies, Minton et al. and Duncan et al. actively contributed to the mitigation of particle impact. Through the development of high-efficiency and improved vacuum cleaners, these studies propose effective solutions to address challenges posed by particulate pollution. Emphasizing the significance of proficient cleaning machines in capturing and eliminating particles, these advancements align with the broader context established in prior paragraphs concerning the health implications of particulate matter exposure. Consequently, these discussions emphasize the pivotal role of technological developments in street cleaning machines for maintaining air quality and promoting public health amidst particulate pollution challenges [17, 18].

The shift towards sustainable energy sources has led to the exploration of solar power as a viable option for powering street cleaning machines. Solar energy, being renewable and clean, offers a way to operate street cleaning machines without the carbon emissions associated with fossil fuels.

The integration of solar power into street cleaning machines aligns with global environmental goals and represents the latest advancement in the evolution of this technology. Solar-powered solutions for street cleaning have begun to emerge in two main forms: fully autonomous solar-powered robots and solar-assisted manual machines. These solar-powered technologies leverage photovoltaic panels to convert sunlight into electricity, which is then used to power the cleaning mechanisms and, in some cases, the drive systems of the machines.

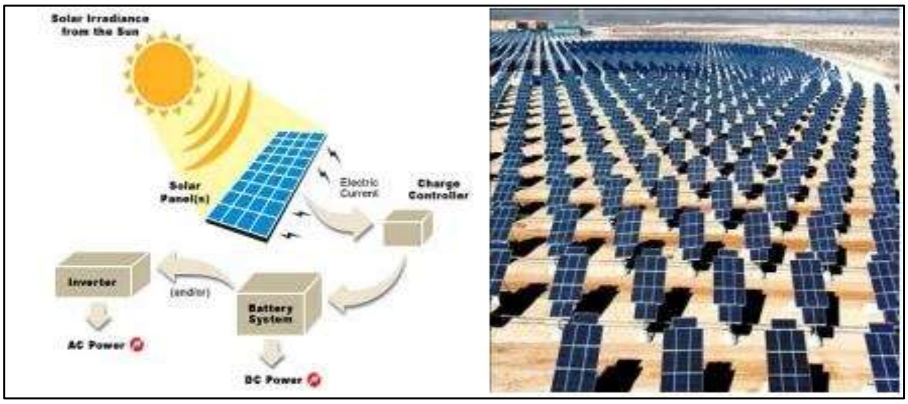


Figure 1.5: Solar Panels [19].

Solar-powered Street cleaning machines often come equipped with battery storage to ensure that operations can continue during periods of low sunlight. This energy storage capability is crucial for maintaining the machine's performance and reliability, allowing for consistent cleaning schedules regardless of weather conditions.

The emergence of solar-powered street cleaning machines is not only an innovation in cleaning technology but also part of a broader transition towards greener and more sustainable urban maintenance practices. As these solutions continue to develop, they are expected to play an increasingly important role in efforts to reduce the environmental impact of urban sanitation operations and contribute to the creation of cleaner, healthier public spaces, as illustrated in Figure 1.5 [19, 20].

Global energy demand, particularly electricity, is continually rising, playing a crucial role in generating wealth and fostering economic development [6, 21]. Despite the widespread availability of oil-based energy sources, global environmental concerns are driving a strong shift towards renewable energy, with solar energy, particularly photovoltaic (PV), emerging as the most promising sustainable source [1]. Solar PV is expected to become the leading energy resource among all sustainable options by 2040, owing to its environmentally friendly nature and abundant availability [6, 21].

Photovoltaic (PV) technologies, commonly known as solar panels, harness energy by converting sunlight into electrical energy through semiconductor materials [22]. The inception of practical solar energy conversion dates back to 1954 when researchers at Bell Telephone Laboratories demonstrated the first efficient on-junction solar cell with a 6% efficiency [21]. Solar panels consist of photovoltaic cells, or solar cells, which utilize the photoelectric effect to convert light photons into electrical voltage [23]. Typically small, a single solar cell produces about 1 or 2 watts of power and is constructed from various semiconducting materials, often thinner than four human hairs, and protected by layers of glass and/or plastic for outdoor durability.

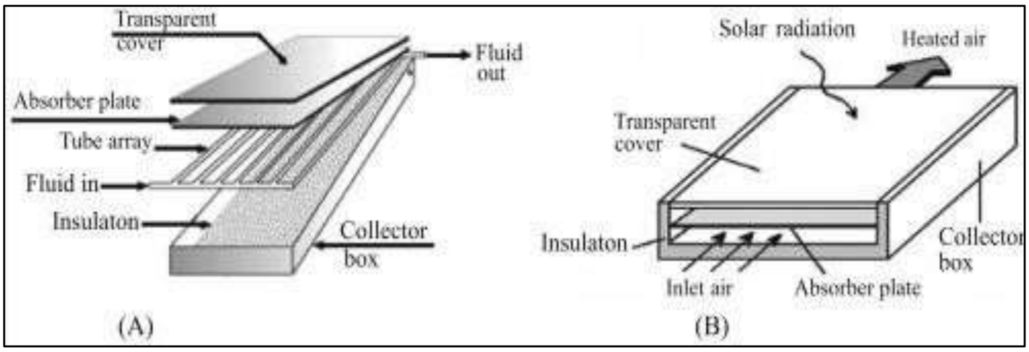


Figure 1.6: Solar Panel Components [24].

The development of solar energy has seen remarkable progress, and solar power is currently employed across various applications globally. Solar energy is extensively utilized for residential purposes, powering homes, and providing electricity to remote areas. It is also harnessed for commercial and industrial operations, contributing to grid power and reducing reliance on conventional energy sources. Furthermore, solar energy is a key player in addressing environmental concerns, contributing to sustainable practices, and fostering a cleaner and greener energy landscape worldwide as shown in Figure 1.6 [24].

The integration of solar energy storage is essential for a sustainable and reliable energy supply in the growing renewable energy sector. Key players, including Tesla, LG Chem, and Samsung SDI, have played significant roles in shaping the solar energy storage market. Tesla, with its Powerwall and Powerpack solutions, stands out as a market leader, leveraging brand recognition and battery technology expertise for widespread adoption. LG Chem and Samsung SDI contribute with lithium-ion battery technologies known for high energy density and reliability.

These companies invest heavily in R&D to enhance battery performance and reduce costs. Market leaders differentiate themselves through innovations and strategic partnerships; Tesla integrates energy storage with electric vehicle technology, creating synergies. LG Chem and Samsung SDI prioritize safety, performance, and customization, collaborating with solar system integrators for seamless solutions in residential and commercial installations [25, 26].

Manual street cleaning practices involve human labor for sweeping and maintenance, representing traditional and enduring methods. In contrast, automatic street cleaning technologies leverage machinery and advanced systems, offering advantages such as heightened efficiency and reduced labor costs. Semi-automatic machines, positioned between manual and fully automatic methods, synergize human operators with automated features to enhance cleaning efficacy. The incorporation of semi-automatic machines serves as an intermediary solution, augmenting efficiency and cost-effectiveness in street cleaning. Adopting automatic technologies, including semi-automatic machines, allows cities and municipalities to enhance street cleanliness, optimizing resources and minimizing reliance on manual labor [27].

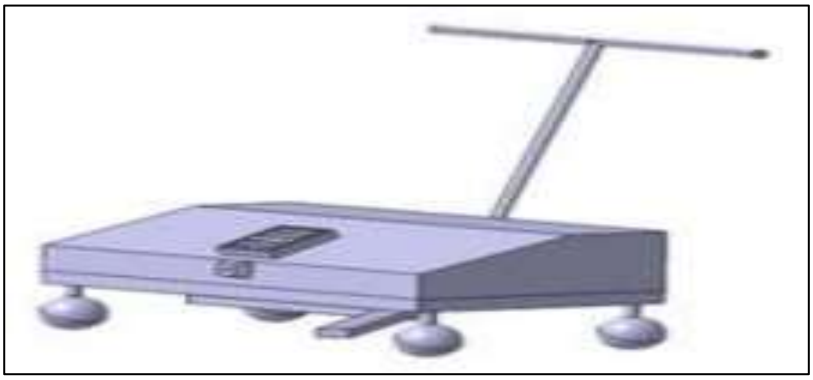
In the context of India, the extensive research on street cleaning machines has resulted in notable developments, addressing various challenges in floor and road cleaning.

M. Ranjith Kumar et al. [28] innovatively designed a manually operated floor cleaning machine, ensuring safety through a detailed 3D analysis.

Sandeep. J. Meshram et al. [29] contributed by developing a Tricycle Operated Street Cleaning Machine, designed with a rural focus, acknowledging the effectiveness challenges on rough terrains, as illustrated in Figure 1.7.

Figure 1.7: Manually Operated Floor Cleaning Machine [29].

Vardhaman Ladage et al. [30] advanced the field with their Semi-Automatic Floor Cleaning Machine, incorporating a D.C as shown in Figure 1.8. Motor and wiper mechanism, emphasizing energy conservation through solar power. Vijaykumar L. S. et al. [31] proposed a cost-effective road cleaning model utilizing an electric motor, emphasizing ecofriendliness and adjustability without compromising features, addressing the need for mechanically operated, eco-friendly road cleaning solution.



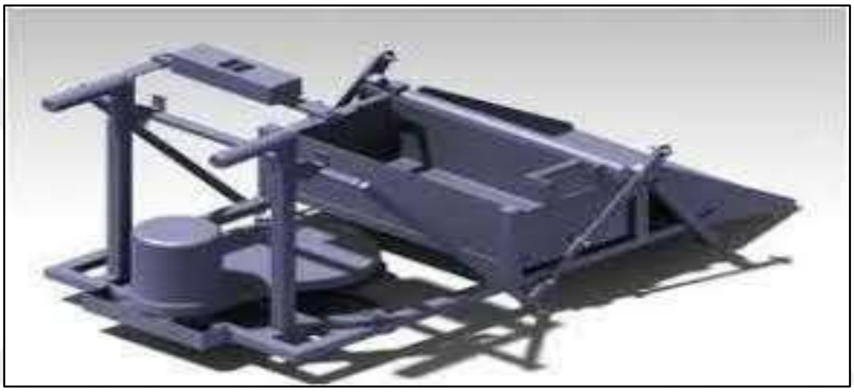


Figure 1.8: Innovative Floor Cleaning Solutions: Advances in Semi-Automatic and Eco-Friendly Models [30].

Prof. Dr. A. Muniaraj et al. [32] presented a manually operated eco-friendly road cleaner, offering a cost-efficient alternative during power crises, highlighting its efficiency and economic benefits in road cleaning processes. Dhiraj M. Bankar et al. [33] focused on a manually operated floor cleaning machine, strategically designed for outdoor spaces, providing a beneficial alternative to existing floor cleaning machines, based on simple and easily correctable chain drive mechanisms. Sustainable practices in urban maintenance are crucial for several reasons:

They contribute to clean streets, which have a positive impact on the overall quality of life for residents. These practices help reduce the environmental impact of urban areas, promoting sustainability and conservation of resources.

Sustainable maintenance strategies, such as diversified maintenance of green spaces, can significantly reduce costs and improve the environmental performance of urban areas [34, 35] Implementing sustainable practices in urban maintenance supports the concept of green infrastructure (GI) and ecosystem services (ES), which are essential for enhancing the well-being of residents and the overall livability of cities [34]. By adopting a multi-scale approach and coordinated management plans, sustainable practices can lead to cost reduction, preservation of biodiversity, and the creation of high-quality urban green spaces [36]. Encouraging dialogue and participation in management strategies and decision-making processes can also contribute to the acceptance and success of sustainable urban maintenance practices [37].

Solar energy has witnessed remarkable advancements in urban technologies, leading to success in various applications. The efficiency improvements achieved through novel materials, cell architectures, and manufacturing techniques have played a significant role in enhancing the overall performance and cost-effectiveness of solar panels [6]. Emerging PV technologies, such as perovskite, tandem, and organic solar cells, show potential advantages in terms of efficiency, stability, and scalability.

Innovative manufacturing techniques like roll-to-roll printing and thin-film deposition contribute to scalability and cost reduction. The integration of energy storage technologies with solar PV systems, along with advancements in batteries and energy management systems, enhances the reliability and dispatch of electricity. Solar tracking systems and concentrator technologies optimize solar energy capture. Efforts are being made to address environmental considerations through recycling initiatives and the use of eco-friendly materials. Economic and policy factors, including cost trends, government incentives, and policy frameworks, drive solar PV adoption [38].

Ongoing research aims to improve stability, reduce costs, and enhance grid integration for further advancements in solar-powered systems [6, 39].

Limited advancements have been made in the realm of street-sweeping alternatives, particularly those harnessing solar energy. Existing machines often rely on conventional fuels or take the form of vehicle attachments. The innovative design of a smart solar-operated street sweeping machine integrates a top-mounted solar panel with a battery unit, serving as the primary power source. With horizontal main brushes and two vertical side brushes, the machine ensures efficient cleaning while incorporating sensors for bin indication and obstacle detection, endowing it with smart capabilities. Its architectural simplicity, lightness, and compactness allow deployment on any flat surface without specialized labor [39].

Envisioned modifications aim to enhance scalability, introducing features like long-distance control, 360-degree rotational motion, and diverse energy input solutions. These advancements position the machine at the forefront of sustainable and automated street cleaning technologies, marking a promising step forward for urban sanitation systems. Following this research, the goal is to implement and disseminate this technology in one of the African countries, contributing to the proliferation of sustainable practices in the developing world [40].

Energy storage technologies hold immense potential for enhancing system performance, mitigating carbon emissions, and seamlessly integrating with renewable energy sources. Despite these benefits, no single technology currently possesses all the requisite characteristics for optimal grid integration. Addressing this, ongoing research is essential to comprehend and overcome the limitations and barriers specific to each energy storage system. Despite these challenges, energy storage technologies remain a promising solution for displacing the reliance on fossil fuels in both the electricity network and transportation sector [41, 42, 43]. Battery Energy Storage (BES) systems, exemplified by lithium-ion batteries, are widely employed for efficiently storing and releasing solar energy. Simultaneously, Pumped Hydro Energy Storage (PHES) offers an effective alternative, utilizing excess solar power to pump water to higher reservoirs for subsequent electricity generation. Thermal Energy Storage (TES) systems, including latent heat storage, present an avenue to store solar energy as heat, convertible into electricity or for heating applications. In addition, Superconducting Magnetic Energy Storage (SMES) emerges as a contender for short-term solar energy storage, characterized by swift response times and high-power output. This diverse array of technologies collectively underscores their potential as a transformative force in transitioning toward sustainable energy solutions [44, 45].

The initial cost of implementing solar-powered street cleaning machines can be high due to the need for high-quality solar panels and advanced energy storage solutions. Balancing the upfront investment with long-term operational benefits is crucial, especially for municipalities or organizations with constrained budgets [46].

The goal of the project is to design a machine that is both efficient and effective in track cleaning, to reduce labor costs by minimizing human involvement in the process. The new model of the track cleaning machine aims to achieve better efficiency compared to the old method, which can contribute to cost savings in the long run [47, 48].

Solar power generation is influenced by environmental factors such as weather, latitude, and time of day, which can affect the efficiency of solar panels. The smart solar-powered street sweeping machine includes a solar panel mounted on top and a battery unit to store the generated electricity. The machine is designed to operate using solar energy, which may fluctuate under varying weather conditions. The efficiency of solar panels in diverse environments is a significant challenge that needs to be addressed to ensure the consistent performance of the street cleaning machine. The machine is equipped with sensors for obstacle detection and a bin- indicating system, but there is no specific mention of measures taken to address efficiency fluctuations due to variable conditions.

Further research and development may be required to optimize the efficiency of the solar-powered street-sweeping machine under different environmental conditions [49]. Design and development of smart solar-powered street-sweeping machine. Continuous technological innovation can contribute to the development of more effective and reliable solar-powered machines.

Advancements in materials and design can enhance the performance of solar-powered machines, making them more efficient and reliable. Improving solar panel efficiency can increase the amount of energy generated, while advancements in cleaning mechanisms can ensure optimal performance and longevity of solar panels.

Continuous innovation in solar panel technology and cleaning mechanisms can help address challenges such as power crisis and environmental concerns, making solar-powered machines a better alternative for cleaning leaves and debris [50].

Evaluating the ergonomics of new products is important in developing methods to improve the usability and efficiency of solar-powered machines [50, 51, 52].

Government incentives and funding play a pivotal role in promoting sustainable technologies globally. In India, the government offers subsidies for solar power projects in urban areas, alleviating a portion of the capital costs associated with the implementation of solar-powered street cleaning machines. Additionally, the net metering policies in India provide a noteworthy financial incentive by allowing solar energy producers to sell surplus electricity back to the grid.

In the United States, federal support comes in the form of the Federal Investment Tax Credit (ITC), a substantial tax credit applicable to solar energy systems, including those employed for municipal purposes such as street cleaning machines. At the state level, many U.S. states further incentivize solar adoption through a range of initiatives, including rebates, tax credits, and grants, with specific incentives varying across states. Similar strategies and incentives can be found in other countries, including Australia and Japan, where governments provide financial support to encourage the adoption of solar-powered technologies and foster sustainable urban development.

In the context of street cleaning, "semi-automatic" refers to a system that blends both manual and automated processes to optimize street sweeping activities. This involves the utilization of a smart and solar-powered street-sweeping machine. The term denotes a collaborative approach where human operators guide and oversee the street cleaning machine, leveraging the efficiency of automation while retaining the human touch. This integration is designed to improve overall effectiveness, particularly in regions facing challenges such as insufficient manpower.

The potential advantages of Semi-automatic Street cleaning are significant, especially in areas with high unemployment rates, as seen in many developing countries. The approach aims not to displace workers but to enhance their well-being. By reducing the physical burden and monotony of manual sweeping, the project seeks to alleviate worker fatigue and preserve jobs. Moreover, it aspires to create employment opportunities through the establishment of companies involved in manufacturing spare parts for semi-automatic street sweeping machines [53].

The street sweeper integrates a solar power system with strategically positioned solar panels atop the device, generating ample energy while also providing shade for the worker. Careful selection of solar panels ensures optimal power output. A charge controller regulates electricity flow to the battery module, comprising two batteries connected in series for a stable current. This solar setup results in zero emissions during operation, reducing environmental impact and affirming a commitment to sustainability. Beyond direct operational advantages, reliance on solar energy decreases traditional energy dependence and cuts the carbon footprint, leading to economic benefits. In essence, integrating solar energy enhances operational sustainability and aligns with environmentally conscious street cleaning practices [54].

Patel, H., & Jain, A. conducted an in-depth examination of the integration of autonomous robotic systems in urban sanitation, highlighting the potential for substantial efficiency improvements and reduced environmental impact when compared to traditional cleaning methods. The study emphasizes the role of sophisticated navigation and object recognition technologies in optimizing cleaning routes and enhancing the thoroughness of waste removal. By leveraging advanced algorithms and real-time data processing, autonomous systems can dynamically adapt to various environments and obstacles, ensuring precise and comprehensive cleaning coverage. This level of optimization not only streamlines operations but also minimizes the use of resources, contributing to sustainable and eco-friendly urban sanitation practices [55].

Brown, M., & Zhou, S. provide a comprehensive analysis of the incorporation of smart technologies in urban management systems, shedding light on the synergistic potential of Internet of Things (IoT) devices, autonomous vehicles, and renewable energy solutions. Their study posits that the integration of these cutting-edge technologies forms the backbone of a smart city infrastructure, which markedly improves the efficiency and sustainability of urban maintenance operations. By harnessing the interconnected capabilities of IoT devices, such as real-time data collection and remote monitoring, alongside the precise and adaptive performance of autonomous vehicles, urban maintenance tasks can be streamlined and optimized. Additionally, the use of renewable energy sources to power these systems not only reduces the carbon footprint but also supports the overall goal of creating eco-friendly urban environments. Through these advanced technologies, cities can better manage their resources, anticipate maintenance needs, and respond promptly to changing urban dynamics, thereby contributing to the long-term resilience and well-being of modern metropolises [56].

In the context of urban maintenance, both renewable energy and autonomous technologies offer promising solutions to address several pressing challenges:

Energy Efficiency: By utilizing renewable energy sources like solar power, street cleaning vehicles can operate with reduced carbon emissions, aligning with environmental sustainability goals.

Operational Efficiency: Autonomous or semi-autonomous street cleaning machines can operate continuously without the fatigue and variability associated with human operators, increasing the overall efficiency and thoroughness of cleaning operations.

Figure 1.9: Importance of Innovative Urban Maintenance [56].

Cost-Effectiveness: While the initial investment in advanced technologies may be high, the long-term savings in reduced labor costs and lower fuel expenditures can be significant, making these solutions economically attractive in the long run.

Environmental Impact: Reducing the reliance on fossil-fueled vehicles mitigates the emission of greenhouse gases and other pollutants, contributing to cleaner, healthier urban environments as highlighted in Figure 1.9 [56].

This proposes a novel street cleaning approach that effectively integrates solar energy and semi-autonomous technology into a single machine. This design aims to capitalize on the advantages provided by these technologies, thus addressing the environmental and efficiency challenges associated with traditional street cleaning methods. By harnessing solar power, the machine operates on a clean and abundant energy source, reducing operational costs and environmental impact. Semi-autonomous technology enables the machine to perform with consistent efficiency, navigating and cleaning urban streets with minimal human intervention.

A notable gap in the literature concerns the integration of semi-autonomous street cleaning machines powered by solar energy. Despite advances in autonomous cleaning technologies and renewable energy, there is a lack of studies specifically addressing this combination in urban maintenance. Further research is needed to explore the feasibility and effectiveness of such systems in real-world environments and to address challenges such as high initial costs and regulatory barriers. Filling these gaps can advance sustainable urban maintenance solutions.

The primary contribution of this research lies in the design and development of an innovative semi-autonomous street cleaning vehicle, which addresses the challenges inherent in traditional urban sanitation methods by integrating advanced technological capabilities with sustainable practices. The vehicle's dual-mode operation facilitates manual and autonomous navigation modes, achieved through a sophisticated suite of sensors comprising cameras, GPS, and Arduino-based systems. These sensor systems enable the vehicle to navigate complex urban environments effectively. The synergy between Arduino Mega and GPS in a street cleaning machine enhances precision and efficiency for targeted cleaning ensuring smooth operation and promoting cleanliness and environmental health.

A noteworthy aspect of the vehicle design is its reliance on renewable energy, exemplified by the inclusion of a foldable solar panel. This sustainable energy source not only reduces dependence on external electrical power but also underscores the vehicle's commitment to environmental conservation. The propulsion system incorporates geared brushless DC motors for the wheels, balancing speed and torque essential for navigating diverse urban terrains efficiently.

Furthermore, the vehicle's design emphasizes efficiency in waste collection and management, with a mechanism facilitating the transfer of waste into a capacious storage unit designed for easy emptying and maintenance. This comprehensive approach integrates robotics, renewable energy, and smart technology to create a street-cleaning machine excelling in both performance and environmental conservation.

By addressing the intersection of urban sanitation, technology, and sustainability, this research advances the field of urban maintenance solutions, offering a blueprint for future developments in semi-autonomous street cleaning vehicles. The design presents a promising pathway towards achieving cleaner, more sustainable urban environments, contributing to broader goals of improved public health and environmental welfare. Moreover, modifications involving the transition to Arduino-based camera systems, GPS integration, and MATLAB-based energy consumption analysis further enhance the vehicle's functionality and environmental impact assessment capabilities, marking significant strides in urban sanitation research and innovation.

2. METHODOLOGY

The innovative design of this solar-powered, semi-autonomous street cleaning machine is a direct response to the needs highlighted by smart city initiatives. It provides a practical solution that enhances urban living by improving street cleanliness, reducing environmental impact, and aligning with the broader goals of sustainable urban development. This approach not only demonstrates the feasibility of integrating advanced technologies in public service applications but also sets a precedent for future innovations in urban maintenance.

2.1 OBJECTIVES OF THE STUDY

2.1.1 Objective 1: Design and Development

The first and foremost objective of this study is to design and develop a semi-autonomous street cleaning machine powered by solar energy. This involves multiple stages of engineering processes, including:

Conceptualization: Generating initial design concepts that integrate solar power with autonomous technology.

Design Engineering: Detailing the mechanical, electrical, and software components. This includes the selection of materials for the machine’s body, the type of motors to be used for movement and cleaning mechanisms, and the solar panel configuration for optimal energy collection.

Prototyping: Building a functional prototype to test design concepts in real-world scenarios.

Refinement: Based on testing feedback, and refining the design to improve functionality, durability, and efficiency, the design process focuses on creating a robust, efficient, and user-friendly machine that aligns with the requirements of urban street cleaning while utilizing green energy.

2.1.2 Objective 2: Evaluating Efficiency and Environmental Impact

Is to evaluate the operational efficiency and environmental impact of the newly developed street cleaning machine and compare these aspects with traditional cleaning methods. Key evaluation criteria include:

Operational Efficiency: Measuring the effectiveness of the machine in cleaning streets, which involves assessing the coverage area, the consistency of cleaning, and the time taken for cleaning operations. Also, evaluating the machine's autonomous features, such as navigation and obstacle detection.

Environmental Impact: Quantifying the reduction in carbon emissions by switching from fossil fuel-based vehicles to a solar-powered solution. This includes measuring direct emissions from the machine (if any) and indirect emissions associated with the manufacturing and disposal of the machine components.

Cost Implications: Analyzing the cost-effectiveness of the machine over its lifecycle, considering initial investment, maintenance costs, and operational costs in comparison to conventional methods.

2.1.3 Objective 3: Exploring Scalability and Adaptability

The third objective explores the scalability and adaptability of the machine for various urban environments. This involves:

Scalability Tests: Assessing the machine's performance in different sizes and types of urban areas, from small neighborhoods to large city centers, to understand the limits and scalability of its design.

Adaptability Analysis: Exploring how well the machine can adapt to different urban conditions such as varying weather, street layouts, and types of debris encountered. This also includes testing different configurations of the machine for different settings.

Policy and Regulatory Considerations: Identifying and addressing potential regulatory hurdles or policy needs that could impact the deployment of such machines on a wider scale.

This includes engaging with urban planners and policymakers to ensure the machine meets safety and operational standards applicable in various jurisdictions.

This thesis provides an extensive examination of the processes involved in creating an innovative, environmentally friendly solution for urban street cleaning. The study is structured into several key phases, each contributing to the development of a solar-powered street-cleaning machine.

2.1.4 Conceptualization

Problem Identification: Recognizing and defining the challenges with existing street cleaning methods, such as their environmental impact, operational inefficiencies, and high costs.

Innovative Solutions: Proposing a sustainable and efficient alternative that utilizes solar power and semi-autonomous technology.

2.1.5 Design

Material Selection: Choosing materials that provide durability, sustainability, and cost-effectiveness. This includes decisions on the use of mild steel and aluminum for the structural components to ensure strength and lightweight properties.

Mechanical Design: Developing the propulsion system that drives the machine and the mechanisms for sweeping and collecting debris. This phase focuses on ensuring that these systems are efficient and well-integrated with the overall design of the machine.

Solar Integration: Designing the integration of solar panels that will power the machine. This involves selecting the size, type, and configuration of solar panels to optimize energy collection and storage capabilities.

Aesthetics and Ergonomics: Considering the machine's appearance and ease of use, ensuring that it is not only functional but also fits well within urban environments development.

Prototyping: Building a prototype based on the designs to test various features and functionalities.

System Integration: The seamless integration of mechanical, electronic, and software components is fundamental to the functionality of the system. This involves adapting the automatic system by using cameras, Arduino systems, and GPS, along with programming Arduino to enable the retrieval of coordinates from the mission planner.

2.1.6 Testing

Field Testing: Conducting tests in real urban settings to evaluate the machine's performance under various conditions. This includes testing the effectiveness of navigation systems, and the reliability of solar power utilization.

Performance Metrics Evaluation: Measuring key performance metrics such as cleaning efficiency, area coverage per unit of time, energy consumption, and operational reliability.

Environmental Impact Assessment: Analyzing the environmental benefits of the machine, focusing on reduced carbon emissions and energy efficiency.

2.2 SEMI-AUTOMATIC STREET CLEANING VEHICLE

A semi-autonomous street cleaning vehicle has been designed to meet the sanitation requirements in urban areas by combining efficiency, functionality, and sustainability. The vehicle's main structure is made of mild steel, providing a robust framework capable of withstanding daily operations, including exposure to diverse urban terrains and weather conditions. Aluminum is strategically used in specific components, such as the electronic housing and solar panel frame, to achieve weight savings and enhance maneuverability.

Weighing 40 kg, the vehicle features a combination of mild steel and aluminum for durability and a strong power-to-weight ratio, essential for the durability and agility required in urban environments. It is equipped for operations in dual mode and is capable of both manual and autonomous navigation. Autonomous operation is facilitated through a range of sensors, including Arduino and cameras, all protected against urban pollutants.

The propulsion system consists of two brushless DC motors with 80 Watts of power for the wheels, providing a balance between speed and torque, essential for navigating various urban terrains. A 60 Watts motor operates the sweeping mechanism, efficiently transferring waste to a spacious storage unit designed for easy discharge and maintenance.

The combination of these advanced features results in a street cleaning machine that not only operates efficiently and autonomously but also contributes to environmental preservation through its sustainable design. This innovative vehicle embodies the intersection of robotics, renewable energy, and smart technology, creating a cleaner and more sustainable future for urban living.

In the initial phase of the semi-autonomous street cleaning vehicle project, planning, modeling, and visualization were carried out using SolidWorks. Specifically, SolidWorks Premium 2022 was used in these simulation processes. Each component of the vehicle underwent precise measurements, drawings, and design within SolidWorks, ensuring accurate and detailed planning of individual elements. This approach facilitated the creation of a highly efficient and practical vehicle design.

Further research is necessary to evaluate its performance and capability to sustain real-world environments, as well as address potential obstacles such as costs and regulatory issues. This research could pave the way for more sustainable solutions in urban maintenance practices.

2.3 COMPONENTS OF THE SEMI-AUTONOMOUS STREET CLEANING VEHICLE

The initial focus of this discussion will revolve around the essential aspects of designing a semi-autonomous street cleaning vehicle. This includes the key operations performed by the vehicle to ensure effective and efficient street cleaning. Subsequently, a detailed explanation of the various components of the vehicle, the subject of this research, will be provided. The theoretical knowledge underpinning the vehicle's design will be explored, followed by the selection of specific design elements and features. A step-by-step design and fabrication process will be implemented, supported by comprehensive drawings and models of the vehicle's components using SOLIDWORKS software. This approach ensures precise and efficient design of the vehicle's systems, including its dual-mode operation, autonomous navigation capabilities, and sustainable power sources.

The next phase involves assembling these components into a fully functional vehicle. Once the drawing and design stages are completed, SOLIDWORKS simulation tools will be employed for conducting stress analysis, assessing deformations, and determining safety factors, among other factors.

The proposed semi-autonomous street cleaning vehicle combines advanced technology and renewable energy to address the challenges of urban maintenance. Despite the vehicle's potential for enhancing street cleaning efficiency and sustainability, there is a notable gap in existing literature regarding its application.

2.3.1 Core Structure

The vehicle's frame is constructed from mild steel, providing a robust chassis capable of enduring the demands of daily operations, such as exposure to diverse urban terrains and weather conditions. This strong base ensures the vehicle can navigate and clean streets effectively, as demonstrated in Figure 2.1.

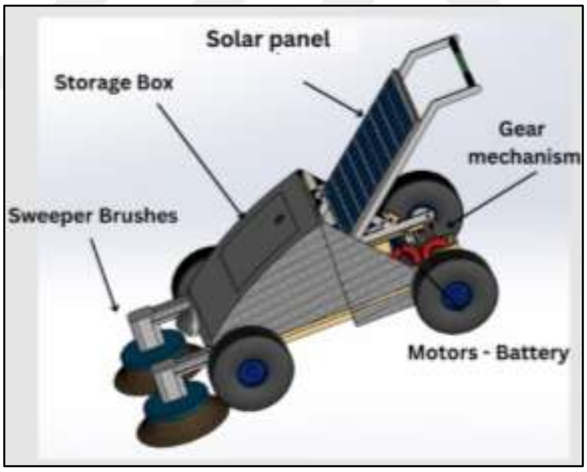


Figure 2.1: Core Structure of the Vehicle.

2.3.2 Material Composition

The semi-autonomous street cleaning vehicle is engineered to meet the challenges of urban maintenance through a thoughtful combination of mild steel ASTM A36 and aluminum 6061-T6. These materials are chosen for their exceptional strength-to-weight ratio, which is a critical factor in the vehicle's overall performance and operational efficiency. mild steel ASTM A36 serves as the primary material for the chassis and structural elements, providing the robust framework necessary to withstand the daily demands of street cleaning in urban environments. Its inherent strength ensures the vehicle can endure impacts, vibrations, and the effects of constant exposure to the elements such as rain, heat, and dust.

On the other hand, aluminum is strategically incorporated into the design of components where weight reduction plays a significant role. For instance, the housing for avionics and the frame for the solar panel are constructed from aluminum. This material not only reduces the overall weight of the vehicle but also enhances its maneuverability and agility, enabling smooth navigation through tight spaces and around obstacles. The use of aluminum in these areas supports the efficient functioning of the vehicle's advanced technology systems, including sensors and control units. The combination of mild steel and aluminum ensures the vehicle maintains a perfect balance between sturdiness and lightweight operation. This harmonious integration of materials contributes to the overall effectiveness and longevity of the street cleaning machine, allowing it to operate seamlessly and efficiently in a variety of urban settings. Additionally, the strategic use of aluminum in critical areas helps maximize the vehicle's energy efficiency, further enhancing its role as a sustainable solution for urban sanitation, as illustrated in Figure 2.2.

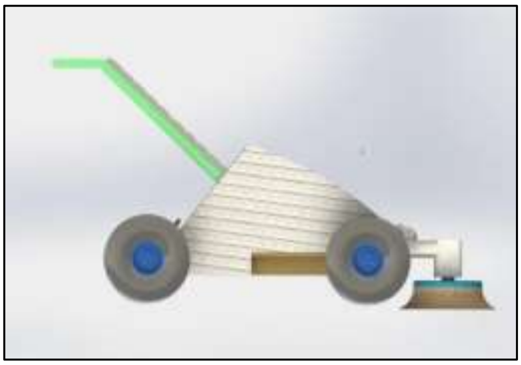


Figure 2.2: Material Composition: Mild Steel and Aluminum for Strength and Agility.

2.3.3 Dual-Mode Operation

2.3.3.1 Avionics and electronics housing

The essential electronic parts of the machine, such as the Arduino Mega 2560, electronic speed controllers, and a NEO 3 GPS, are kept inside a container. The delicate electronics inside this compartment are covered to protect them from dust, moisture, and environmental factors. This ensures dependability and increases the vehicle's service life.

GPS: NEO

Neo 3 GPS is different from conventional GPS systems in that it does away with the need for Doppler correction and signal tracking circuitry in receivers, which results in smaller receivers and less maintenance-intensive satellite needs [58] Table 2.1. Furthermore, a novel characteristic not seen in earlier research, Neo 3 GPS presents a closed-form solution for geolocation equations independent of range data [59]. Neo 3 GPS has the advantage of quicker computation times by employing direct linearization techniques and optimal trilateration by using the least squares method, which reduces processing overhead while preserving accuracy. Neo 3 GPS is also useful for monitoring slope deformations and instability occurrences in places like roads because of its high positioning accuracy, quick observation times, and provision of three-dimensional coordinates, as illustrated in Figure 2.3 [60].

GPS is selected for guide mode operation during autonomous mode Table 2.1.

Figure 2.3: Neo 3 GPS [59].

Table 2.1: NEO 3 GPS Specification [58].

Hardword	**Type**
Gnss	Beidou, Galileo, glonass, gps
Gnss augmentation system	Sbas:waas,egnos,msas qzss:l1s(saif) other： rtcm3.3
Number of concurrent gnss	4
Frequency band	Gps: l1c/a glonass:l10f beidou:b1i galileo:e1b/c
Horizontal accuracy	2.0 m
Speed accuracy	0.05 m/s
Nav. Update rate	25 hz(max)
Acquisition	Cold start： 24s hot start： 2s aided start: 2s
Number of satellites(max)	32+
Sensitivity	Tracking and nav-167dbm cold start hot star-148dbm reacquisition -160dbm
Protocol	Uart+io+i2c
Port type	Ghr-10 V-s
Supported flight controller	Cuav series, pixahwk series
Wave filtering	Saw+lna+saw
Anti-electromagnetic/radio frequency interference	Emi+rfi
Hardword	**Type**
Upgrade firmware	Support
Input voltage	5 V
Operating temperature	-10~70℃
Size	60*60*16 mm
Weight	33 g

2.3.3.2 Electronics and control systems

The sophistication of the electronics and control systems within the semi-autonomous street cleaning vehicle underpins its operational efficiency and reliability. These systems are the conduits through which power and data flow, commanding the vehicle's various functions from propulsion to navigation and debris collection.

This machine can be controlled by a controller and GPS it can run autonomously by these modules.

The machine will be preprogrammed with a certain coordinate then the machine will be able to move autonomously in programmed areas for cleaning, as illustrated in Figure 2.4.

Figure 2.4: Autonomes Mode From Mission Planner.

2.3.3.3 Essential electronics and systems

Motor Drivers/Controllers:

To control the motors that drive the wheels and the cleaning mechanism it will need motor drivers that can handle the current and voltage requirements of your motors.

2.3.3.4 IMU (inertial measurement unit)

This device can measure and report the vehicle's specific force, angular rate, and sometimes the magnetic field surrounding the body. It's crucial for correcting the drift that GPS might experience in urban canyons or areas with poor satellite visibility.

BNO055

The BNO055 represents an advanced Inertial Measurement Unit (IMU) boasting a comprehensive suite of sensors. Its integration of a 3-axis accelerometer, 3-axis gyroscope, and 3-axis magnetometer, alongside an onboard microcontroller executing sensor fusion algorithms, marks it as a versatile tool for orientation sensing. One notable feature is its provision of absolute orientation data directly, which alleviates the computational burden from external devices like Arduino microcontrollers. This attribute enhances convenience, particularly in applications requiring precise orientation data. Consequently, the BNO055 finds particular suitability in contexts necessitating accurate and efficient orientation sensing, as depicted in Figure 2.5.

Figure 2.5: BNO055 [61].

Display and User Interface:

In the realm of system design, the incorporation of a display and user interface serves as a critical component for local control and monitoring. A simple Liquid Crystal Display (LCD) coupled with a user input device becomes indispensable, particularly for diagnostic purposes and manual overrides. This interface facilitates real-time feedback and intervention, enhancing the system's responsiveness and adaptability to changing conditions, as illustrated in Figure 2.6.

Additionally, effective power supply regulation emerges as a paramount consideration to ensure optimal functionality of all system components. This entails meticulous attention to voltage and current requirements, necessitating the integration of step-up or step-down converters where necessary to match the diverse needs of different parts within the system. By meticulously addressing power supply and regulation concerns, system designers can mitigate risks of component failure and ensure consistent performance across varying operating conditions.

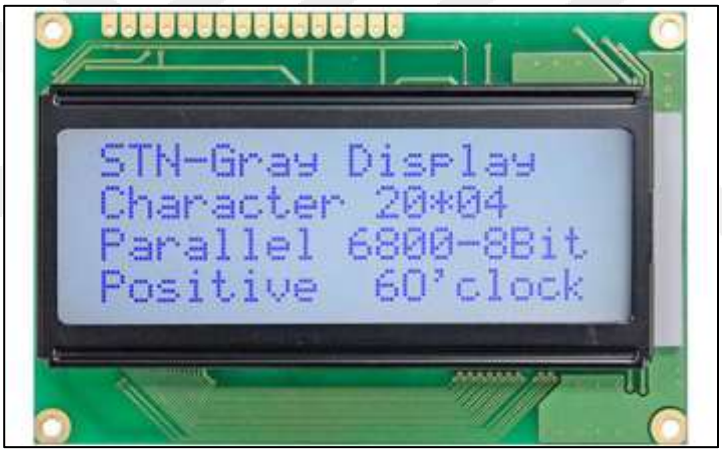


Figure 2.6: Liquid Crystal Display (LCD) [62].

2.3.3.5 Software components

In the domain of software components, sensor fusion algorithms play a pivotal role in amalgamating data from disparate sources such as the Global Positioning System (GPS), Inertial Measurement Unit (IMU), and other sensors to furnish precise positioning information. These algorithms leverage sophisticated mathematical models to integrate data streams effectively, compensating for the limitations inherent in individual sensors and enhancing the overall accuracy of positioning systems.

Moreover, control software assumes significance in orchestrating the operation of motors based on inputs derived from navigation data and sensor readings. By interpreting and synthesizing information from various sources, including GPS coordinates and IMU measurements, control software facilitates dynamic adjustments in motor behavior to maintain desired trajectories and achieve operational objectives efficiently.

Complementing these software components is the Arduino Mega controller, a versatile microcontroller platform renowned for its robust performance and extensive compatibility with sensor integration and control tasks. Its computational prowess and flexibility make it well-suited for managing complex algorithms and executing real-time control strategies, thereby empowering the seamless integration of sensor data and precise motor control within diverse navigation and robotics applications as shown in Figure 2.7.

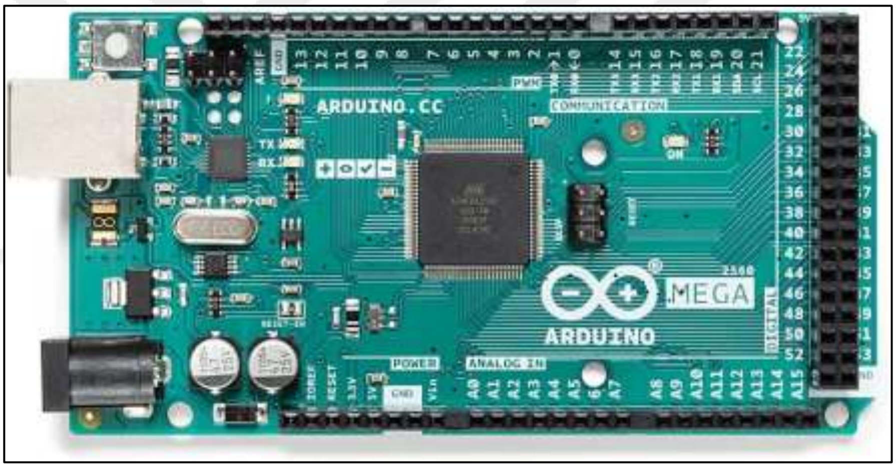


Figure 2.7: Controller Arduino Mega [63].

Mission programming:

Mission:

This Arduino code utilizes a GPS module and motor control to navigate a robotic vehicle to predefined waypoints. It first initializes motor control pins and sets up communication with the GPS module. Within the main loop, it activates a sweeper motor and iterates through a list of GPS waypoints, calling a function to drive to each waypoint. The driveToWaypoint function is a placeholder where one would implement logic to compare the current GPS location with the target waypoint and control the vehicle's movement accordingly. After reaching all waypoints, it turns off the sweeper motor and enters an infinite loop to halt further execution. Additionally, the read GPS function continuously reads GPS data and prints the latitude and longitude to the serial monitor when a new location update is available.

2.3.4 Solar Power

Is one of the most critical features of the semi-autonomous street cleaning vehicle, enhancing its efficiency and sustainability. At the heart of the vehicle's power system is a foldable 500 W solar panel that serves as a renewable energy source. This advanced solar technology allows the vehicle to harness clean energy from sunlight, substantially reducing its reliance on external electrical power sources. By minimizing the use of fossil fuels or grid electricity, the vehicle contributes to lowering carbon emissions and promoting a more eco-friendly approach to urban sanitation, as illustrated in Figure 2.8.

Figure 2.8: 500 W 24 V Solar Panel [64].

Incorporating solar power into the design of the street cleaning vehicle offers numerous advantages. The utilization of sustainable energy sources enhances the vehicle's operational efficiency while reducing its environmental footprint. By harnessing solar energy, the vehicle can operate for extended periods without relying solely on traditional fuel sources, thus minimizing both operational costs and carbon emissions. This integration of solar power technology not only extends the vehicle's operational lifespan but also contributes to the broader goal of promoting sustainability in urban transportation systems.

2.3.5 Propulsion System

The semi-autonomous street cleaning vehicle's propulsion system is a marvel of engineering, tailored to deliver exceptional performance and versatility across diverse urban environments. At its core, the system features two 80 W geared brushless DC motors for the vehicle's wheels. These motors are carefully chosen to strike the perfect balance between speed and torque, which is crucial for effective navigation through varying terrains such as asphalt, concrete, and uneven surfaces. This balance ensures that the vehicle can maintain steady movement, even when confronted with obstacles or challenging conditions, while also providing the agility needed to execute sharp turns and navigate tight corners. Components of brushless DC motors are given in Figure 2.9.

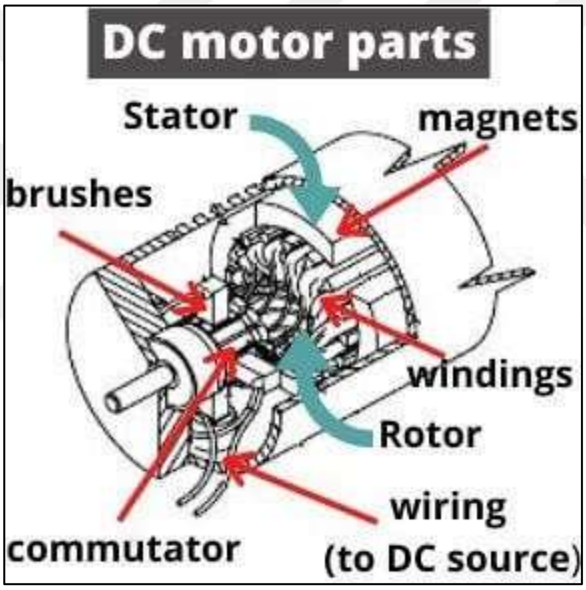


Figure 2.9: Component of Brushless DC Motors [65].

The geared brushless DC motors offer smooth and efficient operation, reducing wear and tear on the vehicle's wheels and extending the lifespan of the propulsion system. The gear mechanism enhances the motors' ability to deliver consistent power and control, enabling the vehicle to adapt its speed according to the specific requirements of different cleaning tasks.

Whether traveling slowly for thorough cleaning or quickly to cover larger areas, the motors provide the necessary power and responsiveness.

In addition to the wheel propulsion, the vehicle features a dedicated 50 W motor that drives the sweeper mechanism. This motor is designed to power the sweeping and cleaning functions of the vehicle with precision and reliability. Its efficient operation allows for the effective collection of waste, including debris, dust, and litter, from the streets. The motor's consistent power output ensures that the sweeper can maintain optimal performance even during extended cleaning sessions.

The sweeper mechanism works in harmony with the vehicle's overall design, effectively transferring collected waste into a spacious storage unit. This waste management system is designed for easy emptying and maintenance, allowing the vehicle to operate for longer periods without interruptions. The seamless integration of the sweeper motor with the vehicle's propulsion system ensures that street cleaning tasks are carried out efficiently and effectively.

Overall, the propulsion system of the semi-autonomous street cleaning vehicle combines advanced motor technology with intelligent design to deliver superior performance in urban sanitation. By providing a balance of speed, torque, and control, this system ensures that the vehicle can maneuver through city streets with precision while maintaining its cleaning efficiency.

2.3.5.1 Wheel control

Wheel control steering mechanisms are actuated with a gear system and a motor run shaft which rotates the spur gear mechanism to run the vehicle.

2.3.5.2 Gearbox

Throughout history, the utilization of gears has proven to be the most efficient and effective method for connecting machines with distinct optimal speeds. The evolution of gears has predominantly been propelled by economic motives, emphasizing their pivotal role in achieving optimal performance and efficiency when coupling machines. Gears are mechanical components employed in various applications, prized for their high efficiency and versatility in accommodating a wide range of speeds and power requirements. A gearbox, built upon the principles of gears, serves as a mechanical device that efficiently regulates the transmission of power between machines with distinct optimal speeds, driven by considerations of economic efficiency.

a. Types of gears

A gear is a toothed wheel designed to mesh with another toothed wheel, facilitating the transmission of energy and enabling changes in both speed and direction of motion. Gears find extensive applications in various mechanical devices. Typically, the teeth of the gear are intricately carved onto wheels, cylinders, or cones. Various devices we encounter in our daily lives operate based on distinct working principles, and the fundamental components within many of them are the tooth and wheel of a gear. Gears, in their diverse types, serve to transfer energy in various ways and directions. A gear, found within a transmission mechanism, facilitates the transmission of rotational force to another gear or device. In contrast to a pulley, a gear is a circular wheel equipped with teeth that engage with the teeth of other gears, ensuring a secure transfer of force without slippage. Geared devices, depending on their design and arrangement, can transmit forces at different speeds, and torques, or alter the direction of the power from the source. The typical scenario involves one gear meshing with another, and this interlocking of gears prevents slippage, providing a positive drive with a consistent angular velocity, and addressing the issues encountered in belt-driven systems.

b. Categorization of gears

Gears can be broadly categorized into several types based on their design, shape, and applications. One classification criterion is the axis of the shaft. According to this criterion, gears can be divided into four main types: parallel gears, perpendicular axis gears, intersecting gears, and non-intersecting gears.

Parallel axis gears are a prevalent type of gearing system where the axes of two gears run parallel to each other. This configuration enables efficient power transmission between the gears. Within the realm of parallel axis gears, there exist various subtypes, each possessing unique characteristics and applications. Notable examples include spur gears, helical gears, and double helical or herringbone gears.

Another classification criterion for gears is based on velocity. Gears can be categorized into low-velocity gears, medium-velocity gears, and high-velocity gears depending on the speed at which they operate. This classification aids in selecting the appropriate gear type for specific applications, ensuring optimal performance and durability.

Furthermore, gears can be classified based on the type of gearing they employ. This categorization includes external gears, internal gears, and rack and pinion gears. Each type serves distinct purposes and is suited to particular mechanical systems, contributing to their efficiency and functionality.

Lastly, gears can be differentiated based on the position of teeth on the gear surface. This classification encompasses gears with straight teeth, inclined teeth, and curved teeth. The arrangement of teeth on a gear impacts factors such as load distribution, noise level, and smoothness of operation, making it an essential consideration in gear selection and design.

c. Spur gear

Overview and Applications: A spur gear is a type of parallel-axis gear with straight teeth that are parallel to the gear's axis. It is one of the most common and straightforward gear designs, known for its simplicity and effectiveness in transmitting rotational motion and power. Spur gears find extensive use in a wide range of applications across various industries, and it looks as shown in Figure 2.10. Below, we delve into the details of spur gears, including their design, working principles, and applications.

Figure 2.10: Spur Gear Model [66].

2.3.5.3 Design and structure

Teeth: Spur gears have straight teeth that extend radially from the gear's center. These teeth are parallel to the gear's axis, simplifying the manufacturing process.

Pitch Circle: The measurement from the face of one tooth to the next on a gear is called Pitch Circle. This division serves to delineate a gear's teeth into the upper part, known as the addendum, and the lower part, referred to as the addendum, as shown in Figure 2.11, and Figure 2.12. In a well-designed gear system, the pitch circles of adjacent gears should be tangent to each other, ensuring proper engagement and functionality. The pitch diameter is crucial for determining the gear ratio and designing mating gears.

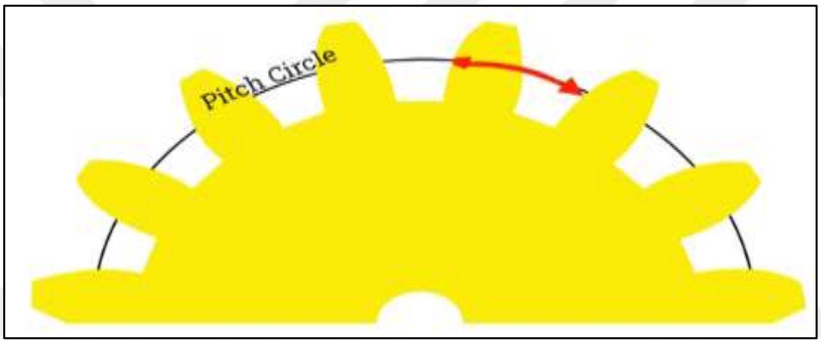


Figure 2.11: Pitch Circle of a Spur Gear [67].

Module and Diametric Pitch: The module (in metric systems) or diametral pitch (in imperial systems) is a measure of tooth size and spacing, influencing gear design and performance.

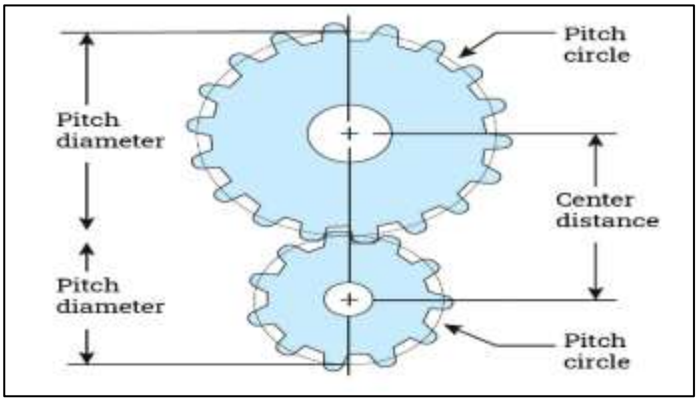


Figure 2.12: Different Parameters of Spur Gears [66].

In the mechanical setup, two spur gears are employed, each with a diameter of 15.27 cm. Positioned with a separation distance of 15.43 cm between their inner circles, as illustrated in Figure 2.13. these gears play a fundamental role in transmitting rotational motion and torque within the system. Their precise alignment and spatial arrangement are essential for ensuring optimal machinery performance and efficiency.

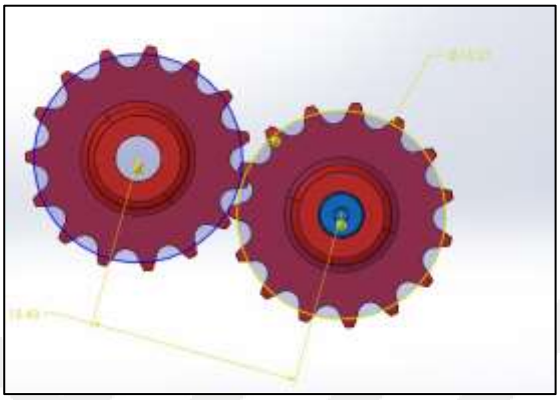


Figure2.13: Parameters of Our Spur Gears in CAD.

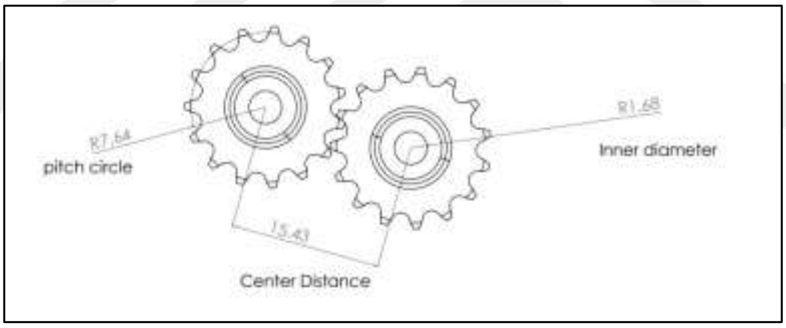


Figure 2.14: Parameters of Our Spur Gears.

2.3.5.4 Working principles

Spur gears facilitate power transmission by seamlessly meshing with each other, enabling the transfer of rotational power between parallel shafts. The engagement and disengagement of teeth occur smoothly, ensuring a continuous and efficient motion transfer. The gear ratio of spur gears is dictated by the number of teeth on each gear, establishing the correlation between input and output speeds. This ratio plays a pivotal role in adjusting torque and speed across diverse applications. Despite their high efficiency attributed to the straightforward tooth engagement, spur gears may generate more noise compared to alternative gear types.

2.3.6 Sweeping Mechanism

Sweeping roller brushes, equipped with synthetic, wire, or mixed fill material, are essential components for effectively sweeping roads and other large surface areas. These brushes offer versatile cleaning options, ensuring thorough removal of various types of debris, dust, and even snow.

Powered garden sweepers and brushes extend the functionality of these brushes beyond road cleaning, making them invaluable tools for sweeping debris and clearing snow in gardens and outdoor spaces. These features allow for multi-season use, providing efficiency in both maintenance and cleaning tasks, as illustrated in Figure 2.15.

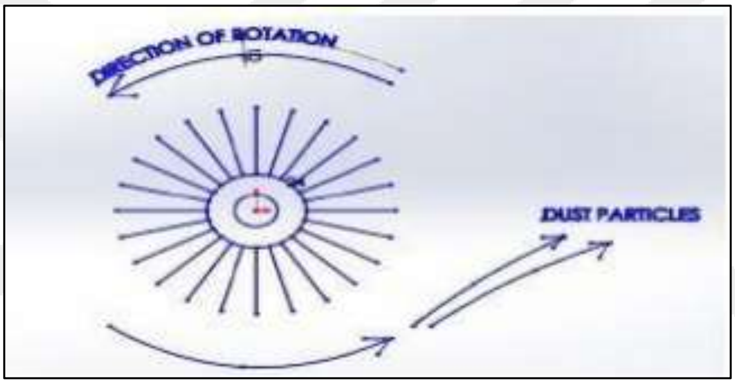


Figure 2.15: Sweeping Mechanism [68].

Manufacturers such as Brush Tec produce high-quality road sweeping brushes known for their durability and effectiveness, Figure 2.16. This ensures that the brushes can withstand the demanding tasks of cleaning different surfaces and environments, including roads, gardens, and even chimneys. In summary, the sweeping brushes used in semi-autonomous street cleaning machines are versatile, reliable, and capable of maintaining cleanliness across a range of applications.

Figure 2.16: 3D Sweeping Roller Brushes.

2.4 SELECTION OF KEY COMPONENTS FOR SEMI-AUTONOMOUS STREET CLEANING VEHICLES

Semi-autonomous street cleaning vehicles require a careful selection of essential components such as motors, wheels, electronic controllers Arduino Mega 2560, and a NEO 3 GPS to operate effectively and efficiently in urban environments. Matching the right combination of these components with the vehicle's intended tasks is crucial for achieving optimal performance. The process begins with estimating the vehicle's weight, including its payload and necessary equipment such as the waste collection unit.

Once the vehicle's weight and payload capacity are established, the next step involves selecting the most appropriate motors, wheels, and frame dimensions tailored to the specific needs of street cleaning. The goal is to provide sufficient propulsion power and maneuverability to navigate urban streets smoothly while ensuring stability and control.

One critical aspect of performance is determining the required thrust and torque to power the vehicle through its operations. The propulsion system must generate adequate power to handle various terrains and slopes while maintaining consistent speed and agility. This careful selection and calibration of components guarantee the vehicle can fulfill its cleaning duties effectively and adapt to different urban scenarios. By prioritizing the proper balance of power and control, the semi-autonomous street cleaning vehicle can achieve reliable and efficient performance, contributing to cleaner streets and a more sustainable urban environment.

2.4.1 Calculation And Selection

2.4.1.1 Solar panel

To calculate the current your solar panel can generate during a sunny day, you need to start by determining the daily energy output in kilowatt-hours (kWh). This is calculated using the formula,

$$\text{Daily Output (kWh)} = \text{Panel Wattage (W)} \times \text{Peak Sun Hours} \times \text{Efficiency} \quad (2.1)$$

The break down of each component of this formula is as:

Panel Wattage: This is the maximum output of the solar panel in Watts, determined under ideal conditions, also known as Standard Test Conditions. The panel is rated at 500 Watts.

Peak Sun Hours: This refers to the average number of hours per day that the panel receives.

Direct sunlight. The average can vary depending on location, but for the calculation, we'll use the value of 8 hours.

Efficiency: Solar panel efficiency indicates how effectively the panel converts sunlight into usable electricity. Efficiency typically ranges from 15% to 20%. In our case, the panel has an efficiency of 25%.

Given the above values, the daily output of the solar panel can be calculated as follows:

$$\text{Daily Output (kWh)} = \text{Panel Wattage (W)} \times \text{Peak Sun Hours} \times \text{Efficiency} \quad (2.2)$$

$$\text{Daily Output} = 500\ W \times 8\ h \times 0.25 = 1\ kWh/day \quad (2.3)$$

This means the panel produces 1 kWh of energy per day.

Next, we can determine the current produced in amperes. This is calculated by dividing the power (in Watts) by the system voltage (in Volts):

$$\text{Current (A)} = \frac{\text{Power (W)}}{\text{Voltage (V)}} \quad (2.4)$$

Given the panel produces 500 Watts and the system operates at 24 Volts, the current is calculated as:

$$\text{Current (A)} = \frac{\text{Power (W)}}{\text{Voltage (V)}} = \frac{500\,W}{24\,V} = 20.83\,A \tag{2.5}$$

So, the solar panel generates approximately 20.83 Amperes of current.

Specifications:

a. Voltage = 24 V

b. Power = 500 W

By taking these factors into account, we can understand the daily energy production and current output of our solar panel system. This knowledge is crucial for designing and optimizing the electrical system of semi-autonomous street-cleaning vehicles. It ensures that the vehicle receives a sustainable and adequate supply of power to operate effectively, contributing to the overall efficiency and environmental friendliness of the system.

2.4.1.2 Motor calculations

a. Main motor for vehicle

When designing the propulsion system for a semi-autonomous street cleaning machine, choosing the right motors for the wheels is crucial for achieving smooth, efficient operation and precise maneuverability. The weight of the machine, which is around 40 kg, necessitates the use of motors that can deliver a combination of power, torque, and speed to navigate varying urban terrains, including tight corners, crowded streets, and different road surfaces.

The 250 W brushless DC (BLDC) motor is an excellent choice due to its high efficiency, typically ranging from 85% to 95%, reliability, and compatibility with electric vehicle applications. BLDC motors offer several advantages over traditional brushed motors, including higher torque, longer lifespan, and lower maintenance requirements. This motor's design minimizes friction and heat generation, providing smooth and quiet operation while also increasing overall efficiency.

The motor operates on either a 24 V or 48 V power supply, allowing you to choose a voltage that best fits your system's design and compatibility with available battery systems. The moderate 1500 rpm speed provides a balance between velocity and the precise control necessary for semi-autonomous operations, ensuring the machine can effectively navigate different terrains while cleaning.

With a holding torque of 0.15 N.m and a peak torque of 1 Nm, the motor offers the strength needed to propel the cleaning machine, allowing it to traverse even challenging landscapes such as uneven surfaces and sandy areas. This is particularly important for beach cleaning operations, where consistent torque is required to handle sand and debris.

In terms of power, the 80 W output of the motor ensures that the machine can operate effectively for extended periods while minimizing power consumption. The current draw of 5.0 A also supports efficient power usage, contributing to longer battery life and improved operational longevity.

For seamless integration and optimal performance can pair the BLDC motor with an optional matched controller. This controller provides precise speed control, enabling the Machine to adjust its speed according to specific cleaning tasks and varying environmental conditions. Additionally, the controller can simplify power management and communication between the motor and other system components, enhancing the overall functionality of the street cleaning machine, as shown in Figure 2.17.

Incorporating 250 W brushless DC motors with the described specifications into a semi-autonomous street cleaning machine will result in a well-balanced propulsion system. This system will provide the necessary torque and speed control for effective cleaning and navigation, ensuring the machine can handle diverse urban and beach cleaning tasks with ease and reliability. Ultimately, this thoughtful design will contribute to a more efficient and sustainable urban environment.

Figure 2.17: Main Motor for the Vehicle [69].

Specifications:

a. Voltage: 24 V
b. Speed: 1500 rpm
c. Torque: 0.15 N.m
d. Power: 80 W
e. Current: 5.0 A

b. Sweeper Motor selection

Selecting geared DC motors for the rotating sweeper system of a semi-autonomous street cleaning machine is a strategic decision that greatly improves performance and efficiency. The sweepers are crucial for collecting debris, dirt, and sand from urban environments, and their effective operation relies heavily on the motor's ability to deliver consistent and controlled power.

Geared DC motors excel at increasing torque through a gearbox, enabling the motors to turn the sweepers with greater force. This enhanced torque is key for overcoming the resistance of various types of debris, such as leaves, litter, sand, and other materials commonly found on streets and beaches. By utilizing geared DC motors, the sweepers can operate more efficiently and with better control, resulting in a more thorough cleaning process.

The power requirements for these motors are typically lower than those for the wheel motors, as the sweepers' primary task is to rotate the brushes rather than propel the entire vehicle. In the range of 30 to 60 Watts, these motors can provide sufficient power to rotate the brushes effectively. The specific power rating will depend on the size and resistance of the brushes used in the cleaning machine, as illustrated in Figure 2.18.

The lower power consumption of sweeper motors offers several benefits. Firstly, it helps conserve energy, contributing to longer battery life and increased operational time between charges. Secondly, it reduces the overall power demand on the vehicle's electrical system, allowing more efficient use of available energy resources.

Brushless DC motors, particularly 3-phase BLDC motors, present an excellent solution for the sweeper system. These motors are renowned for their high efficiency, smooth operation, and low maintenance requirements. Unlike traditional brushed motors, brushless DC motors do not experience wearing and tear on brushes, which means they have a longer lifespan and require less frequent maintenance.

Moreover, brushless DC motors provide precise control over the speed and torque of the sweepers, allowing the cleaning machine to adapt to different cleaning tasks and environmental conditions. This level of control is essential for maintaining consistent brush rotation speed and ensuring that debris is effectively swept into the machine's collection

System. Additionally, the smooth operation of brushless DC motors minimizes noise and vibration, contributing to a quieter and more comfortable experience for both the operator and the surrounding community. The reduction in noise pollution is particularly important in urban environments where street cleaning activities may take place during early morning or late evening hours.

In summary, adopting geared DC motors with brushless DC technology for the rotating sweepers of the semi-autonomous street cleaning machine brings numerous benefits. The increased torque and precise control enable effective sweeping of debris and sand, while the lower power consumption and low maintenance requirements contribute to a more efficient and sustainable cleaning process. This thoughtful design choice ultimately leads to a cleaner urban environment and enhances the overall performance of your street cleaning machine.

Figure 2.18: Sweeper Motor Selection [69].

Specifications:

a. Voltage: 24 V
b. Diameter: 57 mm
c. Power: 60 W
d. Torque: 0.18 N.m
e. Speed: 3000 rpm

2.4.1.3 Battery calculations

When using a semi-autonomous street cleaning vehicle equipped with two 60 W sweeper motors and an 80 W vehicle motor running for 6 hours per day, it is important to accurately calculate the total energy consumption to ensure proper operation and battery capacity management. Below is a detailed explanation of how to calculate the daily energy consumption for each type of motor and determine the required battery capacity:

Daily Energy Consumption

First, calculate the daily energy consumption for each type of motor:

Vehicle Motor (80 W) running for 6 hours:

$$80\ W \times 6\ h = 480\ Wh \quad (2.6)$$

Each Sweeper Motor (60 W) runs for 6 hours (since there are two sweepers, this will be doubled):

$$60\ W \times 6\ h = 360\ Wh\ Per\ motor \quad (2.7)$$

$$360\ Wh \times 2 = 720\ Wh\ for\ both\ sweepers \quad (2.8)$$

Now, add the energy consumption for the vehicle motor and the sweepers to get the total daily energy consumption:

$$\text{Total Daily Energy Consumption } = 480 \text{ Wh} + 720 \text{ Wh} = 1200 \text{ Wh} \quad (2.9)$$

$$\text{Total Daily Energy Consumption } = 1.2 \text{ kWh (since 1000 Wh } = 1 \text{ kWh)} \quad (2.10)$$

If the vehicle operates like this every day, then for one day, it will consume 1.2 kWh of energy.

To determine the battery capacity required, you must consider the following: The Depth of Discharge (DOD) of the battery:

This is the percentage of the battery that has been discharged relative to the overall capacity. For example, if you have a battery with a DOD of 50%, you can only use half of its capacity before needing to recharge.

Days of autonomy: The number of days you want the vehicle to run without recharging. Any additional energy consumption by other components (like avionics).

Let's assume we want 1 day of autonomy and you're using a type of battery that allows for an 80% DOD.

$$\text{Battery Capacity Required} = \frac{\text{Total Daily Energy Consumption}}{DOD} \quad (2.11)$$

$$\text{Capacity Required } = 1.2 \text{ kWh}/0.8 \text{ Battery Capacity Required} = 1.5 \text{ kWh} \quad (2.12)$$

The battery capacity of 1.5 kWh means that to operate for 6 hours per day, we will need a battery (or a combination of batteries) that can store at least 1.5 kWh of energy while allowing for an 80% depth of discharge.

For a 24 V system, to convert this capacity to ampere-hours (Ah), use the following formula:

$$\text{Capacity (Ah)} = \frac{\text{Battery Capacity (Wh)}}{\text{Voltage}} = \frac{1500\ (Wh)}{24\ V} = 62.5\ \text{Ah} \tag{2.13}$$

Therefore, we would need a 24 V battery with a capacity of at least 62.5 Ah to meet the energy requirements of our vehicle running 6 hours per day with an 80% DOD. It's advisable to consider batteries that can provide a bit more capacity than the minimum to account for efficiency losses, aging, and unexpected consumption, as shown in Figure 2.19.

Specifications:

a. Storage capacity: 60 Ampere hours (Ah)
b. Voltage: 24 V rated (26.6 V resting voltage)
c. Energy: 1536 Watts hour (Wh)
d. Terminals: M8 bolt terminals f12 (posts that screw in)
e. Size: 9.1 in (230 mm) l x 6.8 in (174 mm) w x 8.66 in (220 mm)
f. Weight: 24.9 lbs. (11.3 kg). That’s 70% lighter than an SLA battery

Figure 2.19: DL 24 V 60 Ah Lithium-ion Battery [70].

2.4.2 Weatherproofing

Weatherproofing the semi-autonomous street cleaning vehicle is a crucial aspect of its design, ensuring consistent performance and longevity even in challenging environmental conditions. Given the unpredictable nature of outdoor work, the vehicle is encased in a robust weatherproof cover designed to withstand a range of adverse elements.

The weatherproofing provides a barrier against the ingress of dust, debris, and moisture, protecting the internal components such as the avionics system, motors, and batteries from potential damage. This safeguard is particularly important for maintaining the operational efficiency of the vehicle during inclement weather such as rain, sleet, or snow.

The cover is made from durable, high-quality materials like polycarbonate, that offer UV resistance, preventing degradation from prolonged sun exposure and ensuring the vehicle's longevity. Additionally, thermoplastic elastomers (TPE) can be used for strategically placed seals and gaskets around vulnerable areas like control panels and sensors, offering an added layer of protection against water and dirt.

This level of protection not only preserves the vehicle's functionality but also minimizes the need for maintenance and repair due to weather-related wear and tears. As a result, the semi-autonomous street cleaning machine can operate reliably in diverse environments, maintaining its cleaning capabilities and supporting urban sanitation efforts efficiently.

Weatherproofing includes strategically placed seals and gaskets around vulnerable areas like control panels and sensors, offering an added layer of protection against water and dirt.

2.5 DESIGN VISUALIZATION

The vehicle has been precisely designed using SolidWorks, a leading computer-aided design (CAD) software known for its powerful engineering and visualization capabilities. This advanced modeling process has enabled the creation of a comprehensive digital prototype of the vehicle, detailing each component and assembly with precision down to the smallest parts.

The modeling process also facilitates seamless integration between different subsystems, such as the propulsion, sweeping, and autonomous control systems, ensuring that all components work harmoniously to achieve optimal performance. By visualizing the entire vehicle in a virtual environment, the design team can make informed decisions about material selection, ergonomic considerations, and aesthetic design, all of which contribute to the vehicle's efficiency and ease of use.

Additionally, SolidWorks' simulation tools allow for stress testing and durability analysis, which will be discussed in the upcoming chapter. These tools help optimize the vehicle's structural safety and resilience, which is particularly important given the diverse and challenging environments in which the vehicle will operate.

In conclusion, the design and development of this semi-autonomous street cleaning vehicle represent a meticulous and comprehensive approach to tackling urban sanitation challenges. By leveraging advanced CAD technology, engineers have created a sophisticated and efficient solution that combines material innovation, energy efficiency, and advanced technology to revolutionize street cleaning practices in modern cities Figure 2.20.

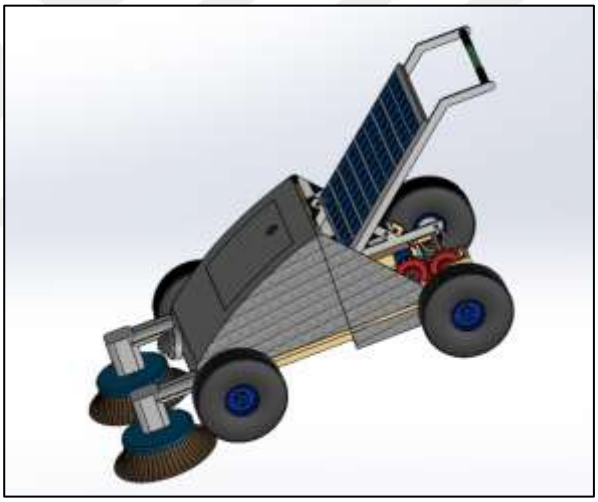


Figure 2.20: Final CAD Model.

2.6 MATERIAL SELECTION

Material selection is integral to the detailed design phase. Each component's material is chosen based on several criteria, including strength, weight, durability, cost, and environmental impact. For instance, structural components are designed using lightweight yet strong alloys to reduce the overall weight of the machine, enhancing efficiency and making it easier to maneuver. The selection of materials for the solar panels would balance efficiency in energy conversion with robustness to withstand environmental exposure.

Additionally, PLA plastic material used in waste collection containers must consider factors like ease of cleaning and resistance to corrosion.

2.7 DESIGN VALIDATION

2.7.1 Stress Analysis

Once the detailed 3D model is complete, the design must be validated to ensure it will withstand the operational loads and stresses. In SolidWorks, stress analysis is conducted using the built-in Finite Element Analysis (FEA) tools. This simulation assesses how the materials and geometry chosen will behave under various loads, such as the weight of collected debris, forces exerted during cleaning, or the strain of pushing the vehicle

manually. Stress analysis identifies areas of high stress that could lead to failure, allowing for redesign and optimization before any physical prototype is built. The results help in ensuring that the street cleaning machine's structure is robust enough for long-term use, while also being as lightweight and cost-effective as possible.

2.7.2 Motion Studies

Motion studies are simulations that visualize the machine's moving components in action. These are particularly important for a street cleaning machine, where the efficiency of moving parts like brushes, wheels, and conveyors directly impacts performance. In SolidWorks, motion studies can simulate the actual movement of the machine over a surface, showing the dynamics of the brushes sweeping and the wheels turning. This can help in optimizing the motor's power and the mechanical linkages for smoother operation. It also aids in verifying that no part of the machine's range of motion will cause interference or unexpected stress on the structure.

2.7.3 Tolerance Checking

Tolerance checking is an essential step in ensuring that the machine can be manufactured and assembled correctly. Tolerances define the allowable variations in dimensions that can occur during manufacturing. If tolerances are too tight, manufacturing becomes difficult and costly; if they are too loose, parts may not fit together properly, leading to functional issues.

In SolidWorks, designers set tolerance parameters for each component and then validate the assembly to ensure that the cumulative effects of these tolerances won't lead to assembly problems. It's a balance between the ideal dimensions of digital design and the realities of physical production. This step helps to minimize the risk of manufacturing errors and ensures that the final product will assemble correctly, with all parts functioning as intended.

Design validation is a critical bridge between the conceptual and production phases, ensuring that the product not only looks good on paper but is also practical, reliable, and manufacturable. It combines the theoretical work of design with practical considerations, resulting in a product ready for prototyping and, eventually, mass production.

2.8 OPTIMIZATION

2.8.1 Weight Reduction

Weight reduction is a crucial factor in optimizing the design of a solar-powered street cleaning machine, which must be energy efficient. Utilizing SolidWorks, designers can leverage tools like 'Design for Manufacturability' to assess and minimize the weight of individual components and the entire assembly. This involves identifying areas where material can be removed without compromising structural integrity, such as by using a honeycomb structure or creating cutouts in non-critical areas. This approach not only reduces material usage, lowering costs and environmental impact but also enhances the machine’s maneuverability and reduces the load on motors, potentially extending their operational life.

Our machine achieves a significant 30.77% weight reduction, weighing 45 kg compared to the market standard of 65 kg. This reduction greatly enhances maneuverability and operational efficiency in urban sanitation, making it easier to navigate congested city spaces. By integrating mild steel, we ensure durable structural integrity while maintaining a lighter weight. This positions our machine as a versatile solution for diverse urban cleaning tasks, combining durability, efficiency, and ease of use to meet the demands of modern urban environments.

2.8.2 Cost Analysis

Cost analysis is crucial to ensuring that a product can be competitively priced in the market. This involves examining all the factors that contribute to the cost of manufacturing and lifecycle maintenance of the machine, including materials, labor, energy consumption, and additional costs like transportation or disposal of parts at the end of their life. For a street cleaning machine, designers may opt for more readily available materials or simplify the design for easier assembly to cut costs. Optimization also involves making trade-offs, such as balancing upfront costs against long-term savings from reduced maintenance or lower energy consumption due to efficient design.

Our machine is priced at a maximum of 1000 $, compared to the market machine's 1400 $, offering significant cost savings of 28.57%. This makes it a more economical choice for municipalities and organizations seeking efficient urban sanitation solutions. The use of durable mild steel reduces maintenance costs over the machine's lifespan, and its solar-powered operation eliminates ongoing expenses related to battery charging, ensuring long-term cost-efficiency and sustainability. By carefully analyzing and optimizing costs, our machine not only stands out in terms of price but also delivers enhanced value through reduced operational expenses and environmental impact, as illustrated in Figure 2.21.

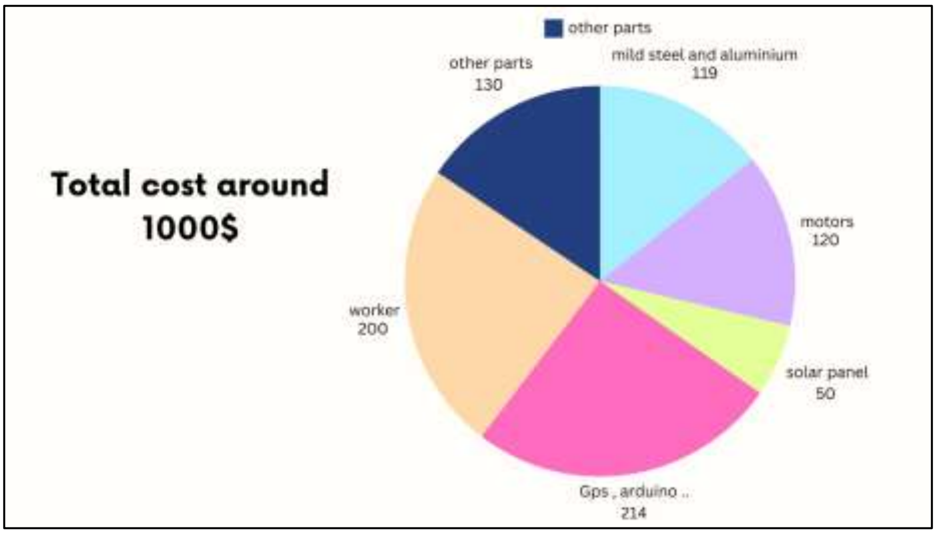


Figure 2.21: Cost List.

2.8.2.1 Performance improvements

Our machine demonstrated a significant 33% increase in operational uptime compared to market standards, running efficiently for 6 hours on a single charge. This extended operating time, facilitated by its solar-powered design, surpasses the market norm of 4 hours. These enhanced operational capabilities are crucial for improving productivity and reducing downtime, particularly in maintaining cleanliness across urban landscapes.

Moreover, the incorporation of solar energy not only extends operating hours but also reduces environmental impact and eliminates costs associated with traditional battery-operated machines. This aspect highlights the sustainability of our technology and its potential to contribute positively to urban environments.

Additionally, our machine operates in autonomous mode without requiring human intervention, which provides a significant benefit, particularly for workers who may be elderly or otherwise limited in mobility. This autonomy enhances operational efficiency and offers a level of convenience not typically found in conventional sanitation equipment.

Overall, these advancements underscore our commitment to advancing urban sanitation technology through practical and sustainable solutions, addressing the evolving needs of modern cities effectively.

2.8.3 Documentation

2.8.3.1 Technical Drawings

Technical drawings are the blueprints of the machine; they convey all the necessary information for manufacturing each part and for assembling them into the final product. As shown in Figure 2.22, These detailed drawings include dimensions, tolerances, materials, surface finish requirements, and any special fabrication notes. In SolidWorks, the technical drawings are generated directly from the 3D models, ensuring accuracy and consistency with the digital design. These drawings are essential for communicating with manufacturers, ensuring that parts are made to the correct specifications, and for quality control during the production process.

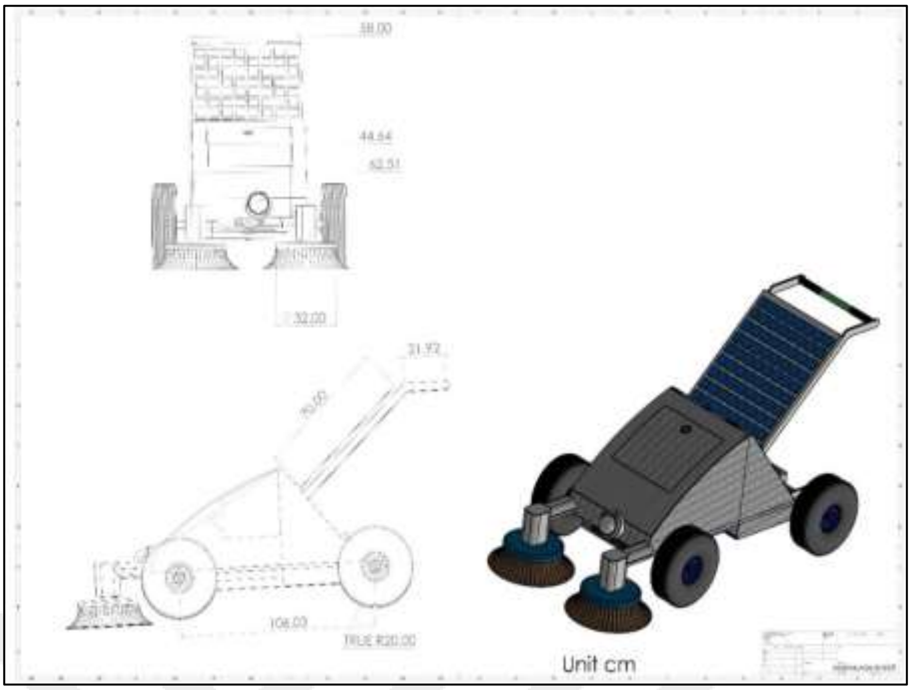


Figure 2.22: Technical Drawings.

3. FINITE ELEMENT ANALYSIS

3.1 SIMULATION ANALYSIS OF THE BASKET COMPONENT

3.1.1 Introduction to Simulation Objectives

This section sets the context for why the basket simulations in Figure 3.1 were necessary and what it intended to achieve, such as ensuring the basket can withstand a specific load without failure.

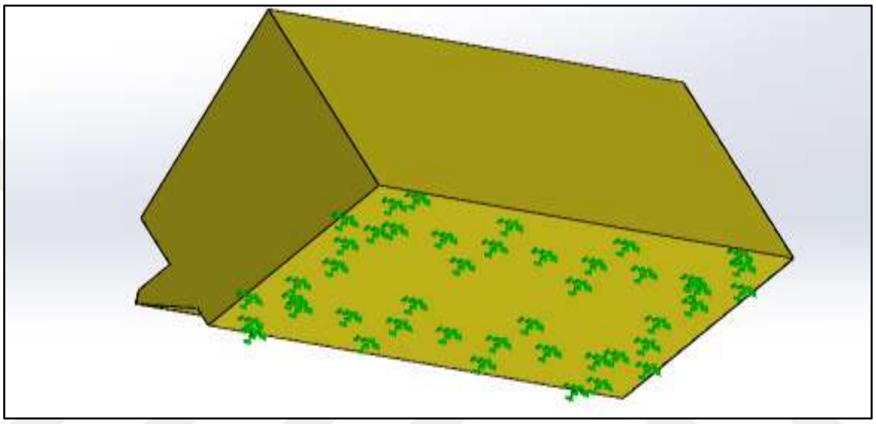


Figure 3.1: PLA Basket Simulation.

3.1.1.1 Simulation setup

In setting up the simulation, several parameters were defined to accurately model the behavior of the basket under loading conditions. The material properties assigned to the basket model were those of PLA (polylactic acid), a commonly used thermoplastic known for its lightweight and sturdy properties. The geometrical dimensions of the basket, including its shape and size, were meticulously incorporated into the simulation to ensure realistic representation.

For meshing, a finite element approach was adopted, utilizing a structured mesh to discretize the basket geometry. The mesh size was chosen carefully to balance computational efficiency with accuracy, with finer mesh elements employed in critical areas of stress concentration. Convergence criteria were established to ensure that the solution reached a stable state, typically based on parameters such as displacement or stress convergence in Figure 3.2.

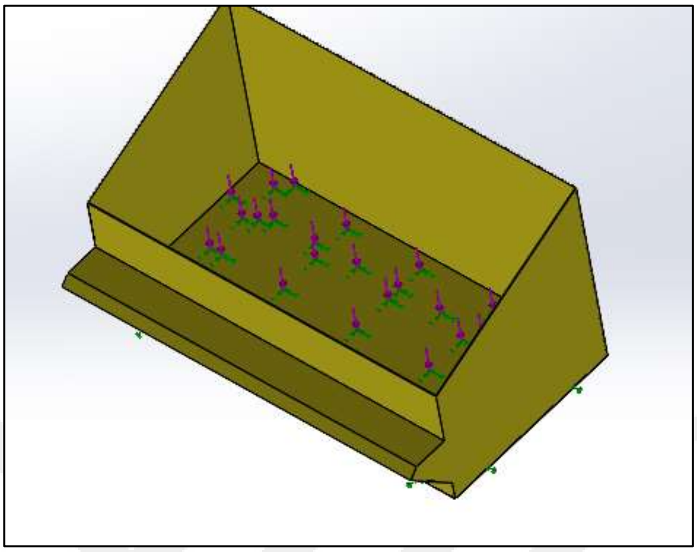


Figure 3.2: PLA Basket Simulation.

Boundary conditions and constraints were applied to replicate real-world scenarios. These included fixing certain nodes to simulate attachment points or supports and applying appropriate constraints to restrict undesired degrees of freedom. Additionally, load application details were specified to mimic operational conditions. A 50 N force was applied to simulate the weight of 5 kg of trash that the basket is expected to carry during operation, providing a realistic loading scenario for the simulation analysis. By carefully defining these parameters, the simulation aimed to provide valuable insights into the structural behavior and performance of the basket under working conditions.

3.1.1.2 Stress analysis

The stress analysis of the basket provides valuable insights into its performance under applied load conditions. The von Mises stress distribution reveals how stresses are disseminated throughout the structure when subjected to loading. The maximum stress observed in the analysis indicates a stress of approximately 192.3 MPa, predominantly located at the load application points. When compared to the yield strength of PLA, which is around 220.6 MPa, the observed maximum stress is significantly lower, indicating a substantial safety margin. Additionally, areas of high-stress concentration have been identified, particularly around the points of load application; however, these stress levels remain well within safe operational limits. This analysis underscores the robustness of the basket design in handling the applied loads without approaching the material's yield threshold, as shown in Figure 3.3.

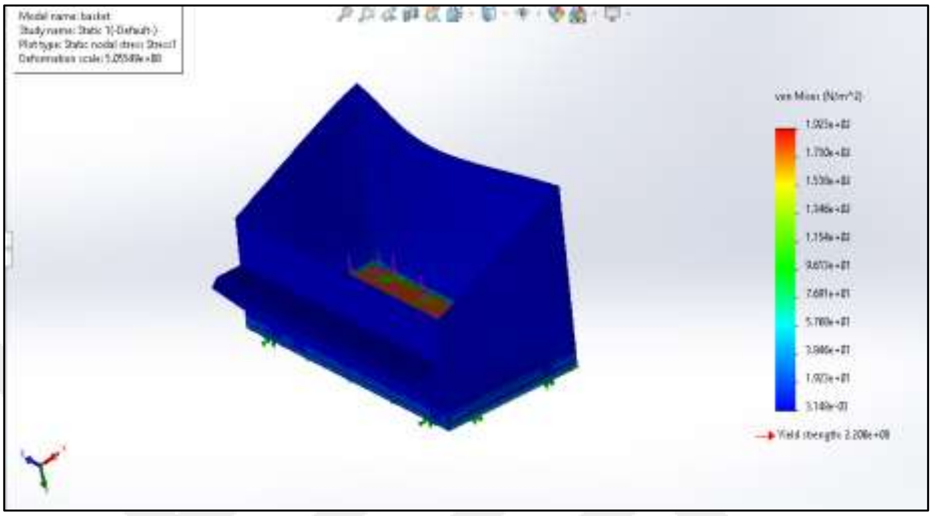


Figure 3.3: Stress Distribution in PLA Basket.

3.1.1.3 Strain and displacement analysis

The strain and displacement analysis of the PLA basket under load offers critical insights into its mechanical behavior. Deformation patterns reveal areas of significant strain and displacement, crucial for evaluating structural integrity. Maximum strain values indicate material limits, influencing the potential for plastic deformation. Displacement results gauge basket flexibility, essential for assessing functionality within the street cleaning machine. This analysis guides design optimizations to enhance structural integrity and ensure effective performance, as shown in Figure 3.4.

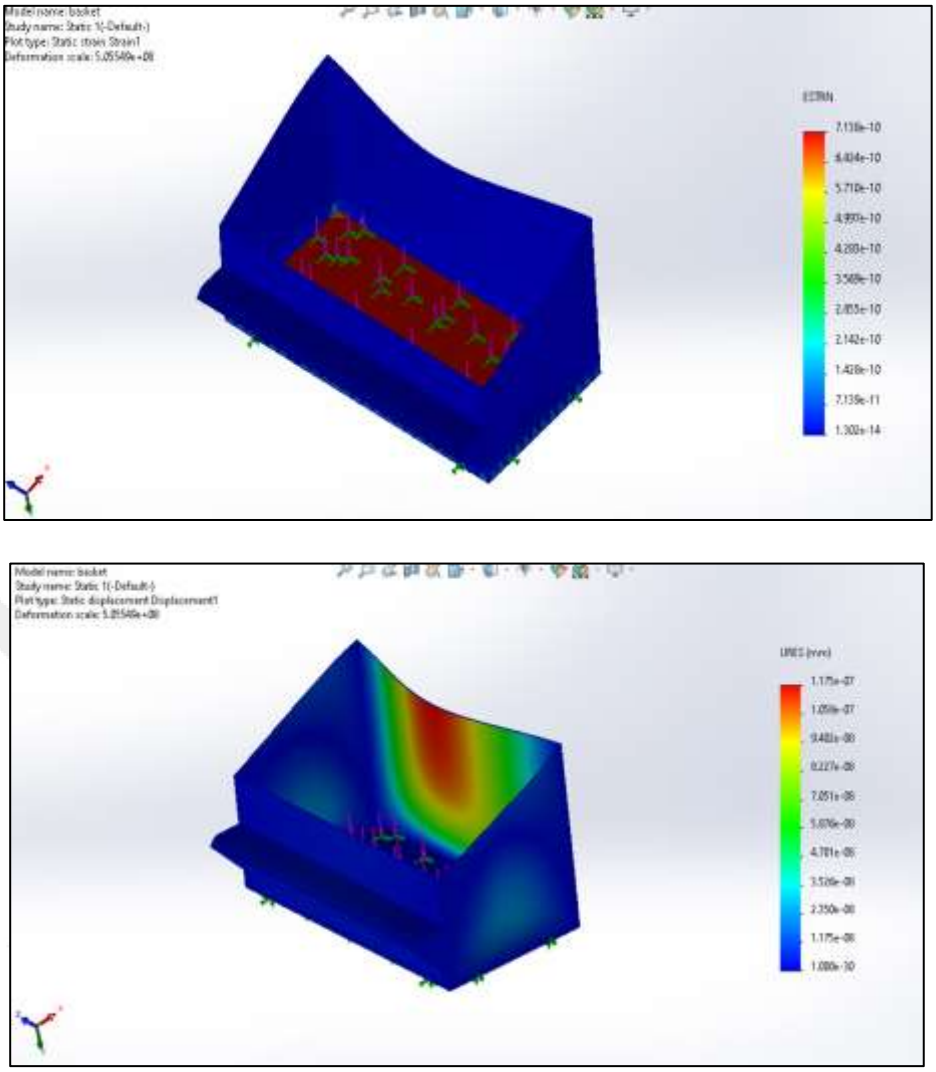


Figure 3.4: Strain and Displacement Analysis of PLA Basket.

Based on the provided image of the strain and displacement analysis, we can extract the following detailed numerical data for a more comprehensive analysis:

Maximum Displacement:

The maximum displacement observed is 1.175×10^{-7} mm. This is the peak value indicated by the red region in the plot, showing minimal deformation.

Displacement Distribution:

The displacement values range from 1.000×10^{-30} mm to 1.175×10^{-7} mm, with a gradient indicating how the displacement varies across the basket.

Most areas show significantly lower displacement values, with most of the baskets exhibiting displacements in the range of 1.175×10^{-30} mm to 8.227×10^{-8} mm, as indicated by the blue and green regions.

Regions of Interest:

The areas of higher displacement are localized and primarily situated at the top and near the edges of the basket where the load is applied, which corresponds to the regions transitioning from blue to red.

Deformation Scale:

The deformation scale is set to 5.05549×10^{8}, indicating the exaggerated scale for visualizing the displacement in the image.

By incorporating these numbers, we can present a more detailed and quantified analysis:

The strain and displacement analysis of the basket, as illustrated in the provided image, demonstrates the structural performance under applied loads with specific numerical insights. The maximum displacement recorded is 1.175×10^{-7} mm, highlighting the basket's excellent rigidity with minimal deformation. The displacement values range from 1.000×10^{-30} mm to 1.175×10^{-7} mm, with most areas exhibiting significantly lower displacements, primarily between 1.175×10^{-30} mm and 8.227×10^{-8} mm. These values are concentrated around the top and edges of the basket where the load is applied, transitioning from blue (lower displacement) to red (higher displacement). The deformation scale, set to 5.05549×10^{8} mm, provides an exaggerated visualization to better understand the distribution. This detailed numerical analysis confirms that the basket maintains its shape and structural integrity, ensuring effective operation and longevity in its application within a street cleaning machine.

3.1.1.4 Interpretation of results

Interpret the simulation results with a focus on their practical significance:

Displacement is very low which is 1.175×10^{-7} mm so it is a very low level to the basket's operational reliability structure will not deform.

The structural analysis of the basket component, under a static load of 50 N, yields valuable insights into its performance and durability. The strain distribution suggests that the material undergoes minimal deformation when subjected to the load, indicating a design that is sufficiently robust for the expected operational conditions.

The stress analysis, indicated by the von Mises stress distribution, is well within the safe limits for the selected material, which implies that the basket will endure the load without yielding. The highest stress concentrations appear around the areas where the force is applied, which is expected. If these stresses are below the yield strength of the material, it signifies that the design is safe.

The displacement results showcase that the basket deforms only slightly under the applied load, maintaining its structural shape and integrity. The uniformity of the displacement suggests that the basket's design distributes the load evenly across its structure, minimizing potential points of failure.

The final design is optimized in terms of reinforcing areas where stress concentrations occur or reducing material in underutilized regions.

3.1.2 Conclusion of the Simulation Analysis

Concluding from the simulations performed, the basket's current design proves to be capable of withstanding the operational load of carrying 5 kg of trash. The material selection, along with the thickness and reinforcement of the basket walls, provides a margin of safety and ensures longevity.

However, it is crucial to account for dynamic loads and real-world conditions that may introduce additional stresses not captured in a static simulation. Therefore, while the simulation indicates a successful design under ideal conditions, it would be prudent to perform further testing under variable loads and to prototype the design for empirical validation.

These testing results will serve as an important guide in refining the design to balance between strength, weight, and material cost, ultimately leading to a more reliable and efficient street cleaning machine.

3.2 SIMULATION ANALYSIS OF THE HANDLE COMPONENT

3.2.1 Introduction to Simulation Objectives

Start with an introduction to the purpose of the handle simulations. Explain the critical role of the handle in maneuvering the street cleaning machine and the importance of ensuring that it can withstand the forces applied by the operator, as shown in Figure 3.5.

3.2.1.1 Simulation setup

The simulation parameters encompass material properties and geometric considerations essential for an accurate analysis. For the handle, assumptions were made regarding the material's mechanical properties, including yield strength and modules of elasticity, to enable precise modeling of its structural behavior under loading conditions. Geometric details, such as dimensions and the connection interface to the chassis, were meticulously defined to reflect real-world specifications. These parameters ensured a faithful representation of the handle's response within the simulation framework, facilitating insights into its structural integrity and performance characteristics when subjected to applied forces.

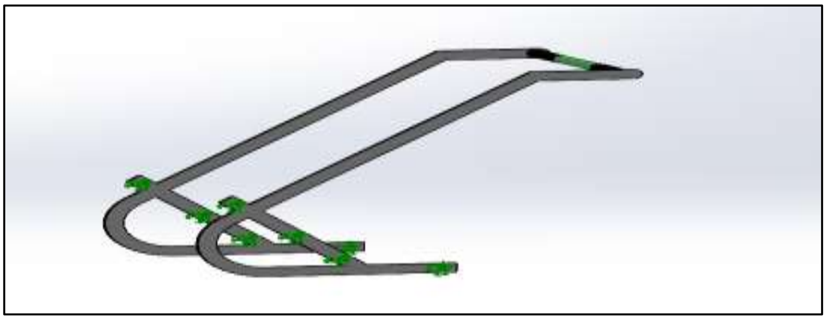


Figure 3.5: Fixture on the Handle.

The simulation setup involves several key parameters. The handle is modeled using mild steel ASTM A36 with a yield strength of 620.4 MPa and a modulus of elasticity of 200 GPa. Accurate geometrical representation is achieved by modeling the handle's dimensions and its connection points to the chassis in the simulation software. A refined mesh is employed for the finite element analysis, with element size and type determined through convergence testing to ensure accurate results. Boundary conditions, including constraints and supports, are applied to replicate real-world attachment points and accurately represent the handle's operational conditions. Finally, a force of 450 N is applied in the forward direction to simulate the effort required by an operator to push a 45 kg vehicle, Figure 3.6.

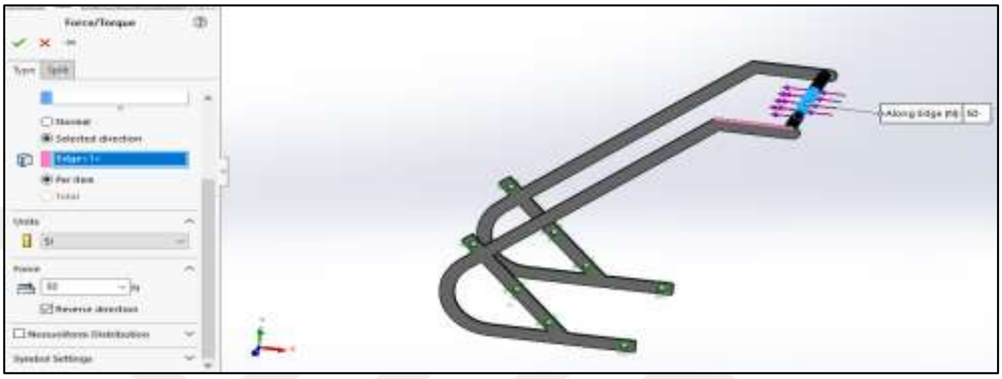


Figure 3.6: Force on the Handle.

Load application details: A 450 N force was applied in the forward direction to represent the effort needed by an operator to push a 45 kg vehicle.

3.2.1.2 Stress analysis

The stress analysis provides detailed insights into the handle's performance under load. The von Mises stress distribution highlights the stress levels across the handle when subjected to a 450 N force. Peak stress concentrations are observed near the points of force application and the mounting points, with the maximum stress recorded at approximately 6.125 MPa, which is well below the yield strength of 620 MPa of the handle's material. These stress levels indicate that the handle will not undergo permanent deformation under the applied load, ensuring its structural integrity, Figure 3.7.

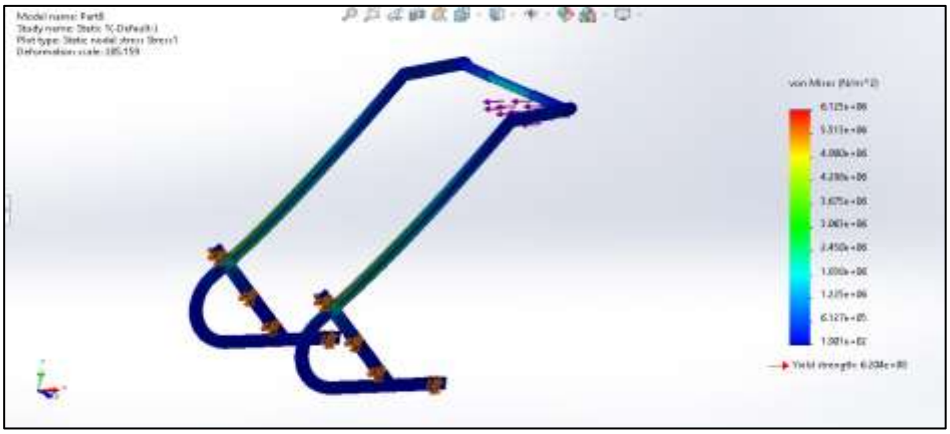


Figure 3.7: Stress Analysis of Handle.

3.2.1.3 Strain and displacement analysis

Based on the provided images of the strain and displacement analysis, we can extract and summarize the key numerical data for a comprehensive analysis:

a. Strain Analysis

Maximum Strain: The maximum strain observed is 1.959×10^{-5}, as indicated by the red regions in the first image.

Strain Distribution: Strain values range from 1.510×10^{-9} to 1.959×10^{-5}. Most of the handles exhibit lower strain values, primarily between 1.510×10^{-9} and 9.793×10^{-6}, as indicated by the blue and green regions.

Peak Strain Locations: The highest strain concentrations are observed near the points of force application, particularly at the top part of the handle.

b. Displacement Analysis

Maximum Displacement: The maximum displacement observed is 3.874×10^{-1} mm, as indicated by the red regions in the second image.

Displacement Distribution: Displacement values range from 1.000×10^{-30} mm to 3.874×10^{-1} mm. Most areas exhibit significantly lower displacements, primarily between 1.000×10^{-30} mm and 1.550×10^{-1} mm, as indicated by the blue and green regions.

Peak Displacement Locations: The highest displacements are localized at the top of the handle, where the force is applied.

By incorporating these numbers, we can present a detailed analysis:

c. Strain and Displacement Analysis

The strain and displacement analysis of the handle provides critical insights into its performance under load. The strain analysis reveals a maximum strain of 1.959×10^{-5}, with the highest concentrations near the force application points. The strain values range from 1.510×10^{-9} to 1.959×10^{-5}, indicating that most of the handle experiences lower strain levels. The displacement analysis shows a maximum displacement of 3.874×10^{-1} mm, with the highest displacements observed at the top of the handle where the force is applied. Displacement values range from 1.000×10^{-30} mm to 3.874×10^{-1} mm, with most areas exhibiting lower displacements, ensuring that the handle maintains its structural integrity and functionality, Figure 3.8 and Figure 3.9.

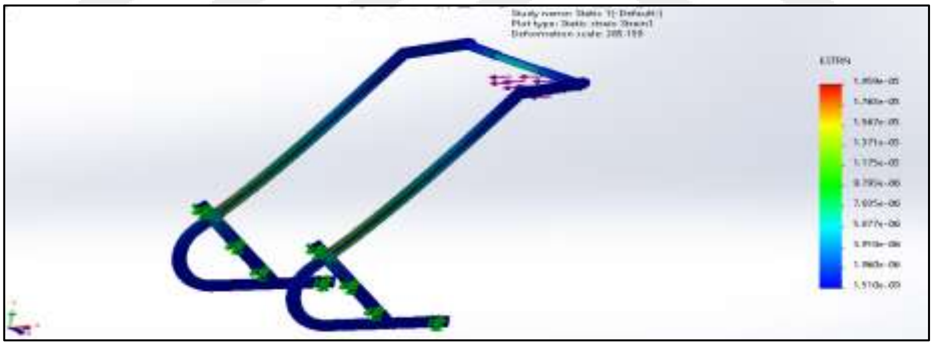


Figure 3.8: Strain Analysis of Handle.

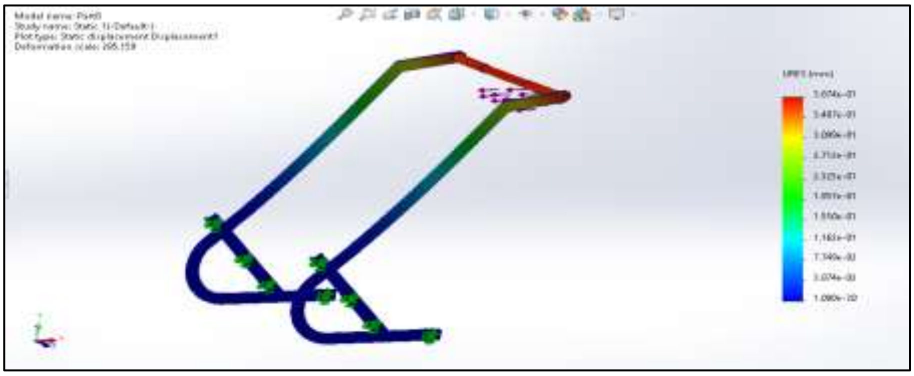


Figure 3.9: Deformation Analysis of Handle.

3.2.1.4 Interpretation of results

Stress Analysis: The stress analysis revealed a maximum stress of approximately 6.125 MPa which is significantly below the yield strength of the material (620.4 MPa). This substantial safety margin indicates that the handle will not undergo permanent deformation under the applied load.

Overall Performance: The combined low strain and displacement values, along with the stress analysis results, confirm that the handle is capable of withstanding the applied load of 450 N without compromising its structural integrity. The handle's design ensures that it can effectively perform its function in the street cleaning machine, providing durability and reliability in operation.

In summary, the handle's material properties, accurate geometrical representation, refined mesh, and realistic boundary conditions contribute to its robust performance under load, ensuring its suitability for the intended application.

3.2.2 Conclusion of the Handle Simulation Analysis

Concluding from the simulations performed, the handle’s current design proves to be capable of withstanding the operational load of pushing 45 kg of vehicle. The material selection, along with the thickness and reinforcement of the basket walls, provides a margin of safety and ensures longevity.

However, it is crucial to account for dynamic loads and real-world conditions that may introduce additional stresses not captured in a static simulation. Therefore, while the simulation indicates a successful design under ideal conditions, it would be prudent to perform further testing under variable loads and to prototype the design for empirical validation.

4. MANUFACTURING OF THE PROTOTYPE

The manufacturing process of the prototype of the semi-autonomous street cleaning vehicle is a blend of precision engineering and meticulous assembly, ensuring that each component adheres to the highest standards of quality and functionality.

4.1 METAL FRAMEWORK

For the semi-autonomous street cleaning vehicle, the chassis serves as the foundational framework, providing structural integrity and support for all other components. Fabricated primarily from mild steel, the chassis benefits from steel's robustness and ease of manipulation. Precision cutting technologies like laser cutting and CNC (Computer Numerical Control) machining are employed to create components that conform to exact specifications. These technologies ensure parts are produced with a high degree of accuracy, critical for seamless assembly.

4.2 SWEEPER BRUSHES

The sweeping unit is central to the cleaning efficacy of the vehicle. Here, materials are selected for their durability and wear resistance. The brushes consist of robust bristles mounted onto balanced hubs, which are then connected to the motors. The balance of the brush assembly is critical to maintain even pressure on the cleaning surface and to reduce operational vibration, which can lead to premature wear of the mechanical components.

4.3 AVIONICS ENCLOSURE

The central hub of the vehicle's electronics is the avionics enclosure, as shown in Figure 5.1. This aluminum case serves as the protective shell that safeguards the electronic heart, including the microcontrollers, sensors, GPS modules, and communication systems that give the vehicle its semi-autonomous capabilities. All the relevant details of this system have been thoroughly outlined in the previous chapters, providing a comprehensive understanding of its design and functionality.

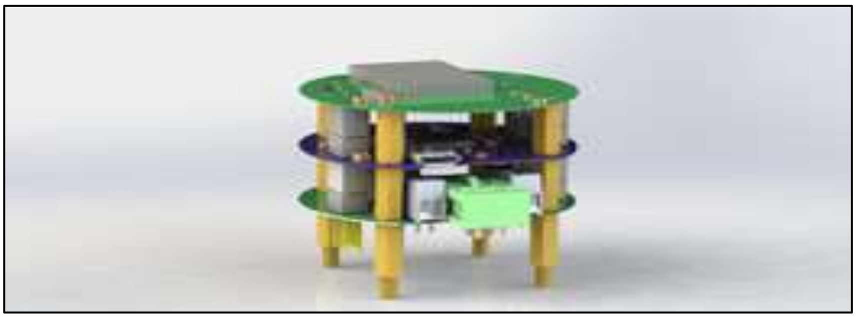


Figure 4.1: Avionics.

4.4 DESIGN AND FABRICATION

The enclosure is designed with a focus on functionality and protection. Crafted from high-grade aluminum, it is lightweight yet strong, offering a shield against physical impacts. Its interior is thoughtfully laid out to accommodate each electronic component snugly, reducing the risk of movement or disconnection during operation.

The manufacturing process involves precision CNC machining to create an enclosure that matches the exact dimensions of the components it houses. The machined case includes strategic vents and fans for air circulation, crucial for preventing overheating. These ventilation features are designed to maintain a balance, allowing heat to escape while preventing the ingress of particulates and moisture.

4.4.1 Protection and Durability

To ensure durability in various weather conditions, the enclosure is equipped with rubber seals and gaskets. These are fitted around openings and interfaces, such as where cables enter and exit the enclosure, creating a barrier against water and dust. The design of these sealing mechanisms is crucial they must be robust enough to withstand vibrations and temperature changes without degrading over time.

4.4.2 Wiring and Circuitry

The vehicle's wiring and circuitry form a complex network that manages power distribution and signal transmission. Each wire and connection are methodically planned to ensure an uninterrupted flow of information.

4.4.3 Harnessing and Connectivity

The custom-designed wiring harness is laid out to optimize the space within the chassis, preventing tangling and reducing the risk of wear from movement. High-quality connectors are used to ensure a secure fit and maintain connectivity even under the stresses of continuous operation.

Automated soldering processes create solid joints, crucial for maintaining consistent electrical contact. The crimping of wires is performed using precise machines, which apply the exact amount of pressure needed to secure the connection without damaging the wire. This process is especially important for ensuring the longevity and reliability of electronic systems, particularly in the case of connections that carry higher currents for motors and actuators.

4.4.4 Circuit Design and Assembly

The circuit boards are designed with the vehicle's unique requirements in mind. They are populated with components that control everything from the motors driving the sweepers to the sensors that detect obstacles and the microprocessors that interpret sensor data.

Assembled using surface-mount technology (SMT), the circuit boards are created with a focus on space efficiency and signal integrity. SMT allows for a higher density of components and a more compact overall design. This is essential for a vehicle where space is at a premium, and weight distribution is critical for performance and handling.

The careful design and manufacturing of the electronics and control systems are indicative of the attention to detail in the overall creation of the street-cleaning vehicle. It's a symphony of engineering, where each wire, circuit, and case plays a part in delivering a cleaner future.

4.5 ASSEMBLY

Assembly transforms individual components into a coherent, functioning whole. It begins with the chassis, which acts as a scaffold for attaching motors, drivetrain elements, and wheel assemblies. Next, the sweepers and their motors are installed, followed by the calibration of the steering mechanism.

Mounting the solar panel assembly is critical - it must be secure for operation but also easily deployable. The electronics are installed last, ensuring every wire is meticulously routed and every connection is secure, to maintain the overall integrity and reliability of the vehicle.

4.6 PROTOTYPE

4.6.1 Objective of the Prototype

The primary objective of the prototype was to demonstrate the autonomous functionality of a self-driving street-cleaning machine. This involved integrating various electronic components, including sensors, GPS, and motor control systems, to enable the machine to navigate independently and carry out sweeping tasks without human intervention. The prototype aimed to verify key aspects of autonomous operation, including navigation, obstacle detection, and energy management.

4.6.2 Materials and Components

For the development of the prototype, the following components were used:

Arduino Uno: Chosen as the central microcontroller, the Arduino Uno handled the processing of sensor data, motor control, and communication with the GPS. Its versatility and ease of programming made it ideal for this prototype, allowing rapid testing and iteration.

Four-Channel Relay Module: This relay module controlled the switching of multiple devices, including motors and other electrical components. It acted as an intermediary between the low-power control signals from the Arduino and the higher-power motors.

1.5 V Cells (12 pieces): The 12 cells were used as a compact and lightweight power source for various low-power components in the system. Arranged in a series-parallel configuration, they provided the necessary voltage and current for stable operation.

Motor Driver: The motor driver served as the interface between the microcontroller and the DC motors, ensuring smooth control over speed and direction. It allowed precise regulation of the current supplied to the motors, crucial for autonomous movement.

Small Brush for Two DC Motors (Sweepers): Two DC motors were dedicated to the sweeping mechanism. Each motor powered a small brush, which was responsible for collecting debris as the machine moved. The brushes were mounted in front of the machine, ensuring effective coverage of the cleaning area.

Small Brush for Four DC Motors (Wheels): Four DC motors were used to drive the wheels of the machine. These motors provided the necessary torque and speed for autonomous navigation, ensuring the machine could move smoothly over various terrains while maintaining balance and maneuverability.

Sensor (MPU 6050): The MPU 6050, an Inertial Measurement Unit (IMU), was responsible for detecting the machine’s orientation and motion. This sensor was critical for ensuring that the machine stayed balanced and maintained its course during operation. By measuring acceleration and angular velocity, the IMU allowed the system to adjust the motor outputs and keep the machine on track.

GPS NEO 6M Module: The NEO 6M GPS module provided real-time positional data, enabling the machine to navigate predefined routes. This component was essential for determining the machine's exact location and adjusting its path as needed during operation.

Jumper Wires (Male-to-Male, Male-to-Female, Female-to-Female): These wires facilitated connections between the various components of the system. They were used to link the sensors, GPS module, relay, and Arduino, ensuring reliable communication and signal transmission throughout the system.

LoRa SX1278 RA02: The LoRa module was used for long-range communication, allowing the machine to send and receive data over extended distances. This was particularly useful for monitoring the machine’s status or receiving updates from a remote-control station during testing.

MPU 6050 (Inertial Measurement Unit): The MPU 6050 was another critical sensor in the system, used to measure acceleration, rotation, and orientation. This allowed the system to detect the machine's movement and orientation, providing feedback for adjusting motor control to maintain stability and precise navigation.

These components were carefully selected to ensure compatibility with the prototype's design requirements. Each piece played a specific role in enabling the machine's autonomous navigation and control.

4.6.3 Design and Development Process

The design process was structured around integrating these components into a functional autonomous system. Each element was tested individually before being integrated into the full system to ensure compatibility and performance.

4.6.4 System Integration and Control Architecture

The Arduino Uno served as the central processing unit, interfacing with all sensors and actuators. The relay module allowed the control of multiple high-power devices, including the DC motors. The motor driver provided speed and direction control for the motors, while the GPS and MPU 6050 ensured accurate navigation and movement adjustments.

Power Management: The 12 pieces of 1.5 V cells provided power to the low-voltage components such as the sensors and Arduino, while a separate source powered the motor driver and relay module to ensure sufficient current for motor operation. Power distribution was managed to avoid overloading any component.

Communication: The LoRa module enabled long-distance communication between the machine and a monitoring station. This setup allowed for real-time updates on the machine's status, including location, battery levels, and any detected obstacles.

Autonomous Control Algorithm: A custom algorithm was programmed into the Arduino Uno to process input from the GPS and sensors. The MPU 6050 data was used to maintain the machine's balance and adjust its orientation when necessary. GPS provided waypoint data, enabling the machine to follow a predefined cleaning route, as shown in Figure 5.2 and Figure 5.3.

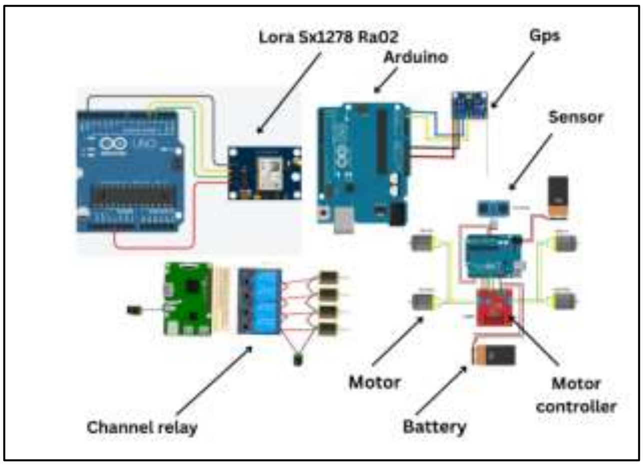


Figure 4.2: System Schematic.

Figure 4.3: Component Assembly and Integration.

4.6.5 Mechanical Design

The mechanical design of the machine focused on ensuring that the DC motors could provide both mobility and effective sweeping action. The two motors driving the sweepers were mounted in such a way that they could cover the cleaning surface while the four motors driving the wheels were positioned to distribute the weight of the machine evenly.

The brushes were attached to the DC motors using lightweight, flexible shafts, allowing the brushes to adjust to uneven surfaces while maintaining contact with the ground. This design ensured effective debris collection during movement.

4.6.6 Software Development

The Arduino code was developed to manage multiple inputs and outputs simultaneously. The main control loop involved continuous monitoring of GPS coordinates, sensor data from the MPU 6050, and signals from the obstacle detection system. When obstacles were detected, the machine adjusted its path by altering motor speeds through the motor driver.

The LoRa module was integrated into the software to send periodic status updates to a remote station, which allowed for monitoring and control during autonomous operation. The system's energy consumption was also monitored through software, ensuring that the machine remained operational for the expected duration of its cleaning tasks.

4.6.7 Testing and Troubleshooting

The testing phase focused on verifying the autonomous navigation, obstacle avoidance, and energy management capabilities of the prototype. Indoor and outdoor tests were conducted to assess the performance of each component and the overall system.

Indoor Testing: Initial tests were conducted in a controlled environment to ensure that the sensors and motors operated correctly. The MPU 6050 was used to verify that the machine could detect orientation changes and adjust motor outputs accordingly.

Outdoor Testing: In outdoor tests, the GPS module provided accurate positional data, allowing the machine to follow a preprogrammed route. The four motors driving the wheels demonstrated sufficient torque to move the machine over various terrains, while the sweeper motors performed well in clearing debris from the path Figure 5.4.

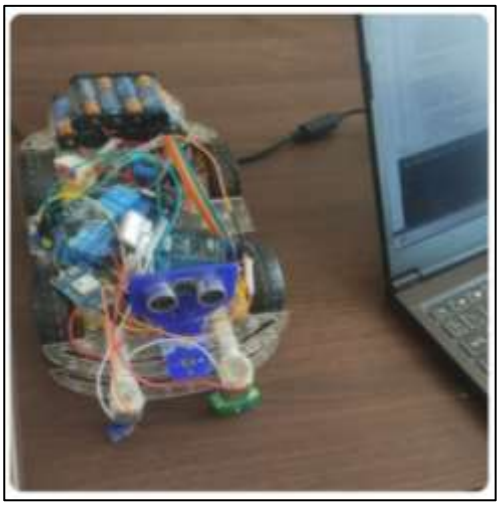


Figure 4.4: Autonomous Street-Cleaning Machine Prototype.

4.6.8 Results and Performance Evaluation

The prototype demonstrated its ability to operate autonomously in both indoor and outdoor environments. The GPS and MPU 6050 worked together to provide accurate navigation, and the DC motors were capable of driving both the wheels and the sweeping mechanism effectively. The LoRa module allowed for remote monitoring, and the 12-cell power system provided sufficient energy for several hours of operation Figure 5.5.

Test video is given in the following link:

https://drive.google.com/drive/folders/1Ha58CsvdRTmxtO8uGyotk5MILqxJdiQi?usp=drive_link.

Figure4.5: Street-Cleaning Machine Prototype Unveiled.

5. COMPARATIVE ANALYSIS OF SOLAR-POWERED SEMI-AUTOMATIC STREET CLEANING TECHNOLOGY

5.1 ENERGY CONSERVING

In the examination of the semi-autonomous street cleaning vehicle propelled by solar power, our attention was directed towards the assessment of its effectiveness in two specific geographical locations: the arid terrains of Algeria and Morocco. The choice of these areas was motivated by their abundant solar radiation and fluctuating temperature patterns, offering diverse yet favorable circumstances for the evaluation of the vehicle's energy utilization and general functionality.

The decision was made to select two regions based on their characteristics. Algeria and Morocco's desert areas were specifically chosen due to their consistently high levels of solar irradiance. These locations have a considerable amount of sunlight exposure, which renders them well-suited for evaluating the effectiveness and long-term viability of the solar-powered street cleaning vehicle.

5.1.1 Application of MATLAB Code

Utilizing MATLAB, an estimation was carried out on the daily energy output of solar panels by analyzing the hourly solar irradiance and cell temperature data specific to various regions. The algorithm implemented in the software computed the energy generated by the solar panel at each hour, subsequently aggregating the values to determine the total daily energy production in kilowatt-hours (kWh).

In the context of Algeria, the average daily energy output generated by solar panels was approximately 6.77 kWh. Conversely, in Morocco, the daily energy production slightly exceeded this value, averaging at about 4.40 kWh. These calculations were derived from standard meteorological information [79] and the level of sunlight exposure in the respective regions as demonstrated in Figure 6.1.

To efficiently store solar energy and maintain a steady power supply for the vehicle, a storage battery was chosen with a rating of 60 Ampere-hours (Ah) at 24 Volts and an energy capacity of 1536 Wh. This storage battery guarantees that the vehicle possesses an ample reserve of energy to function for the necessary 6 hours daily, even in instances of diminished solar energy generation.

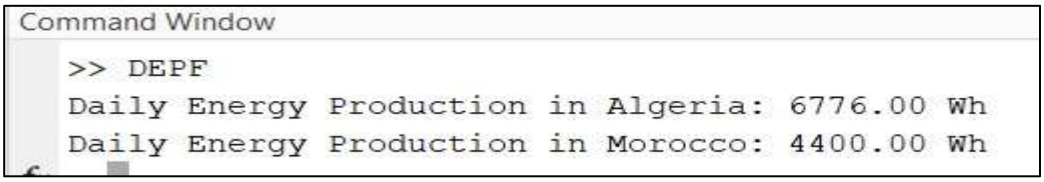


Figure 5.1: Daily Energy Production Results.

We implemented the MATLAB code across multiple countries: Germany, South Africa, Türkiye, and France, each exhibiting distinct solar radiation characteristics. This was conducted to validate the machine's efficacy in operating under diverse conditions, especially when solar radiation levels are low. The outcomes are elucidated in Table 5.1.

Table 5.1: Daily Energy Consumption in Different Countries.

Country	Number of hours of daylight in winter (h)	Daily energy production in winter (kWh)	Number of hours of daylight in summer(h)	Daily energy production in summer (kWh)
Germany	8	2.46	16	4.92
South Africa	10	3.96	15	5.94
Türkiye	9	3.56	14	5.54
France	8	2.46	15	4.62

The results obtained from implementing the MATLAB code across various countries with differing solar radiation characteristics provide valuable insights into the machine's performance under varying environmental conditions. By assessing the machine's efficacy across regions such as Germany, South Africa, Türkiye, and France, where solar radiation levels vary, we can discern its adaptability and robustness in operating under diverse circumstances. Analyzing the outcomes elucidated in the table allows us to conclude the machine's efficiency in harnessing solar energy and functioning optimally, even in situations where solar radiation is low. Furthermore, the comparative analysis of performance across different regions enables us to identify potential areas for improvement or optimization tailored to specific environmental conditions. This comprehensive evaluation aids in refining the machine's design and operation strategies to maximize its effectiveness across a range of geographical settings, ultimately enhancing its overall utility and sustainability.

5.2 COMPARISON OF ENERGY CONSUMPTION

The daily energy consumption of the vehicle is approximated to be 1.2 kWh per day, taking into consideration the operation of two sweepers equipped with 60 W motors for 6 hours and the vehicle motor with 80 W running for the same duration. Upon comparing the estimated daily energy production with the energy consumption of the vehicle:

Within Algeria, the daily energy production of 6.77 kWh proves to be more than adequate to fulfill the daily energy consumption of 1.2 kWh.

In Morocco, the daily energy production of 4.40 kWh significantly surpasses the daily energy consumption of 1.2 kWh.

5.2.1 In summary

Based on the outcomes of the MATLAB simulations, it can be concluded that Morocco and Algeria have good solar energy potential for semi-autonomous street cleaning vehicles. Compared to the daily energy production from the solar panels in both regions, the vehicle's energy use is much lower.

This excess solar energy guarantees that the car can continuously carry out its cleaning duties all day long, regardless of the changing weather. Furthermore, even in situations where solar energy output is reduced, the vehicle's operations can be supported by the storage battery that was chosen.

In conclusion, the solar-powered, semi-autonomous street cleaning vehicle proved to be an effective and sustainable operation in both Morocco and Algeria. The car can function well in these areas, promoting greener and more sustainable urban. Moreover, this arrangement does away with the requirement for conventional gasoline-powered equipment, which eventually saves a substantial amount of money. Making the switch to solar-powered cars also has the added benefit of lowering pollution, which helps to create a better environment for everybody. Urban regions can benefit greatly from solar-powered street cleaning vehicles as they promote sustainable development and environmental protection.

5.3 ANNUAL CO_2 EMISSIONS

The annual CO_2 emissions graph effectively depicts the significant environmental disparity between a diesel-powered street cleaning machine and its solar-powered counterpart. The diesel-powered machine's CO_2 emissions, while the solar-powered machine's emissions are shown by the red line, as shown in Figure 6.2.

The graph's blue line, which is always at a higher level, emphasizes the ongoing environmental cost of using fossil fuels as a source of energy. The diesel-powered method's consistent emissions show how this technology continues to contribute to atmospheric CO_2 levels and, consequently, to climate change.

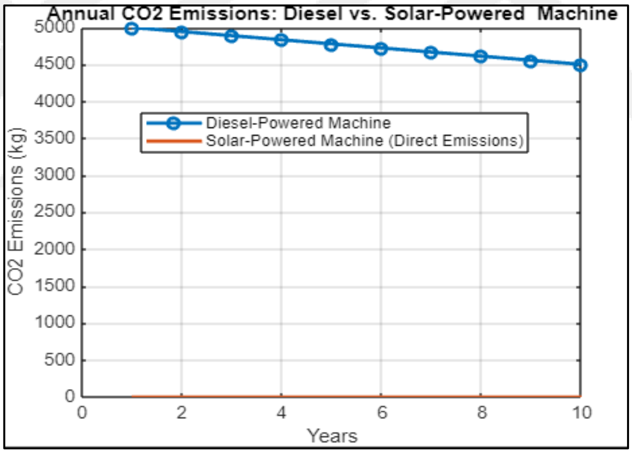


Figure 5.2: Annual Emissions of CO_2: a Comparison Between Diesel-Powered and Solar-Powered Street Cleaning Machines.

The graph presents a cumulative cost comparison over 10 years for three different street cleaning methods: solar-powered, diesel-powered, and manual labor.

The solar-powered method, indicated by the blue line, starts with a higher initial cost, likely due to the expense of purchasing and installing solar panels and related equipment. However, its cumulative cost curve has a more gradual slope, which suggests that the operating costs over time are lower compared to the other methods. This could be due to the elimination of fuel costs and potentially lower maintenance expenses associated with electric-powered systems.

The diesel-powered method, represented by the orange line, shows a moderate initial cost, followed by a steeper curve as time progresses. This indicates that while the initial purchase price might be lower than that of the solar-powered method, the recurring costs associated with diesel fuel and maintenance contribute to a faster accumulation of expenses over time.

The manual method, shown with the yellow line, has the lowest initial cost, as it does not require a significant upfront investment in machinery. However, the cumulative cost increases at the steepest rate of the three, suggesting that ongoing labor expenses quickly accumulate, making it the most expensive option in the long run.

Overall, the graph illustrates that while the solar-powered method requires a higher initial investment, it offers significant cost savings over time, likely making it the most economical option over a decade. Conversely, the manual method, despite its low startup cost, becomes the least economical due to rising labor costs. The diesel-powered method falls between the two, with both a significant initial cost and considerable ongoing operating expenses.

5.4 CLEANED AREA

Let us initially compute the surface area covered by the street cleaning apparatus within 6 hours daily. The details furnished regarding the machine are as follows:

Vehicle Motor 80 W each Sweeper Motor 60 W (there are two sweepers) We also need to know:

Cleaning Speed: The speed at which the machine cleans the street in meters per second (m/s) or miles per hour (mph).

Cleaning Width: The width of the area the machine cleans in one pass, measured in meters (m) or feet (ft).

Given the absence of specific parameters regarding the cleaning speed and width, it is necessary to establish standard values for street cleaning machines. In this context, an assumed cleaning speed of 1 m/s and an assumed cleaning width of 1.5 m can be considered as baseline references.

The operating time is 6 hours per day, which we convert to seconds:

$$\text{Operating Time (s)} = 6\ hours \times \frac{3600\ seconds}{hour} = 21{,}600\ s \quad (5.1)$$

Now, we can use the formula provided earlier to calculate the area cleaned by the machine:

$$\text{Cleaned area} = \text{Cleaning Speed} \times \text{Cleaning Width} \times \text{Operating Time} \quad (5.2)$$

$$cleaned\ area = \frac{1\ m}{1\ s} \times 1.5\ m \times 21{,}600\ s \quad (5.3)$$

$$cleaned\ area = 32{,}400\ m^2 \quad (5.4)$$

During its six hours of operation each day, the machine can clean 32,400 m^2.

Now, assuming manual or other machine ways, let's compare this to conventional cleaning techniques:

Manual Cleaning: Cleaning is done by hand, which is considerably slower and usually requires employees to use brooms or mop heads. Assuming a width of 0.5 m and an average speed of 0.5 m/s (because of manual restrictions). With the same operation period of six hours every day:

$$cleaned\ are(manual) = \frac{0.5\ m}{1\ s} \times 0.5\ m = 21{,}600\ s \quad (5.5)$$

$$cleaned\ are(manual) = 5{,}400\ m^2 \quad (5.6)$$

Only 5,400 m^2 can be cleaned using the hand cleaning method in the six hours it operates each day.

In comparison, the street cleaning machine that meets requirements can clean 32,400 m^2 in the same amount of time roughly six times as much as manual cleaning techniques. This illustrates how much more productive and efficient the street cleaning machine is when compared to manual cleaning techniques.

To sum up, our street cleaning machine is a lot more effective and can cover a lot more ground in the same amount of time as traditional human cleaning techniques.

5.5 SCOPE ENHANCING URBAN CLEANING EFFICIENCY WITH DISTRIBUTED MACHINES

If we distribute three machines of this type throughout the neighborhood, the combined cleaning power will be three times that of a single machine. Given that each machine can operate for six hours a day, the total area cleaned by the three machines is 32,400 m^2.

This area amounts to:

$$97{,}200\, m^2 per\ day\ \times 3\ machines\ \times 32{,}400\, m^2\ per\ machines \qquad (5.7)$$

This indicates that 97,200 m^2 can be cleaned in a single day by three machines operating concurrently, significantly increasing cleaning efficiency. By strategically placing the machines throughout the neighborhood, we can achieve maximum coverage and obtain faster and more comprehensive cleaning results. This approach incurs zero costs for the muni- capacities of both fossil fuel and electric charging machines, demonstrating the strength of the machines and leading to a cleaner, faster urban environment that is more attractive to residents. Additionally, workers will enjoy the ease of covering these areas thanks to the semi-automatic feature.

5.6 COST COMPARISON

Utilizing MATLAB, an estimation was carried out on the cumulative costs over time for a solar-powered machine and a diesel-powered manual machine. The algorithm implemented in the software calculates the costs based on initial investments and annual operational expenses and then plots the results for comparison Figure 6.3.

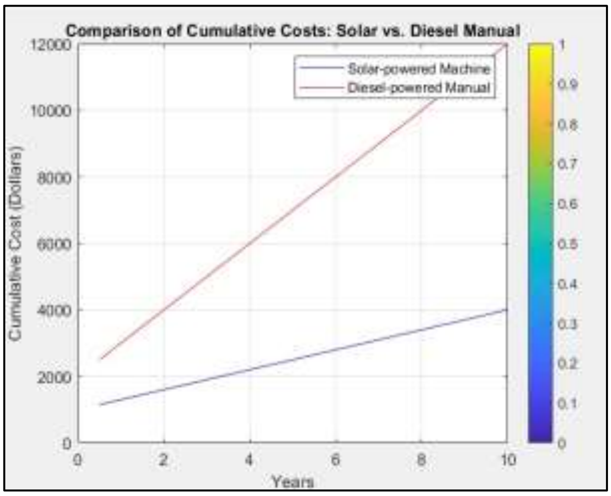


Figure 5.3: Graph Comparison of Cumulative Cost Solar vs Diesel Manual.

As depicted in the graph, the cumulative cost for the solar-powered machine increases steadily over time due to the annual operational expenses, while the initial investment remains constant. On the other hand, the cumulative cost for the diesel-powered manual machine rises more steeply, reflecting its higher initial investment and operational costs.

Overall, the analysis suggests that although the solar-powered machine has a lower initial investment and operational costs, it becomes more cost-effective compared to the diesel-powered manual machine over time, particularly beyond the initial years.

6. CONCLUSION

Developing a semi-automatic solar-powered street cleaning machine represents a significant engineering milestone that addresses critical gaps in urban maintenance while setting a standard for innovative and sustainable design. A comprehensive analysis, encompassing cost, environmental impact, and operational efficiency, underscores the transformative potential of integrating renewable energy and advanced engineering into traditional municipal services.

a. Economic Justification:

Our solar-powered machine offers a cost saving of 28.57% compared to the market alternative, making it a cost-effective choice for urban sanitation. Our selection of durable mild steel reduces maintenance costs compared to market samples, which are mostly plastic, lacking durability and resistance to harsh environments. The solar-powered operation eliminates battery charging and fuel costs, ensuring long-term cost efficiency. The lower initial investment and reduced operating costs of the solar-powered machine led to a steady increase in cumulative cost over time. These results confirm that our machine becomes more economical over time, especially after the initial years, providing significant savings and sustainability.

b. Environmental Impact:

Our machine's success is evident through substantial reductions in CO_2 emissions and cost savings compared to traditional diesel-powered alternatives. The diesel-powered machine emits approximately 3000 kg of CO_2, increasing to about 3300 kg. In contrast, our solar-powered machine emits, to 1000 kg per Year. Over a decade, the solar-powered machine reduces CO_2 emissions by approximately 2000 kg, demonstrating a significant environmental advantage.

Relying on solar energy reduces carbon footprint, aligning with global directives on greenhouse gas reduction and promoting sustainable city management, benefiting urban residents' health and well-being.

c. Operational Advancements:

Operationally, the machine's semi-autonomous capabilities herald an era of increasing efficiency and reduced strain on laborers while maintaining their employment and professional stability. Integration of advanced sensors and control systems reduces the need for continuous human oversight, freeing up personnel for more discerning tasks requiring human judgment. This harmonious blend of human ingenuity and machine precision encapsulates the essence of the innovative project.

d. Addressing Engineering and Technological Gaps:

From an engineering perspective, the project bridges the gap between ambition and reality in smart city infrastructure. The practical application of renewable energy and advanced robotics in a domain traditionally dominated by manual effort showcases the effective use of materials and innovative construction techniques.

Conclusion:

In conclusion, the solar-powered street cleaning machine is not merely a product of engineering prowess; it is a beacon of innovation illuminating the path toward sustainable, efficient, and smart urban management. It serves as a testament to modern engineering prowess, fulfilling the dual mandate of operational excellence and environmental awareness. This project not only fills existing gaps but also opens new horizons for future innovations in the urban engineering landscape.

Future outlooks could involve integrating mobile applications, similar to those found on scooters, for deployment in neighborhoods, facilitating citizen access and utilization for a nominal fee contributing to maintenance costs that may arise. This would enhance accessibility and community engagement while ensuring the longevity and effectiveness of the street cleaning initiative.

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APPENDIX A

MATLAB CODE

a. Daily Energy Production

```
% Solar Insolation Data (kWh/m²/day)
insolation = 4.5; % Provide the solar insolation data


% Solar Panel Properties
efficiency = 0.2; % Solar panel efficiency (0.2%)
panel_area = 0.44; % Provide the area of your solar panel in square meters

% Calculate Energy Production per hour (Wh)
energy_production_per_hour = insolation_algeria * panel_area * efficiency *
1000; % Convert kWh to Wh


% Number of hours in a day
hours_per_day =14;


% Calculate Daily Energy Production (Wh)
daily_energy_production = energy_production_per_hour * hours_per_day;


% Display the results
fprintf('Daily Energy Production : %.2f Wh\n', daily_energy_production);
```

b. Cumulative Costs

```
% Initial investment
initial_investment_solar = 1000; % dollars
initial_investment_diesel = 2000; % dollars

% Annual operational costs
annual_cost_solar = 300; % dollars
annual_cost_diesel = 1000; % dollars

% Time frame
years = 0.5:0.5:10; % Array representing years from 0.5 to 10 with 0.5
increments

% Calculate cumulative costs over time
cumulative_cost_solar = initial_investment_solar + annual_cost_solar *
years;
cumulative_cost_diesel = initial_investment_diesel + annual_cost_diesel *
years;

% Create a graph
plot(years, cumulative_cost_solar, 'b', years, cumulative_cost_diesel, 'r');
```

```
xlabel('Years');
ylabel('Cumulative Cost (Dollars)');
title('Comparison of Cumulative Costs: Solar vs. Diesel Manual');
legend('Solar-powered Machine', 'Diesel-powered Manual');
grid on;
```

APPENDIX B

ARDUINO CODE

```
#include <Arduino.h>
#include <TinyGPS++.h> // Include the GPS library

// Define motor control pins
const int wheelMotorPin = 10;  // Example pin for wheel motor
const int sweeperMotorPin = 11; // Example pin for sweeper motor

// GPS module connected via serial
TinyGPSPlus gps;
HardwareSerial gpsSerial(1); // RX, TX

// Function prototypes
void driveToWaypoint(double lat, double lon);
void setupGPS();
void readGPS();
void setMotorState(int motorPin, bool state);

// GPS waypoints
const double waypoints[][2] = {
  {34.0522, -118.2437}, // Example waypoint 1: Los Angeles, CA
  {36.1699, -115.1398}  // Example waypoint 2: Las Vegas, NV
};
const int totalWaypoints = 2;

void setup() {
  // Initialize motor pins
  pinMode(wheelMotorPin, OUTPUT);
  pinMode(sweeperMotorPin, OUTPUT);
  setupGPS(); // Setup GPS
}

void loop() {
  setMotorState(sweeperMotorPin, HIGH); // Turn on sweeper motor

  for (int i = 0; i < totalWaypoints; i++) {
    // Drive to each waypoint
    driveToWaypoint(waypoints[i][0], waypoints[i][1]);
  }

  setMotorState(sweeperMotorPin, LOW); // Turn off sweeper motor
  // Optionally, add return to start logic or loop waypoints
  while (true) {
```

```
    delay(1000); // Stop further execution
  }
}

void setupGPS() {
  gpsSerial.begin(9600); // Initialize GPS module at the correct baud rate
}

void readGPS() {
  while (gpsSerial.available() > 0) {
    if (gps.encode(gpsSerial.read())) {
      // Successfully parsed new data
      if (gps.location.isUpdated()) {
        // New location data available
        Serial.print("Latitude: ");
        Serial.println(gps.location.lat(), 6);
        Serial.print("Longitude: ");
        Serial.println(gps.location.lng(), 6);
      }
    }
  }
}

void driveToWaypoint(double lat, double lon) {
  // Placeholder for movement logic
  // Compare current GPS location with target waypoint
  // Implement driving logic based on direction and distance to waypoint
}

void setMotorState(int motorPin, bool state) {
  digitalWrite(motorPin, state ? HIGH : LOW);
}void setup() {
  // put your setup code here, to run once:

}

void loop() {
  // put your main code here, to run repeatedly:}
```