Design and Development of a Semi-Automatic Grass Cutting Machine with Integrated Suction-Based Waste Collection

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Abstract
In today's automated age, smart technologies are required to automate labor intensive tasks and improve overall operation efficiency. The traditional grass maintenance is still a challenge, which requires a lot of manual work, time and safety risks. Traditional mowing practices often do not have built-in collection systems which leads to waste spread and extra cleaning needs. The present study has suggested the design and development of semi-automatic grass cutting machine with integrated vacuum system for effective waste collection. It is a mechanical cutting blade mower that cuts accurately and also produces suction to drop the clippings into a special storage bin. A wireless mobile application enables the user to control the machine remotely, offering increased operational comfort and a safe operating distance, and cutting cleaning time considerably by combining the cutting cleaning in one synchronized process. The design is focused on a lightweight, compact and affordable design, suitable for residential, commercial and institutional green spaces. Future improvements are planned to make this a fully independent system using obstacle detection and sensor-based navigation techniques. Finally, this project is a contemporary rethinking of landscaping, combining cutting-edge mechanical design with mobile automation technologies.

Keywords: Semiautomatic grass cutter, integrated vacuum system, mobile application control, smart landscaping, waste collection mechanisms, green space maintenance

1. Introduction

Manual grass mowing is a labor-intensive task, and can be very inefficient when mowing large areas, difficult slopes or rough terrain. Due to manual operations, the operator can get fatigued and progressively reduce overall efficiency and output. In addition, conventional cutting operations generally do not have built-in mechanisms to collect the clippings, which leads to a spreading of the cuttings on the ground. This requires extra manpower for post mowing sanitation and a basic decrease in the beauty of the sites, so this project aims to develop a semi -automatic vacuum grass cutting machine in order to overcome these systemic inefficiencies. It is a specialized system that combines the cutting and collection processes in one chamber, thus saving the need of secondary cleaning processes. The cutting assembly is driven by a high-speed electric motor that rotates a precision blade at a speed capable of effectively cutting the vegetation and an integrated vacuum system creates suction for immediate transfer of the cut vegetation to an internal storage compartment. The proposed system is controlled using a mobile application, allowing for safe and efficient control from a distance in various landscapes. The four-motor drive train offers omnidirectional maneuverability, enabling the precise navigation of the machine in confined and uneven areas that are generally problem areas for other machines. Newer technology has also led to the development of autonomous and solar powered cutters, but these can be expensive, complicated and not always be able to gather clippings. In addressing these limitations, this project brings a practical and cost-effective solution that combines cutting and vacuum collection unit within a one-unit user-friendly platform. This design will simplify the maintenance process, and will not require manual post mowing clean up thus providing a better solution to residential, commercial and institutional lawn maintenance. Finally, this semi-automated system serves as a basis for future automation improvements on a scalable level and is user-friendly and controllable over the long term.

2. Literature Review

The development of microcontroller integrated systems has made substantial development in autonomous lawn mower, in which one study developed an intelligent lawn mower that uses ultrasonic sensors to detect obstacles in real time and automatically navigate around them [1]. The use of GPS Based navigation and decision-making algorithms has improved the path planning and autonomous navigation in large scale outdoor areas. These advances help increase navigational capabilities, but GPS systems are expensive and power hungry, which makes them unsuitable for low-cost, home applications [2]. Another research proposes an embedded system based smart grass cutter which emphasizes on user interaction with the embedded wireless communication and remote monitoring capabilities. Although the developments discussed in this paper contribute a great deal to connectivity and convenience, this study primarily considers the remote operation and not the complete autonomy of mowing [3].

The research that paved the way for early automatic mower systems helped to set the stage for boundary wire systems and repeated mowing to delineate operation areas and provide safety. Although these initial ideas were the foundation for automation, the systems were not integrated with current technologies like artificial intelligence, the internet of things or renewable energy sources [4]. Sensor fusion and AI with decision making have enabled the shift from simple automation to intelligent robotic mowing, enhancing navigation and obstacle detection abilities. Although these have improved the intelligence of the system, the research does not consider important aspects like energy consumption optimization, cost reduction, etc. [5]. An electrically powered autonomous mower was developed to successfully demonstrate a sustainable alternative to petrol-based mowers, which have a large impact on air pollution and noise during operation [6]. While this system did not integrate with renewable energy or include operational grass collection capabilities, it did provide enhanced operational convenience and identify the need for connectivity in smart agricultural devices via the implementation of IoT -enabled monitoring and real time alerts [7].

A novel solar powered remotely controlled grass cutter is proposed, which combines the technology of IoT, renewable energy and grass collection technology, to provide a grass management system that is both sustainable and environmentally friendly [8]. The other research suggests a multipurpose innovated and autonomous tool for the purpose of cutting grass and cleaning the floor, which is a result of the modern developments of smart automation and remote-controlled connection [9]. The use of a path memorization algorithm greatly optimized the efficiency of the navigation and the time required to run the operation without redoing the same path, thus obtaining a better energy performance of the autonomous robotic system [10].

3. Problem Definition

In today's landscape, working with grass manually is becoming less and less efficient because large and/or odd-shaped landscapes require too much time and labor to maintain. This constant fatigue of the operator leads to the fact that manual maintenance operations become impractical when they are used in residential and commercial applications on a frequent basis. In addition, the machinery used for mowing today frequently doesn't have built-in debris collection systems, resulting in debris scattered on the ground and requiring labour-intensive debris collection process. Fuel and electricity use also pose environmental and economic issues as it not only raises the running costs but also leads to air and noise pollution in the area. Therefore, it is necessary to develop a multi-functional machine which can cut and collect grass simultaneously and is energy efficient. This innovation would make landscape management much easier, giving users of all abilities a high-performance solution they can use.

4. Objectives

The main focus of the study is to come out with a effective design of semi-automatic grass cutting machine that integrates a high-speed blade with a vacuum collection system and mobile application control to stream line lawn maintenance and eliminate manual clean up. The main goals are as follows.

1. Design a strong cutting system that can cut grass evenly and quickly, in various surfaces, while maintaining operator safety.
2. To create a synchronized vacuum system which will immediately collect grass clipping while cutting, rather than requiring a manual clean up afterwards.
3. To design a small and light chassis to traverse in tight areas (residential gardens, schools, small public parks etc.).
4. To employ a 4-wheel Drive power train which provides stable traction and reliable cutting on rough steep and uneven ground.
5. To introduce a high-capacity battery system using solar energy, which will minimise reliance on fossil fuel and lower long term operational expenses,
6. To create an alternative to the traditional combustion engine mower that is low noise and zero-emission, making it suitable for low noise sensitive areas, such as the residential area.
7. To automate both the cutting and the collection, combining these two tasks in one semi-automated process, thus greatly reducing the physical effort and time needed to maintain the landscape.
8. It should be inexpensive and simple to operate and maintain and is suitable for homes, schools and small patches of grass.

5. Methodology

The method of design and development of semi-automatic grass cutting machine with vacuum system is conceptual design & system architecture, selection of components, fabrication, assembly and performance testing. The different phases of the study are discussed below:

Phase 1: Problem Identification and Needs Analysis

This section presents a complete evaluation of current garden conservation methodologies, which have historically been labor-intensive and inefficient. Accordingly, this study aims to develop an automated system designed for simultaneous waste reduction and processing. The primary design criteria encompass operational simplicity, minimal physical foot print, and optimized energy efficiency.

Phase 2: System design and component selection

In this section, several critical subsystems are identified including the blade assembly unit, vacuum suction unit and drivetrain. The procurement of power source components focused on balancing system performance with cost effectiveness and market availability. This strategy ensured that the functional requirements of the finalized device were met within established budgetary constraints.

Phase 3: Mechanical Design (CAD)

The mechanical architecture and design turned into detailed 3D modelling and assembly drawings were constructed an advanced use of ANSYS, Space Claim and Fusion 360. This virtual prototyping phase has been critical for optimizing the body geometry, positioning the blade assembly unit and collection bin.

Phase 4: CFD Simulation Analysis

In this section, a CFD analysis was performed to evaluate the airflow and particles dynamics within the vacuum device. The simulation provides with critical significance of the system entrainment capabilities and overall suction efficiency.

Phase 5: Prototype Fabrication

During the finalization of the design layout, the chassis was constructed according to the established specifications and data. Key components including the cutting motors, blades, and the vacuum system were assembled. Precise alignment of all subsystems was maintained throughout the assembly process to ensure operational accuracy.

Phase 6: System Integration & Electrical Connections

In this phase, final hardware assembly was performed alongside the establishment of electrical wiring for the motor controllers and the battery management system. The machine features a truncated square pyramid geometry design for both structural stability and user safety. The vacuum, cutting, and locomotive functions are controlled an ESP-based microcontroller, interfaced with a mobile application for remote control operation.

Phase 7: Performance Evaluation

The final phase focused on system operations performance and functional output. This evaluation confirms that the working operation of all integrated key components and subsystems, ensuring that the vacuum system and cutting assembly function works well.

6. System Development

The semi-automatic grass cutting and collection system adopts the integrated design concept, combining the structural design of the system, the power management and control principle. The system foundation is made up of a chassis, which has been optimized using computer aided design (CAD) to ensure maximum structural integrity and stability, thereby ensuring stability during operation and a strong mounting surface for the main components (figure 3 and 4). A 12v battery, located inside the frame, provides the power, with a solar panel mounted on the upper surface to give the system greater autonomy of operation and optimize energy use. The machine is fitted with a 4-wheel drive and has a fully synchronized drive system which ensures stability and maneuverability (Figure 1). Each drive unit is actuated independently for consistent traction, In the proposed system, the operations of the system are analysed by a control module located in the central or master system, which monitors and manages the power delivery and synchronizes the functioning of all mechanical and electrical components.

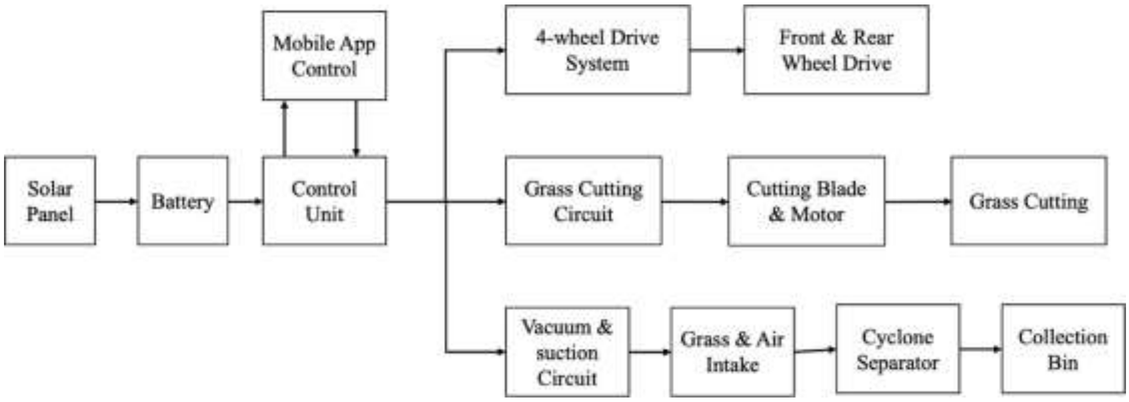

Figure 1: Power Flow diagram of proposed machine.

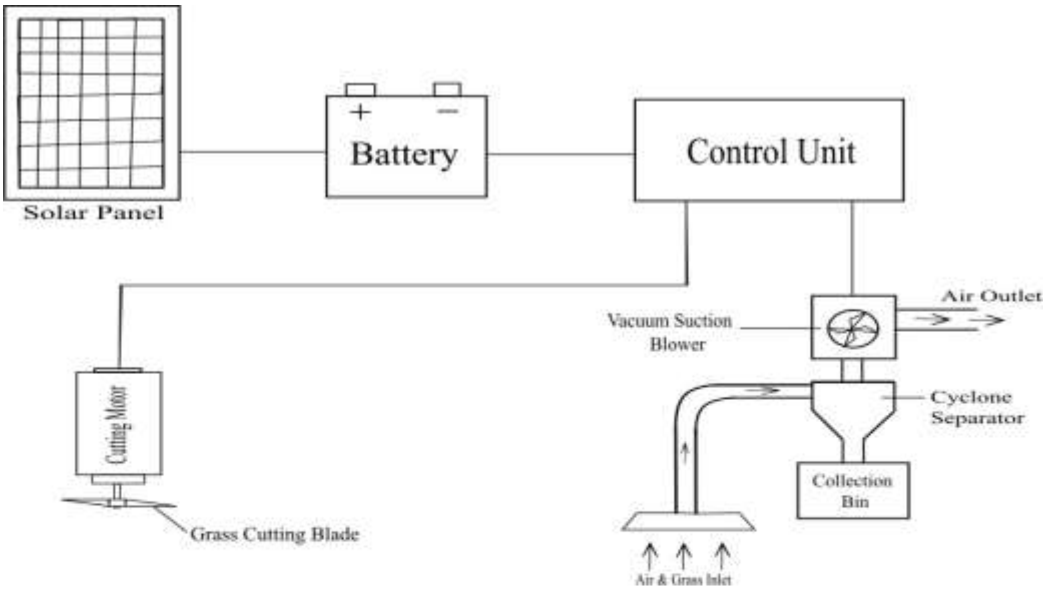

Figure 2: System architecture and Block diagram of proposed machine.

The system architecture (figure 2) includes the exact manufacture of frame, component integration and the creation of strong electrical connections. A high-speed rotary blade is optimally aligned for even and quick grass mowing. An integral part of this assembly is a vacuum collection system that is able to collect the grass clippings at the point of cutting. This system enables debris to be immediately entrained and taken through a ducting system to a centrifugal cyclone separator. This separator is efficient at removing the organic material from the air flow and deposits the clippings into a separate collection bin, eliminating the need for manual clearing of debris after mowing. A high-capacity battery system is integrated into the whole system to reduce the dependence of fossil fuels and reduce the long-term operational costs, while the system is powered by solar energy. The prototype developed, is a compact, economical and high-performance solution in terms of cutting efficiency and material collection.

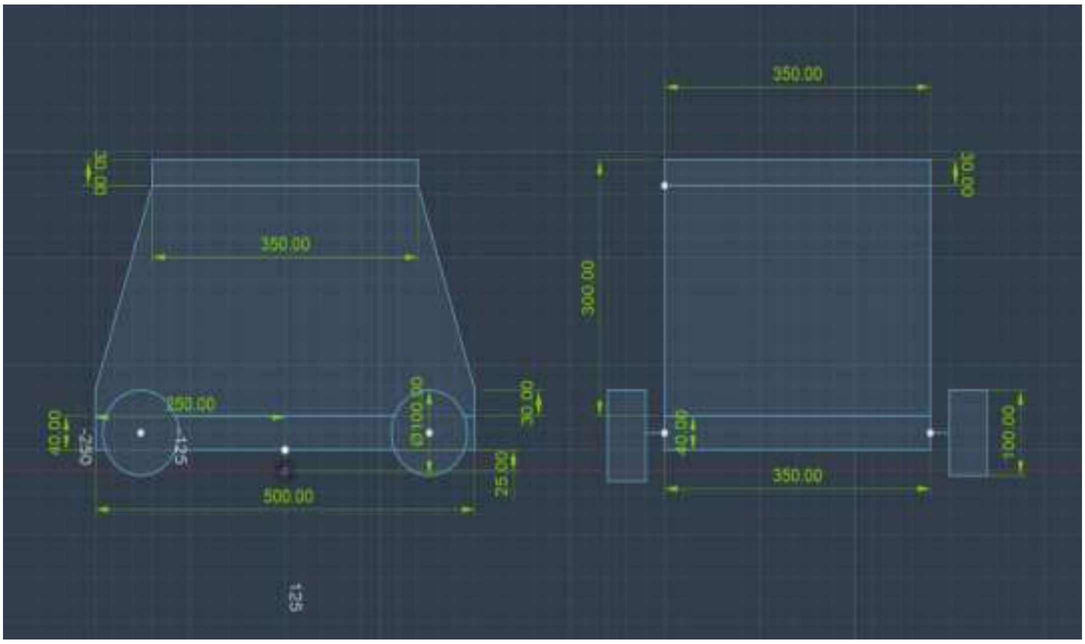

Figure 3: 2D CAD model.

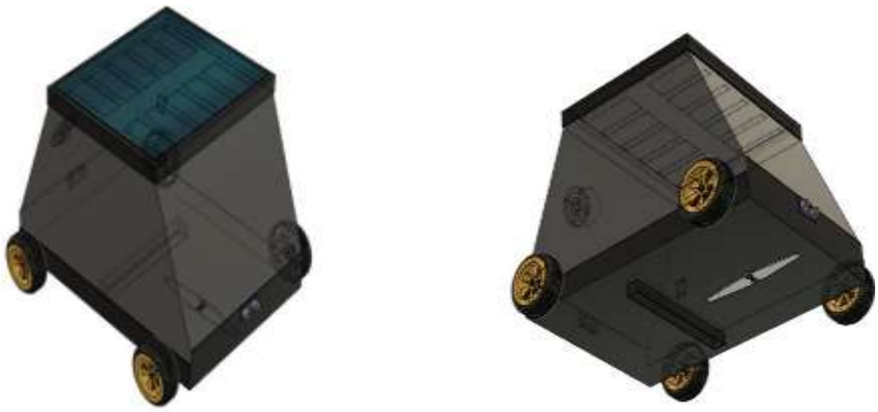

Figure 4: 3D CAD model.

7. CFD Analysis of proposed model

The optimization of the operating of the vacuum suction system in the continuum regime has become a critical need and Computational Fluid Dynamics (CFD) has become an indispensable tool for accomplishing this goal. With CFD, engineers can obtain a detailed visualization of the inside flow field by numerically solving the Navier stokes equation and thus pinpoint areas of high energy loss and potential clogging spots. By analyzing the pressure distribution, velocity profiles and particle trajectories.

The purpose of this study is to determine the best geometric configuration to obtain the maximum pick-up efficiency with minimum power consumption. The computational domain includes the entire suction assembly, which consists of the intake nozzle, a primary suction duct, a 90^0 elbow transition, a cyclone separator and a terminal exhaust outlet (Figure 5).In order to resolve the complex fluid dynamics involved in geometries with high curvature as well as the high gradient regions in the cyclone chamber, a spatially localized mesh refinement strategy (Figure 6) was used. Targeted refinement is performed in the duct bends, and at the core of the cyclone, which allows for capturing of important flow phenomena like the separation of the boundary layer and the formation of a vortex, while also optimizing the computational efficiency and being mesh independent.

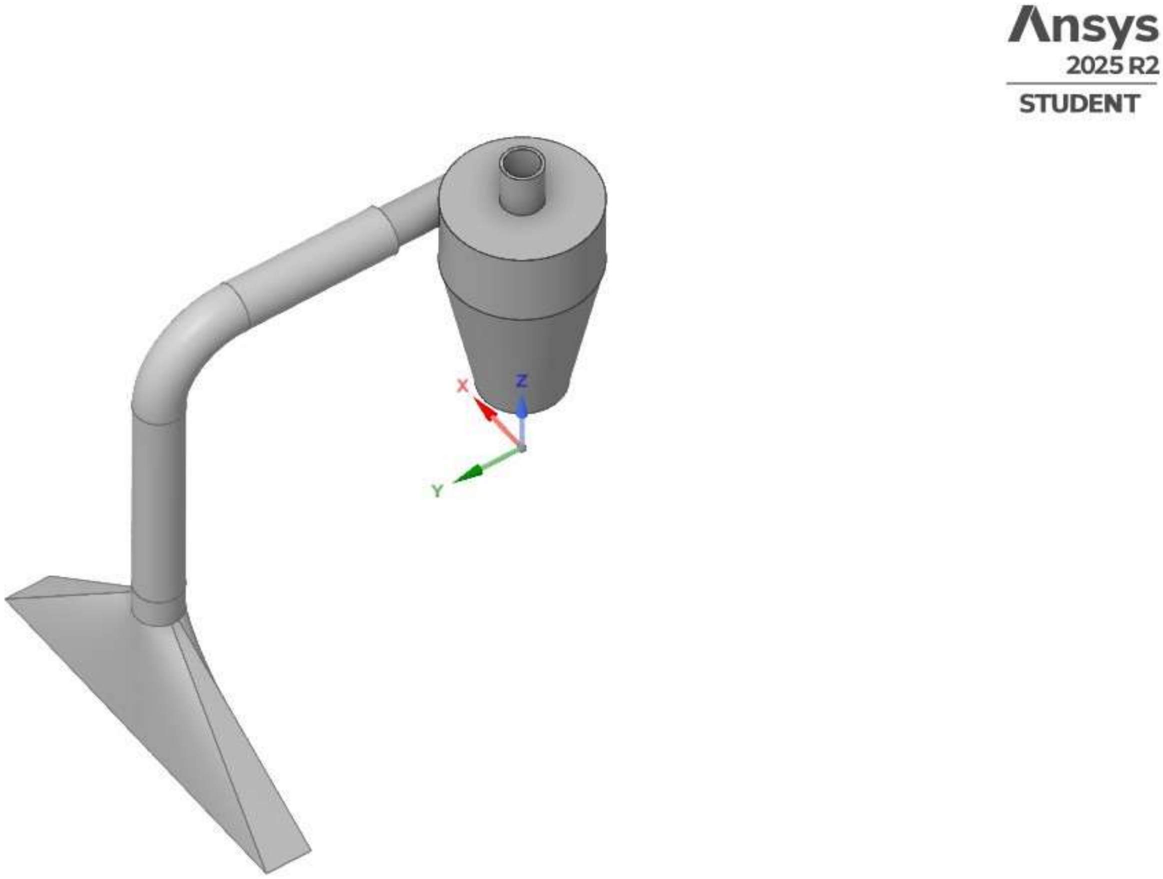

Figure 5: 3D model used in CFD analysis

Figure 6: Meshed image of proposed model.

The static pressure contour map shows the large pressure variations which are significant in the suction process throughout the assembly. The analysis shows that there are three pressure zones. The highest static pressure is found at the intake nozzle and is approximately equal to 1.47 x105 Pa. This is the stagnation point where the velocity of the fluid is relatively low and is being accelerated into the suction duct, with the fluid entering the primary duct, a sharp pressure drop is seen. A slightly higher pressure is observed in the outside radius of the 90^0 elbow when compared to the inside radius of the elbow, a typical effect of centrifugal force in curved flows that can affect the impingement pattern of particles. The lowest static pressures measured are around -4.29 x104Pa, this occurs most in the cyclone separator. This high negative pressure gradient is essential to keep this vortex flow necessary to separate grass clippings from the air flow in centrifugal separation. The overall pressure drop from inlet to cyclone exhaust, represents the energy required by the vacuum source. The flow path in the primary duct appears smooth, indicating an efficient flow path where momentum and turbulence losses are minimal, except for the abrupt changes at the cyclone inlet where the contours get steeper, indicating a high turbulence and momentum exchange region. The pressure profile shows that the system operates with enough vacuum to prevent system clogging and provides continuous vacuum.

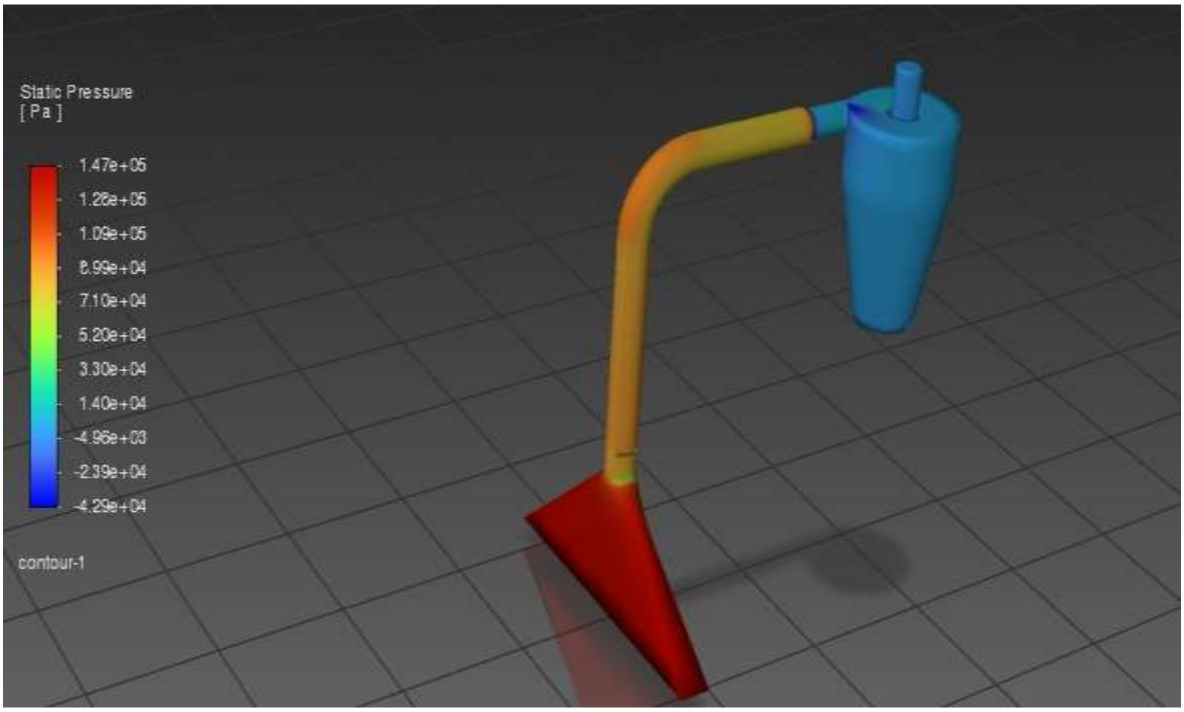

Figure 7: Static Pressure Contour.

The particle path lines illustrate the lagrangian trajectories of individual particles as they are accelerated from the suction inlet through the ducting and in to a cyclone separator. The dense ,swirling patterns observed within the cyclone separator indicate the development of a strong vortex ,which is critical for using centrifugal force to separate particulate matter from the air flow, these visualizations allow for the identification of potential stagnation points or areas of high turbulence that could negatively impact the suction efficiency of the vacuum system.by analyzing these specific flow paths, the design can be refined to minimise pressure losses and ensure that the captured dust is consistently channeled into the collection chamber. The computational fluid dynamics study shows that the vacuum system design can create suction keep the air moving fast and separate the grass particles effectively.

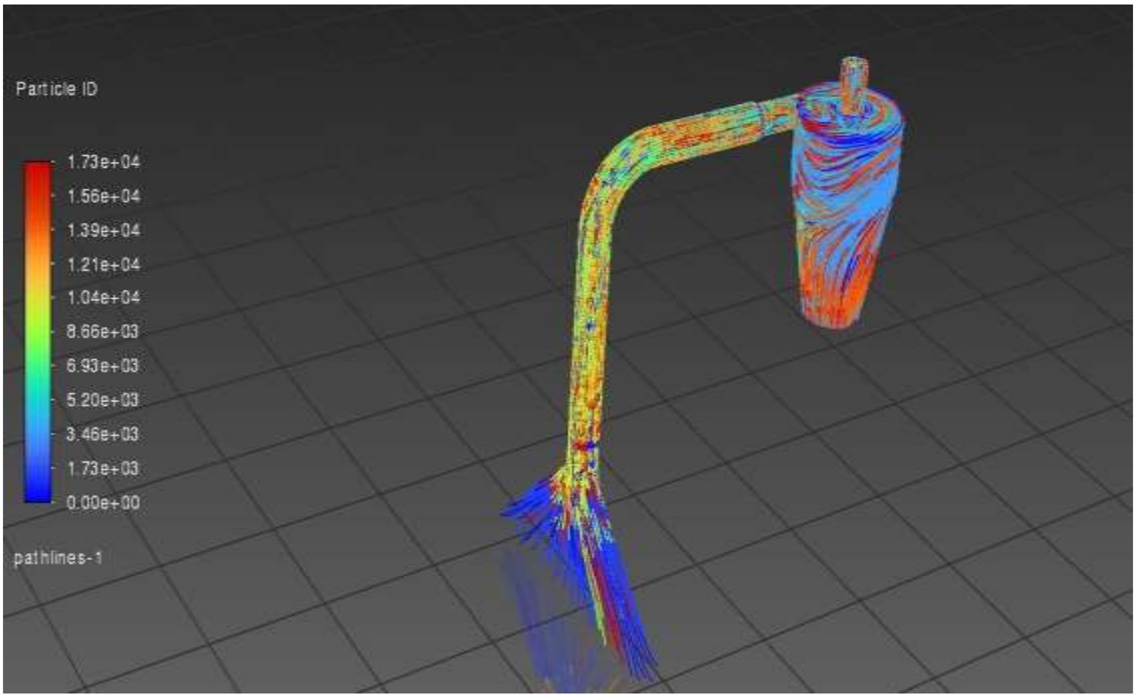

Figure 9:Particles path lines.

8. Proposed Model

Figure 10: Fabricated model.

The developed semi-automatic grass cutting and collection system represents a green and sensible advance in the modern era of lawn maintenance. By integrating dual operational capabilities for simultaneous grass cutting and vacuum-assisted collection the system notably reduces the need for manual efforts after operation. This included feature now not only optimizes average productivity, but guarantees modern garden maintenance with minimal human intervention. The successful integration of the cutting mechanism, vacuum system, mobility unit and onboard power source validates the systems operational reliability and stability

9. Conclusion

The design is mechanically stable and reliable in operation, by integrating a cutting mechanism, a pneumatic vacuum system, a mobility unit and an on-board solar power -battery system. The solar charging system further enhances productivity and promotes sustainable garden care, reducing the need for manual effort. The system design is compact and low in maintenance, and thus, provides a low cost and flexible solution to applications in landscaping. Finally, this work provides a well-defined system design framework for future development of autonomous, multifunctional utility systems.

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