PEOPLE'S DEMOCRATIC REPUBLIC OF ALGERIA

MINISTRY OF HIGHER EDUCATION AND SCIENTIFIC RESEARCH

SAAD DAHLAB UNIVERSITY OF BLIDA 1

FACULTY OF TECHNOLOGY

MECHANICAL ENGINEERING DEPARTMENT

Final Thesis

With a view to obtaining the Master’s Diploma in Mechanical and Productive Manufacturing

Theme:

Development of a Solar Panel Cleaning Robot

Accomplished by:
SEFFAH Sahnoune.
MORSLI Mohammed Amine.

Supervised by:
Mr. CHETTIBI Taha.

Academic year : 2023 / 2024

ACKNOWLEDGMENT

We would like to express our special thanks of gratitude to our teacher Dr CHETTIBI Taha who gave us the golden opportunity to do this piece, which also helped us in conducting this research. Secondly, we would also like to thank our parents and friends who helped us a lot in finalizing this work within the limited time frame.

We are overwhelmed in all humbleness and gratefulness to acknowledge our depth to all those who helped us to put this thesis together within its ideas, well above the level of simplicity and into something concrete. With God’s guidance and plenty of sleepless nights we present this piece of art.

Master Table

List of Table

Table of ANEX

List of Figures

Abstract:

This project explores the development of an innovative solar panel cleaning robot aimed at enhancing the efficiency and longevity of solar energy systems. The study is structured into five comprehensive chapters, each addressing distinct aspects of the project.

Chapter 0: Generalities
The introductory chapter provides an overview of energy sources, focusing on their definition and importance. It classifies energy sources into fossil fuels and renewable energy sources, discussing coal, oil, natural gas, solar energy, wind energy, hydropower, and biomass energy.
Chapter 1: Solar Energy and Solar Panels
This chapter delves into solar energy and solar panels, examining their significance and the impact of dust and dirt on their performance. It presents an overview of solar panel technologies and emphasizes the necessity for effective cleaning to maintain optimal efficiency.
Chapter 2: State of the Art of Cleaning Robots
The second chapter reviews existing solar panel cleaning robots available in the market, categorizing them into autonomous, semi-autonomous, and manual cleaning systems. It evaluates various cleaning methods and identifies their strengths and limitations, providing a basis for the development of a more efficient cleaning robot.
Chapter 3: Functional Analysis of the System
This chapter presents a detailed functional analysis of the proposed solar panel cleaning robot. It includes both external and internal functional analyses and defines the primary and constraint functions. Functional analysis tools such as FAST (Function Analysis System Technique) and SADT (Structured Analysis and Design Technique) are employed to develop a comprehensive functional requirements specification. The chapter concludes with a functional requirements document.
Chapter 4: Design and Realization of the Robot
The final chapter focuses on the design and implementation of the solar panel cleaning robot. It presents detailed CAD models, including sub-assemblies and complete assemblies, and dimensions the principal elements. The chapter also covers the electrical and software components of the robot and includes images of the final prototype. The design phase culminates in a fully functional robot capable of autonomously cleaning solar panels.

Conclusion
The project successfully demonstrates the design and realization of an efficient and practical solar panel cleaning robot. This innovation is expected to significantly improve the performance and maintenance of solar energy systems, offering a sustainable solution to the problem of dirt accumulation on solar panels. The findings suggest that further optimization and scaling could enhance the robot's capabilities and adaptability to different solar installations. Future research could explore advanced cleaning mechanisms and more robust autonomous navigation systems to expand the robot's functionality and efficiency.

Keywords: Solar energy, Solar panels, Cleaning robot, Autonomous systems, Renewable energy, Functional analysis, CAD modeling.

Résumé :

Ce projet explore le développement d'un robot de nettoyage de panneaux solaires innovant visant à améliorer l'efficacité et la longévité des systèmes d'énergie solaire. L'étude est structurée en cinq chapitres complets, chacun abordant des aspects distincts du projet.

Chapitre 0: Généralités
Le chapitre introductif fournit une vue d'ensemble des sources d'énergie, en se concentrant sur leur définition et leur importance. Il classe les sources d'énergie en combustibles fossiles et en sources d'énergie renouvelable, en discutant du charbon, du pétrole, du gaz naturel, de l'énergie solaire, de l'énergie éolienne, de l'hydroélectricité et de l'énergie de la biomasse.
Chapitre 1: Énergie solaire et panneaux solaires
Ce chapitre se penche sur l'énergie solaire et les panneaux solaires, examinant leur importance et l'impact de la poussière et de la saleté sur leurs performances. Il présente un aperçu des technologies des panneaux solaires et souligne la nécessité d'un nettoyage efficace pour maintenir une efficacité optimale.
Chapitre 2: État de l'art des robots de nettoyage
Le deuxième chapitre passe en revue les robots de nettoyage de panneaux solaires existants sur le marché, les classant en systèmes autonomes, semi-autonomes et manuels. Il évalue différentes méthodes de nettoyage et identifie leurs forces et leurs limites, fournissant une base pour le développement d'un robot de nettoyage plus efficace.
Chapitre 3: Analyse fonctionnelle du système
Ce chapitre présente une analyse fonctionnelle détaillée du robot de nettoyage de panneaux solaires proposé. Il comprend des analyses fonctionnelles externes et internes et définit les fonctions principales et de contrainte. Des outils d'analyse fonctionnelle tels que FAST (Function Analysis System Technique) et SADT (Structured Analysis and Design Technique) sont utilisés pour développer une spécification complète des exigences fonctionnelles. Le chapitre se termine par un document de cahier des charges fonctionnel.
Chapitre 4: Conception et réalisation du robot
Le dernier chapitre se concentre sur la conception et la mise en œuvre du robot de nettoyage de panneaux solaires. Il présente des modèles CAO détaillés, y compris des sous-ensembles et des ensembles complets, et dimensionne les éléments principaux. Le chapitre couvre également les composants électriques et logiciels du robot et inclut des images du prototype final. La phase de conception aboutit à un robot entièrement fonctionnel capable de nettoyer de manière autonome les panneaux solaires.

Conclusion
Le projet démontre avec succès la conception et la réalisation d'un robot de nettoyage de panneaux solaires efficace et pratique. Cette innovation devrait améliorer de manière significative les performances et l'entretien des systèmes d'énergie solaire, offrant une solution durable au problème de l'accumulation de saleté sur les panneaux solaires. Les résultats suggèrent qu'une optimisation et une mise à l'échelle supplémentaires pourraient améliorer les capacités et l'adaptabilité du robot à différentes installations solaires. Les recherches futures pourraient explorer des mécanismes de nettoyage avancés et des systèmes de navigation autonomes plus robustes pour étendre la fonctionnalité et l'efficacité du robot.

Mots-clés : Énergie solaire, Panneaux solaires, Robot de nettoyage, Systèmes autonomes, Énergie renouvelable, Analyse fonctionnelle, Modélisation CAO.

الملخص:

يستكشف هذا المشروع تطوير روبوت مبتكر لتنظيف الألواح الشمسية بهدف تعزيز كفاءة وأنظمة الطاقة الشمسية وزيادة عمرها الافتراضي. الدراسة مقسمة إلى خمسة فصول شاملة، كل منها يتناول جوانب مختلفة من المشروع.

الفصل 0: العموميات
يقدم الفصل التمهيدي نظرة عامة على مصادر الطاقة، مع التركيز على تعريفها وأهميتها. يصنف مصادر الطاقة إلى الوقود الأحفوري ومصادر الطاقة المتجددة، ويناقش الفحم، النفط، الغاز الطبيعي، الطاقة الشمسية، طاقة الرياح، الطاقة المائية، وطاقة الكتلة الحيوية.

الفصل 1: الطاقة الشمسية والألواح الشمسية
يتناول هذا الفصل الطاقة الشمسية والألواح الشمسية، ويستعرض أهميتها وتأثير الغبار والأوساخ على أدائها. يقدم نظرة عامة على تقنيات الألواح الشمسية ويؤكد على ضرورة التنظيف الفعال للحفاظ على الكفاءة المثلى.

الفصل 2: التطور التقني لروبوتات التنظيف
يستعرض الفصل الثاني الروبوتات التنظيفية المتاحة في السوق، ويصنفها إلى أنظمة ذاتية التشغيل، شبه ذاتية التشغيل، والتنظيف اليدوي. يقيم الفصل أساليب التنظيف المختلفة ويحدد نقاط القوة والضعف فيها، مما يوفر أساسًا لتطوير روبوت تنظيف أكثر كفاءة.

الفصل 3: التحليل الوظيفي للنظام
يقدم هذا الفصل تحليلًا وظيفيًا مفصلًا للروبوت المقترح لتنظيف الألواح الشمسية. يشمل التحليل الوظيفي الخارجي والداخلي ويحدد الوظائف الأساسية والقيود. مع التركيز على توصيف المتطلبات العامة والمحددة للروبوت و دفتر الشروط.

الفصل 4: تصميم وتنفيذ الروبوت
يركز الفصل الأخير على تصميم وتنفيذ الروبوت لتنظيف الألواح الشمسية. يقدم نماذج التجميعات الفرعية والتجميعات الكاملة، ويحدد أبعاد العناصر الرئيسية. يغطي الفصل أيضًا المكونات الكهربائية والبرمجية للروبوت ويشمل صورًا للنموذج النهائي. تكتمل مرحلة التصميم بروبوت وظيفي بالكامل قادر على تنظيف الألواح الشمسية بشكل ذاتي.

الخلاصة
يثبت المشروع بنجاح تصميم وتنفيذ روبوت تنظيف الألواح الشمسية بشكل فعال وعملي. من المتوقع أن تحسن هذه الابتكار بشكل كبير من أداء وصيانة أنظمة الطاقة الشمسية، مما يوفر حلاً مستدامًا لمشكلة تراكم الأوساخ على الألواح الشمسية. تشير النتائج إلى أن المزيد من التحسين والتوسع يمكن أن يعزز قدرات الروبوت وتكيفه مع مختلف المنشآت الشمسية. يمكن أن تستكشف الأبحاث المستقبلية آليات تنظيف متقدمة وأنظمة ملاحة ذاتية أكثر قوة لتوسيع وظائف وكفاءة الروبوت.

الكلمات المفتاحية: الطاقة الشمسية، الألواح الشمسية، روبوت التنظيف، الأنظمة الذاتية، الطاقة المتجددة.

General Introduction

General Introduction

1.1 Introduction

Energy sources are vital for modern life and are critical to the functioning of modern societies, providing the power needed for industries, transportation, and homes. They are defined as the origins from which energy is derived to perform work or produce heat. The significance of energy sources lies in their role in driving economic growth, improving living standards, and supporting technological advancements [1] [2].

Energy sources can be broadly categorized into two main groups: non-renewable and renewable. Non-renewable sources, like fossil fuels (coal, oil, and natural gas), are finite, deplete over time and have environmental impacts. Renewable sources, such as solar, wind, hydro, and geothermal energy, are in contrast sustainable, environmentally friendly, naturally replenished and offer sustainable long-term solutions [3] [4]. Transitioning to renewable energy sources is essential for reducing greenhouse gas emissions and combating climate change. Each source has advantages and challenges, requiring comprehensive strategies and technological advancements for efficient and widespread adoption.

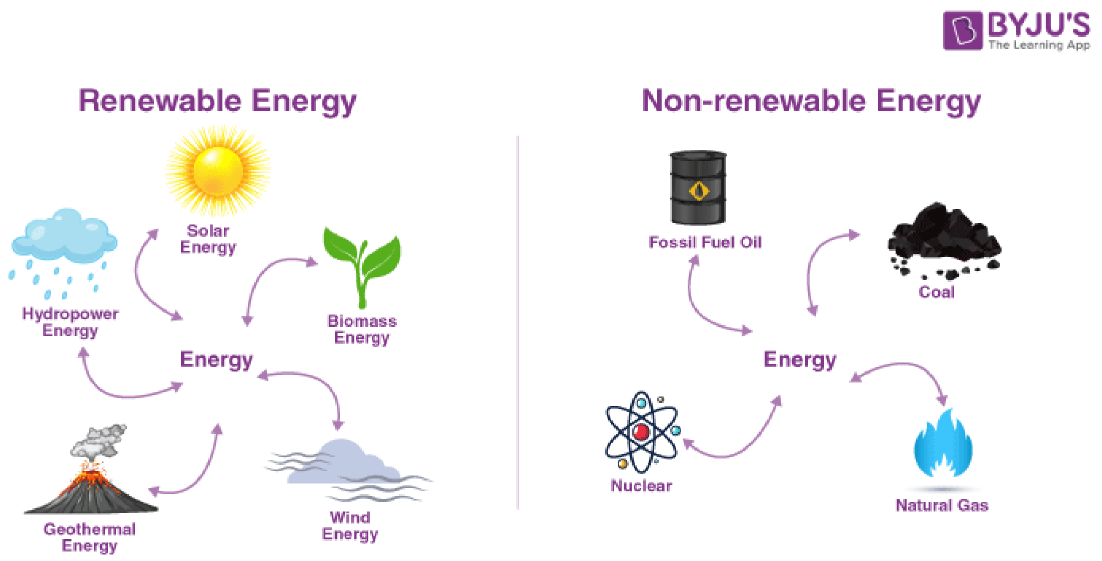


Figure 1:*Sources of energy [5].*

1.2 Fossil Fuels (non-renewable Energy Sources)

Fossil energy sources, such as oil, coal, and natural gas, are non-renewable resources that originated from the remains of prehistoric plants and animals. These remains were progressively buried by layers of rock. Over millions of years, the specific types of fossil fuels developed based on the combination of organic materials, the duration of burial, and the varying temperature and pressure conditions throughout this period [6].

Figure 2:*Non-Renewable Energy Sources [7].*

1.2.1 Coal

Coal is a combustible black or brownish-black sedimentary rock that has been a major energy source for centuries. It is primarily used for electricity generation and steel production. Despite its abundance and relatively low cost, coal combustion releases significant amounts of CO_2 and other pollutants, contributing to climate change and environmental degradation [8].

1.2.2 Oil and Natural Gas

Oil and natural gas are hydrocarbons extracted from the Earth, used extensively for transportation, heating, and electricity generation. While they are more efficient and cleaner than coal, their extraction and use still pose environmental challenges, including greenhouse gas emissions and oil spills [9].

1.3 Renewable Energy Sources

Renewable sources are energy sources that can be naturally replenished and are environmentally friendly [10].

Figure 3: *Types of Renewable Energy [11].*

1.3.1 Solar Energy

Solar energy harnesses the power of the sun through photovoltaic cells or solar thermal systems. It is one of the most abundant and sustainable energy sources, with rapidly decreasing costs making it increasingly competitive with fossil fuels. The main challenge is the intermittent nature of sunlight, which requires advancements in energy storage technologies [4] [12].

1.3.2 Wind Energy

Wind energy is generated by converting wind currents into electricity using wind turbines. It is a rapidly growing energy source due to technological advancements and declining costs. Wind farms can be located onshore or offshore, with offshore farms typically offering more consistent wind speeds [13].

1.3.3 Hydropower

Hydropower uses the energy of flowing water to generate electricity. It is a well-established and reliable source of renewable energy, contributing significantly to the global energy mix. However, it can have ecological impacts, such as altering river ecosystems and displacing communities [14].

1.3.4 Biomass Energy

Biomass energy is produced from organic materials, such as plant and animal waste. It is considered renewable because it relies on the carbon cycle, where CO_2 released during combustion is offset by CO_2 absorbed during the growth of biomass feedstock. Biomass can be used for electricity generation, heating, and as a fuel for vehicles [2].

1.4 Conclusion

Renewable energy sources, while beneficial, do present certain challenges. These include:

- High initial costs: The upfront costs of setting up renewable energy systems can be high, although they often have lower operating costs.
- Energy storage: There's a need for efficient and cost-effective energy storage solutions to ensure a steady supply of power when renewable sources are not producing.
- Infrastructure: Existing energy infrastructure is largely built around non-renewable sources, which can make integration of renewables challenging.
- Geographical limitations: Some renewable sources are location-specific, like solar for sunny regions and wind for windy areas.
- Intermittency: Wind and solar power are dependent on weather conditions and may not always be available when needed.

Additionally, Dust and dirt accumulation on solar panels can have a negative impact on their efficiency. Indeed, Solar panels convert sunlight into electricity, and any layer of dirt or dust can block some of this sunlight, reducing the amount of electricity produced. Regular cleaning and maintenance can help ensure the panels operate at their maximum efficiency. However, it's also worth noting that some studies suggest that the effects of dust and dirt accumulation may be less significant than initially thought, as rain and natural cleaning processes can help keep the panels relatively clean. Still, regular maintenance is generally recommended for optimal performance. This point is addressed in the next chapter.

Despite these challenges, many countries are actively working to overcome them and increase their use of renewable energy.

Chapter 1: Introduction to Solar Energy

Chapter 1: Introduction to Solar Energy

2.1 Introduction

The sun is the central hub of our planetary system, providing light and warmth essential for life. Humanity's progress has always been linked to harnessing this energy for food, medicine, and transportation. Solar energy, a clean and renewable source, is used globally for heating, electricity, and various applications like solar cooking and air-conditioning, making it a vital solution for meeting energy demands [15]. It's an environmentally friendly alternative to fossil fuels, reducing greenhouse gas emissions and dependence on finite resources. With advancements in technology, solar energy systems have become more efficient and affordable, making them an attractive option for both residential and commercial power generation

2.2 Definition and Basics

Solar energy refers to the energy that is derived from the sun's radiation. This energy can be harnessed and converted into various forms of usable energy, such as electricity or heat, using technologies like solar panels or solar thermal collectors. Solar energy is abundant and renewable, making it a sustainable alternative to fossil fuels for generating electricity and powering various applications. It is considered a key component of the transition to cleaner energy sources due to its environmental benefits and potential for widespread adoption. Indeed, Solar energy is pivotal in reducing greenhouse gas emissions and mitigating climate change, offering a clean, renewable, and inexhaustible energy source [16]. Here are some key aspects and benefits of solar energy:

- Renewable and Abundant: Solar energy is a renewable resource, meaning it is continuously replenished by the sun. The sun radiates an enormous amount of energy every day, far more than what is needed to satisfy global energy demand.
- Environmentally Friendly: Solar energy production generates little to no greenhouse gas emissions or other pollutants compared to fossil fuels. It contributes to reducing carbon footprint and mitigating climate change.
- Versatility: Solar energy can be used for a wide variety of applications, including generating electricity (photovoltaic solar panels), heating water (solar thermal systems), and even powering spacecraft and satellites in space.
- Cost-Effective: The cost of solar panels and solar energy systems has decreased significantly over the past decade, making solar energy increasingly affordable and cost-competitive with traditional fossil fuels in many regions.
- Energy Independence: Solar energy can contribute to energy independence by reducing reliance on imported fossil fuels, especially in regions with abundant sunlight.
- Scalability: Solar energy systems can be scaled up from small residential installations to large utility-scale solar farms, providing flexibility in deployment according to energy demand.
- Long-Term Sustainability: Solar energy offers long-term sustainability benefits by reducing reliance on finite fossil fuel resources and promoting energy security.

- Job Creation: The solar industry creates jobs in manufacturing, installation, maintenance, and research, supporting economic growth and local employment opportunities.
- Technological Advancements: Ongoing research and development in solar technology continue to improve efficiency, storage capabilities, and integration with existing energy infrastructure.

2.3 Types of Solar Panels

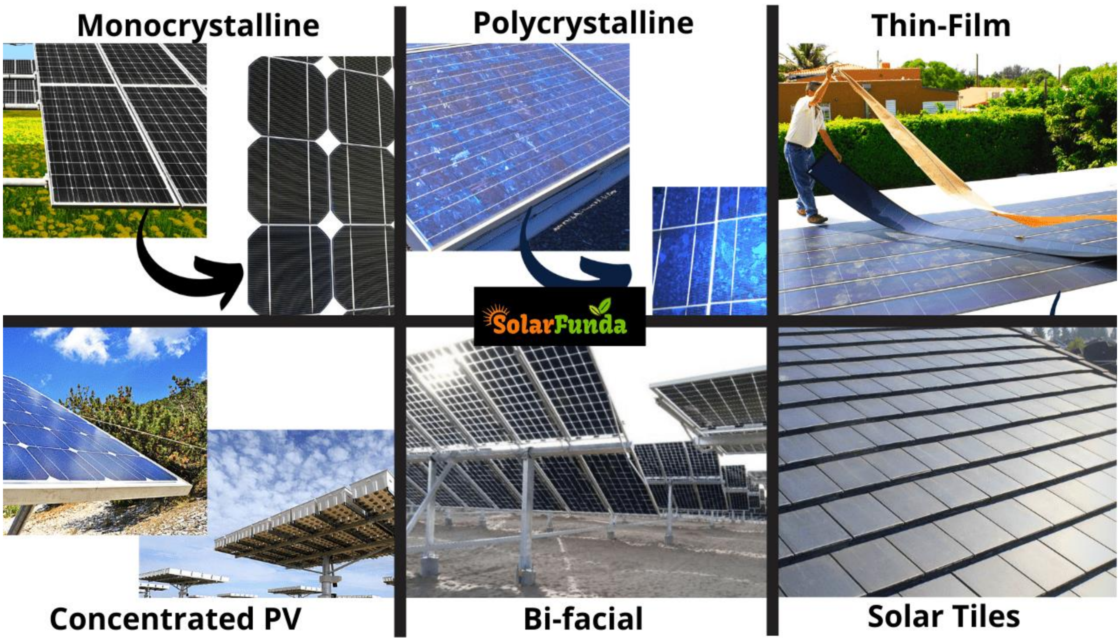


Figure 4: *Types of solar energy [17].*

Solar panels convert sunlight into electricity and come in various types:

a. ***Monocrystalline Solar Panels***: These panels are made from a single continuous crystal structure of silicon, which gives them a uniform black appearance. Monocrystalline panels are known for their high efficiency, typically ranging from 15% to 20%, and their longevity, often exceeding 25 years. They are ideal for applications where space is limited, as they produce more power per square foot compared to other types. However, they are generally more expensive to produce due to the higher purity of silicon required [18].

b. ***Polycrystalline Solar Panels***: Also known as multicrystalline panels, these are made from silicon crystals melted together to form a panel. They have a blueish hue due to the way light reflects off the silicon fragments. Polycrystalline panels are less efficient than monocrystalline panels, with efficiency rates typically between 13% and 16%. However, they are more cost-effective and have a simpler manufacturing process. They are widely used in residential and commercial installations where space constraints are less critical [19].

c. ***Thin-Film Solar Panels***: These panels are created by depositing one or more thin layers of photovoltaic material onto a substrate such as glass, plastic, or metal. Thin-film panels can be made from a variety of materials, including cadmium telluride (CdTe), amorphous silicon (a-Si), and copper indium gallium selenide (CIGS). They are flexible, lightweight, and can be produced in large areas, making them suitable for applications where traditional rigid panels would be impractical. However, thin-film panels generally have lower efficiency, ranging from 7% to 13%, and a shorter lifespan compared to crystalline silicon panels [18].

d. ***Concentrated Solar Panels***: Concentrated PV cells generate electricity like conventional photovoltaic systems but are more efficient, with an efficiency rate of up to 41%. This high efficiency is achieved by using curved mirrors, lenses, and sometimes cooling systems to focus sunlight [20].

Each type of solar panel has its advantages and considerations, such as efficiency, cost, and suitability for different applications. The choice of solar panel type often depends on factors like space availability, budget, and desired efficiency

2.4 Dust and Dirt: Sources and Composition

Dust and dirt accumulation on solar panels can significantly impact their performance. The sources include:

a. ***Natural Sources***: These include dust storms, pollen, sea salt, volcanic ash, and organic debris. Natural sources of dust vary significantly based on geographic location and weather conditions. For instance, regions with dry and arid climates, such as deserts, experience frequent dust storms that can deposit large amounts of particulate matter on solar panels. Coastal areas may encounter sea salt accumulation, while regions with significant vegetation can have pollen and organic debris settling on the panels [21].

b. ***Anthropogenic Sources***: These include industrial emissions, vehicular pollution, construction activities, and agricultural practices. Human activities can significantly increase the concentration of airborne particles that settle on solar panels. For example, industrial areas with high emissions of soot and other pollutants can lead to the rapid accumulation of contaminants on solar panels. Similarly, construction sites generate dust that can be carried by wind and deposited on nearby solar installations. Agricultural activities, such as plowing and harvesting, can also contribute to dust accumulation [22].

Figure 5: *Different types of soiling [23]*.

Understanding the sources and composition of dust and dirt is crucial for developing effective cleaning and maintenance strategies for solar panels. The chemical and physical properties of the accumulated particles can influence the choice of cleaning methods and the frequency of maintenance required.

2.5 Effects of Dust and Dirt on Solar Panels

The accumulation of dust and dirt on solar panels can lead to a significant reduction in their efficiency. This is primarily due to the obstruction of sunlight from reaching the photovoltaic cells, which reduces the amount of electricity generated. The extent of efficiency loss depends on various factors, including the type and amount of dust, the tilt angle of the panels, and the local climate conditions.

Several studies have quantified the impact of dust and dirt on solar panel performance. For instance, research showed that dust accumulation could reduce the efficiency of solar panels by up to 20% or more in heavily polluted areas. Similarly, the efficiency loss due to dust and dirt could range from 2% to 25%, depending on the severity of the contamination and the duration of exposure. Dust not only blocks sunlight but can also create "hot spots" that further damage the panels [24].

Figure 6: *Research about the efficiency loss due to dust and dirt [25].*

Regular cleaning is essential but can be costly. For instance, cleaning a 10-megawatt solar farm once can cost around $5,000. In areas with high dust accumulation, panels may need to be cleaned multiple times a year, affecting the economic returns on investment in solar energy [26].

Overall, while dust poses a significant challenge to solar panel efficiency, ongoing research and technological advancements offer promising solutions to mitigate its impact and maintain optimal performance of solar energy systems.

The rate of dust accumulation can vary depending on the location and climate. Areas with dry and windy conditions tend to accumulate more dust compared to humid regions. Pollution, pollen, bird droppings, and other environmental factors can also contribute to dirt buildup on solar panels.

Also, regular cleaning of solar panels is recommended to maintain optimal performance. Most manufacturers suggest cleaning panels at least once or twice a year, but the frequency may vary based on local conditions.

Cleaning methods should be gentle to avoid damaging the panels. Typically, using a soft brush or sponge with water and mild soap is sufficient for cleaning. Avoid abrasive materials or harsh chemicals that could scratch or degrade the panels.

While cleaning solar panels can enhance their efficiency and longevity, it adds to maintenance costs, especially for large-scale solar installations. Some systems are designed with self-cleaning mechanisms or coatings to minimize dust buildup and reduce the need for frequent manual cleaning.

Neglecting regular cleaning can lead to significant losses in energy production over the lifespan of the solar panels. Proper maintenance and cleaning help ensure that solar panels continue to operate efficiently and maximize the return on investment over their 25 to 30-year lifespan.

2.6 Cleaning Techniques

The soiling of PV modules due to dirt is one of the major issues hindering the development of the solar sector in areas with high dust density. To address this problem, the common solution is to clean the PV modules using the available cleaning resources at the PV system installation sites [27].

There are several ways to clean solar cells:

a. Dry Cleaning: The surfaces of the panels are wiped with a semi-dry cloth for small systems or using special cleaning machines for large systems. The importance of dry cleaning lies in areas that suffer from water scarcity and the difficulty of providing it when needed [28].

b. Cleaning Photovoltaic Modules with Water and Detergent: Cleaning PV modules with plain water and a cloth is the easiest and most common method worldwide. However, studies have shown that this method is effective only for small-scale PV installations, such as domestic setups and experimental platforms in solar research laboratories.

Clean, salt-free, and non-oxidizing water is used to clean photovoltaic panels, as shown in the figure, because salty water with high oxidation levels causes stains on the panel surfaces, reducing system performance efficiency [28].

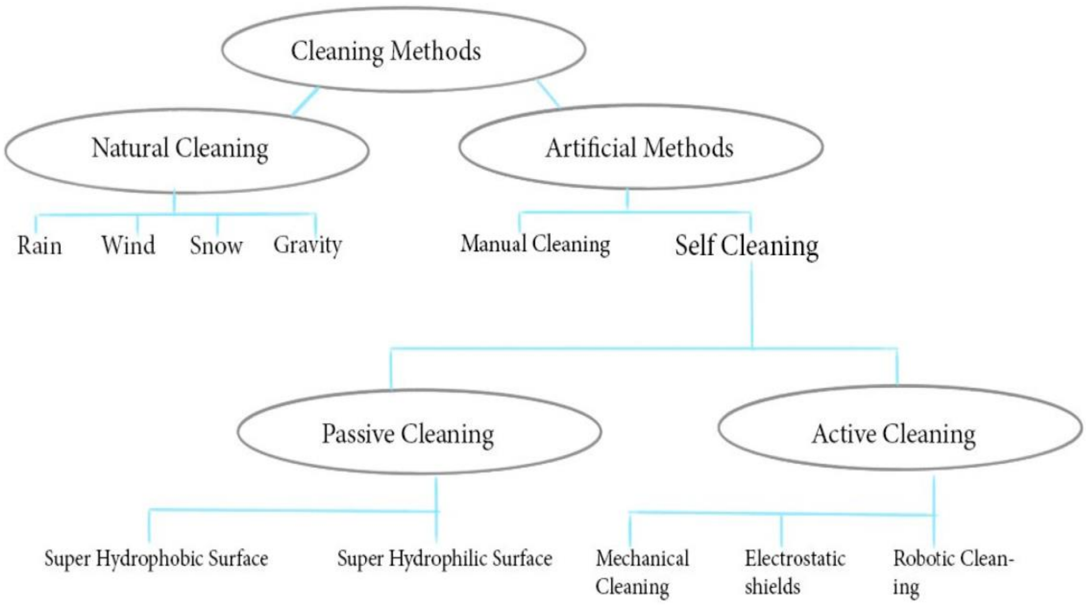


Figure 7: *Various cleaning methods [23].*

Figure 8: *Solar Cell Cleaning Machine [29].*

Figure 9: *Cleaning solar panels using water [30].*

c. Rain is not enough to clean the panels: Contrary to popular belief, rainwater is not sufficient to clean the panels of accumulated dirt over time. While it removes some dirt, it also brings new contaminants. For certain types of dirt, only mechanical action is effective. For skeptics, try a simple test: let the rain clean your car windshield without using the wipers... you will see that it remains very dirty [31].

Figure 10: *Effects of rain on solar panels [32]*.

d. Seasonal Cleaning: Over time, pollution deposits on solar panels interfere with their ability to absorb sunlight.

- Spring Cleaning: This removes pollen and atmospheric pollutants brought by early rains.
- Summer Cleaning: This is when solar panels produce the most, so they need to be in perfect condition.
- Autumn Cleaning: During the summer, panels heat up, causing various pollutants to adhere to the surface.
- Winter Cleaning: Light intensity decreases, and days get shorter. Cleaning panels during this period optimizes their production and keeps the installation free of pollutants until spring [32].

e. Cleaning PV Modules with a Robot: The first robotic PV module cleaning devices were manufactured in the United States, specifically in Boston. This cleaning method involves moving the main cleaner vertically along rails fixed to the edges of the solar panels. The robot is generally combined with an automatic low-pressure water injection system to clean dirt from the PV modules [28].

Figure 11: *Solar panel cleaning robot [28].*

In addition to the previously discussed methods, several other advanced techniques are used for cleaning photovoltaic (PV) modules, including:

- **Electrostatic Cleaning:** Utilizes electrostatic forces to repel and remove dust and dirt particles from the surface of the PV modules.
- **Water Injection Cleaning:** Employs high-pressure water jets to thoroughly clean the module surfaces, effectively removing stubborn contaminants.
- **Titanium Dioxide Cleaning:** Involves the application of a titanium dioxide (TiO_2) coating, which uses photocatalytic properties to create a self-cleaning surface when exposed to sunlight.

2.7 Conclusion

Photovoltaic systems are exposed to numerous faults that reduce their performance efficiency and return on investment, which can lead to serious consequences related to public safety. In this chapter, we have presented the various faults affecting PV system panels, accompanied by definitions of the most commonly used key terms in the PV fault domain and methods of elimination (different types of cleaning). We have shown that these faults can generally be categorized into manufacturing defects, faults due to weather conditions (shade effects, module soiling), and operational conditions (aging of PV modules).

Our concern in the present study is dust and dirt accumulation on solar panels which are a common issue that can reduce their efficiency and energy output. Indeed, Dust and dirt on solar panels reduce the amount of sunlight reaching the photovoltaic cells, thereby decreasing the panels' efficiency in converting sunlight into electricity. Studies have shown that even a thin layer of dust can lead to a noticeable drop in energy production, especially in arid or dusty environments.

Regular cleaning and maintenance are essential practices to mitigate these effects and ensure optimal performance of solar energy systems. Our project aims to develop an automatic system for cleaning solar panels and to maintain their optimal functioning.

Chapter 2:

State of the Art of Solar Panel Cleaning Robots

Chapter 2: State of the Art of Solar Panel Cleaning Robots

4.1 Introduction

The rise of solar energy as a primary renewable resource necessitates the development of efficient maintenance solutions, particularly for cleaning solar panels. Dust, dirt, and other residues significantly reduce the efficiency of solar panels. Traditional cleaning methods are labour-intensive and may not be feasible for large solar farms, thus driving the innovation of automated cleaning robots. This chapter provides a comprehensive review of existing solar panel cleaning robots, categorized by their navigation systems and cleaning methods, and evaluates their characteristics, advantages, and disadvantages. [33]

Solar panel cleaning robots are automated systems designed to efficiently and effectively clean solar panels without the need for manual intervention. They are designed to remove dust, dirt, bird droppings, pollen, and other debris that can accumulate on solar panels over time. They use various cleaning mechanisms such as brushes, squeegees, wipers, or jets of water to dislodge and remove debris from the panel surface.

4.2 Classification of Solar Panel Cleaning Robots

Solar panel cleaning robots can be classified based on their degree of autonomy: autonomous, semi-autonomous, and manual systems. Each category employs different technologies for navigation and cleaning.

4.2.1 Autonomous Robots

Autonomous robots leverage advanced sensing technologies and algorithms to navigate independently across solar panel arrays. In fact, automated robotic systems are equipped with sensors and programming to navigate across the surface of solar panels, detecting areas that need cleaning and avoiding obstacles. Among commonly used techniques for navigating we present three primary methods:

- Cameras and Vision Systems: Robots utilize cameras and computer vision algorithms to perceive their surroundings, identify obstacles, and plan cleaning paths. Advanced techniques like Simultaneous Localization and Mapping (SLAM) enable real-time environment understanding and dynamic adaptation. [34]

- LiDAR: Robots like employ LiDAR technology for precise 3D mapping and obstacle detection. LiDAR offers high accuracy and operates effectively in low-light conditions, making it suitable for complex environments. [34]
- Ultrasonic Sensors: Robots rely on ultrasonic sensors for short-range obstacle detection and proximity sensing. While cost-effective, they offer limited range and may struggle in highly cluttered environments. [34]

4.2.1.1 Examples of Autonomous Robots

Hereafter we present some examples of existing **Autonomous cleaning Robots**

i. SolarCleano F1

Figure 12: *SolarCleano F1 Robot.[35]*

- Characteristics: Fully autonomous cleaning robot equipped with advanced navigation algorithms and obstacle detection capabilities. It utilizes a rotating brush system to effectively clean solar panels, ensuring thorough removal of dust and debris. This robotic system operates independently, navigating across solar arrays with precision to optimize cleaning efficiency. Its autonomous functionality minimizes the need for human intervention, enhancing maintenance operations in solar energy installations [35].

ii. Ecoppia E4

Figure 13: Ecoppia E4 Robot.[36]

- Characteristics: Employs an electrostatic cleaning method using microfiber cloths, effectively removing dust and debris from solar panels without water. It's designed for arid environments, optimizing performance in dusty conditions typical of desert regions. Equipped with autonomous navigation, the robot moves across solar arrays independently, ensuring thorough cleaning coverage. Additionally, it features self-charging capabilities, autonomously returning to recharge stations to maximize operational efficiency in large-scale installations [37].

iii. SandStorm

Figure 14: *SandStorm Robot.[38]*

- Characteristics: An autonomous and eco-friendly solution designed to address the persistent challenge of photovoltaic panel soiling. This robotic system features self-sufficient navigation capabilities, allowing it to operate autonomously across solar arrays. It is equipped with recharging capabilities, ensuring continuous operation without interruption. One of its key strengths lies in its ability to adapt to different panel alignments, optimizing cleaning efficiency across various solar installations. SandStorm represents a versatile and effective approach to maintaining solar panel performance, emphasizing sustainability and operational autonomy in its design [39].

iv. HELIOS

Figure 15: *HELIOS Robot.[40]*

- Characteristics: A fully automated solar panel cleaning service that utilizes autonomous cleaning robots deployed on solar panels using drones. This innovative system eliminates the need for manual intervention by placing cleaning robots directly onto the panels via drones. The robots operate autonomously to clean dust and debris efficiently, ensuring optimal solar panel performance. This approach enhances operational efficiency by streamlining the cleaning process and minimizing downtime. HELIOS represents a cutting-edge solution in solar panel maintenance, integrating drone technology with autonomous robotic cleaning for enhanced performance and reliability [40].

v. Lotus A4000

Figure 16: *Lotus A4000 Robot.[41]*

- Characteristics: The Lotus A4000 is a fully autonomous and waterless solar panel cleaning robot designed for both rooftop and ground-mount photovoltaic (PV) installations. This innovative robot operates independently without the need for water, making it environmentally friendly and suitable for various environmental conditions. Equipped with advanced sensors and navigation systems, the Lotus A4000 ensures thorough cleaning of solar panels to maximize energy output. Its compatibility with both rooftop and ground installations underscores its versatility and effectiveness in maintaining solar panel efficiency. The Lotus A4000 represents a sustainable solution in solar panel maintenance, combining autonomy with eco-conscious design to optimize performance across diverse PV systems [41].

4.2.1.2 Advantages and disadvantages of autonomous Robots

- **Advantages**

- High Efficiency: They can be programmed to clean solar panels at specific times, which can help maximize energy production.[42]
- Reduced Labor Costs: They eliminate the need for manual labor, thus reducing ongoing labor costs.[42]
- Robustness and Thoroughness: They offer inherent robustness, thoroughness, reproducibility, and optimized cleaning speed when compared to traditional cleaning methods.[43]

- **Disadvantages:**

- High Initial Cost: Fully autonomous robots are often more expensive than semi-autonomous ones due to the advanced navigation technology required.[42]
- Limited Flexibility: They might struggle with complex solar installations or harsh weather conditions.[44]
- Maintenance: Regular maintenance and repairs are needed to ensure optimal performance.[44]

4.2.2 Semi-Autonomous Robots

Semi-autonomous robots require some level of human intervention, typically for setting up or initiating the cleaning process. They are using two common control methods:

- Remote Control: Robots rely on human operators using remote controls to guide their movement. This approach offers flexibility but requires constant operator attention and can be physically demanding. [45]
- Line Following: Robots utilize line sensors to follow pre-laid tracks, ensuring precise and repeatable cleaning patterns. However, this method lacks adaptability to changing environments and requires track installation, increasing deployment complexity. [45]

4.2.2.1 Examples of Semi-Autonomous Robots

i. Kiaara Robotics

Figure 17: *Kiaara Robotics System.[46]*

- Characteristics: The Kiaara Robotics solar panel cleaning system is described as “semi-autonomous” because it may require some human intervention for certain tasks, such as setup, maintenance, or moving the robot between different rows of solar panels. However, once the robot is in place and operational, it can clean the solar panels automatically without further human intervention.[46]

ii. The hyCLEANER solarROBOT

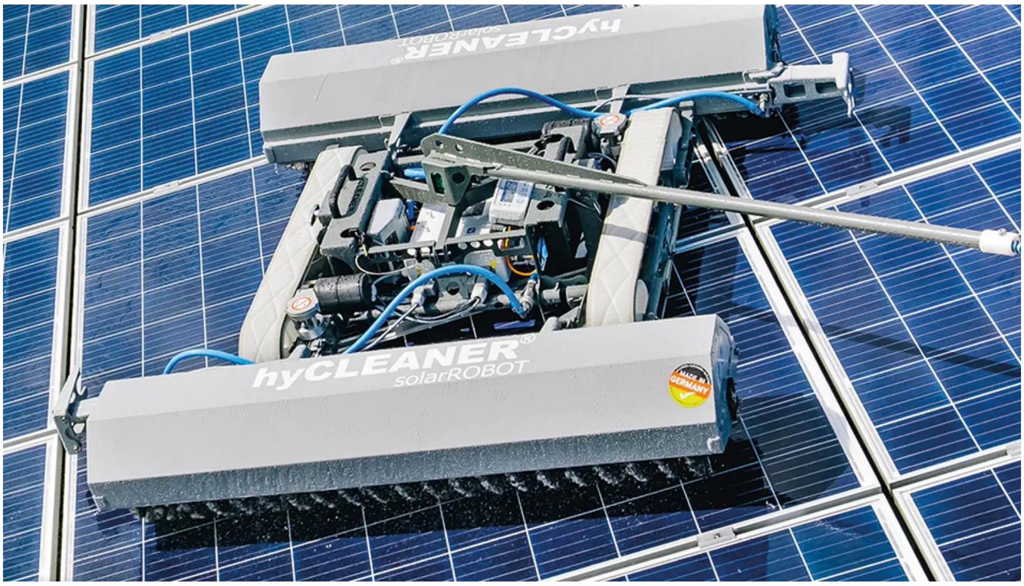


Figure 18: *hyCLEANER solar ROBOT System.[48]*

- Characteristics: The hyCLEANER solarROBOT includes a lane-keeping system and speed control. After the solarROBOT is placed on a row of panels and attached to a hose, it drives along without falling thanks to a standard edge-detection system. That system is especially crucial for rooftop and carport installations. hyCLEANER also makes a similar but more economical cleaning robot that's operated using a remote.
  solarROBOT uses only water and brushes to clean panels, with no additional cleaning agents required. The company suggests a cleaning plan tailored to the specific site, with a general recommendation of three to four cleanings per year.[48]

iii. Noccarc - Model A600

***Figure 19**: Noccarc - Model A600 Robot.[49]*

- Characteristics: The Noccarc - Model A600 is a lightweight, water-less robot designed for cost-effective solar panel cleaning. It operates directly on solar module frames, utilizing an eco-friendly cleaning method that enhances efficiency and environmental compatibility [49].

4.2.2.2 Examples of Semi-Autonomous Robots

- **Advantages:**

✓ Lower Initial Cost: Semi-autonomous robots are often less expensive than fully autonomous ones.[42]
✓ Flexibility: They can be more adaptable to different types of solar installations.[44]

- **Disadvantages:**

✓ Increased Labor Costs: They may require more labor to operate, which can increase costs over time.[42]
✓ Less Efficient: They might not be as efficient as fully autonomous robots.[42]
✓ Maintenance: Regular maintenance and repairs are needed to ensure optimal performance.[44]

4.2.2.3 Manual Systems

Manually operated robots rely on human control for navigation. They rely on a total manual where the robots are directly operated by humans using joysticks or levers. This method offers full control but can be physically demanding and prone to operator error.

4.2.2.4 Examples of Manual Systems

i. Water Fed Pole Systems

These are manual systems where a technician uses a water-fed pole to clean the solar panels.[50]

Figure 20: *Manual cleaning using water-fed pole.[51]*

ii. Soft-Bristle Brush Cleaning

People commonly use a hose and a soft-bristle brush with an extended handle to clean the solar panels.[50]

Figure 21: *Manual cleaning using Soft-Bristle Brush.[52]*

4.2.2.5 Advantages and disadvantages of Manual Systems

Advantages:

- Low Initial Cost: The primary economic advantage of manual cleaning is its low initial cost.[53]
- Adaptability: Manual systems can be more adaptable and flexible, suitable for a variety of solar installations.[54]

Disadvantages:

- Labor-Intensive: Manual cleaning can be labour-intensive and time-consuming, particularly for large-scale solar farms.[54]
- Risk of Injury: The need for physical labour introduces the risk of injury.[54]
- Inconsistent Cleaning: There’s potential for inconsistent cleaning and the risk of damage or inefficiency due to human error.[53]

4.3 Cleaning Methods

The cleaning methods employed by these robots are crucial for their effectiveness and suitability for different environments. The primary methods include brushing, vacuuming, and microfiber cleaning.

a. Brush Cleaning: This method involves rotating or oscillating brushes that physically scrub the panel surface to remove dirt and debris. [54]

b. Vacuum Cleaning: Vacuum systems remove dust and particles without making direct contact with the panel surface.[55]

c. Microfiber Cleaning: This method uses microfiber cloths, often in combination with electrostatic forces, to attract and remove dust.[55]

4.4 Comparative Analysis

To determine the best robot, we must compare based on several criteria:

a. Efficiency: Autonomous robots are highly efficient for large-scale installations due to their advanced navigation and minimal human intervention.

b. Cost: Manual and semi-autonomous robots are more cost-effective initially but may incur higher labour costs over time.

c. Water Usage: water-free cleaning is advantageous in arid regions, while other models may be less suitable due to high water consumption.

d. Maintenance: Robots with complex mechanical parts may require more frequent maintenance compared to simpler models.

4.5 Conclusion

The development of solar panel cleaning robots addresses the critical need for efficient and effective maintenance of solar installations. Autonomous robots offer advanced solutions with minimal human intervention, while semi-autonomous and manual systems provide more accessible options for various operational scales. The choice of cleaning method—whether brushing, vacuuming, or microfiber—depends on the specific needs of the installation environment.

Solar panel cleaning robots represent a promising solution to enhance the performance and longevity of solar energy systems by automating maintenance tasks and optimizing energy production. The adoption of solar panel cleaning robots is increasing, particularly in large-scale solar farms and installations where labor costs and efficiency gains are significant considerations. Technological advancements continue to improve the capabilities and effectiveness of cleaning robots, making them more attractive to solar developers and operators.

Chapter 3: Functional Analysis of the Solar Panel Cleaning Robot

Chapter 3: Functional Analysis of the Solar Panel Cleaning Robot

5.1 Introduction

The functional analysis of the solar panel cleaning robot involves a systematic breakdown of its interactions with external entities, its internal components, and their respective functions. This analysis is critical for understanding the robot's operational requirements and constraints. It is defined by a set of standards such as NF EN 1325, FD X 50-1017, NF EN 16271. The analysis is divided into two main steps: External Functional Analysis, Internal Functional Analysis.
In external functional analysis, the product user's needs are expressed in the form of service functions. So, first we state the need using the need diagram "horned beast diagram", and then we take a close look at its feasibility using the "octopus diagram". In fact, this diagram is used to identify the service functions (constraint functions) of the target product.
In the internal functional analysis, we convert the service functions into technical functions, meaning that we have to look for technical solutions that will enable us to realize the service functions already identified. This can be done using different diagrams such as FAST, SADT, or the functional diagram.

5.2 External functional analysis

5.2.1 Statement of the need

The first step of the analysis is to express the need through the establishment of the need diagram (horned beast diagram). The figure 3.1 illustrates the diagram of our system.

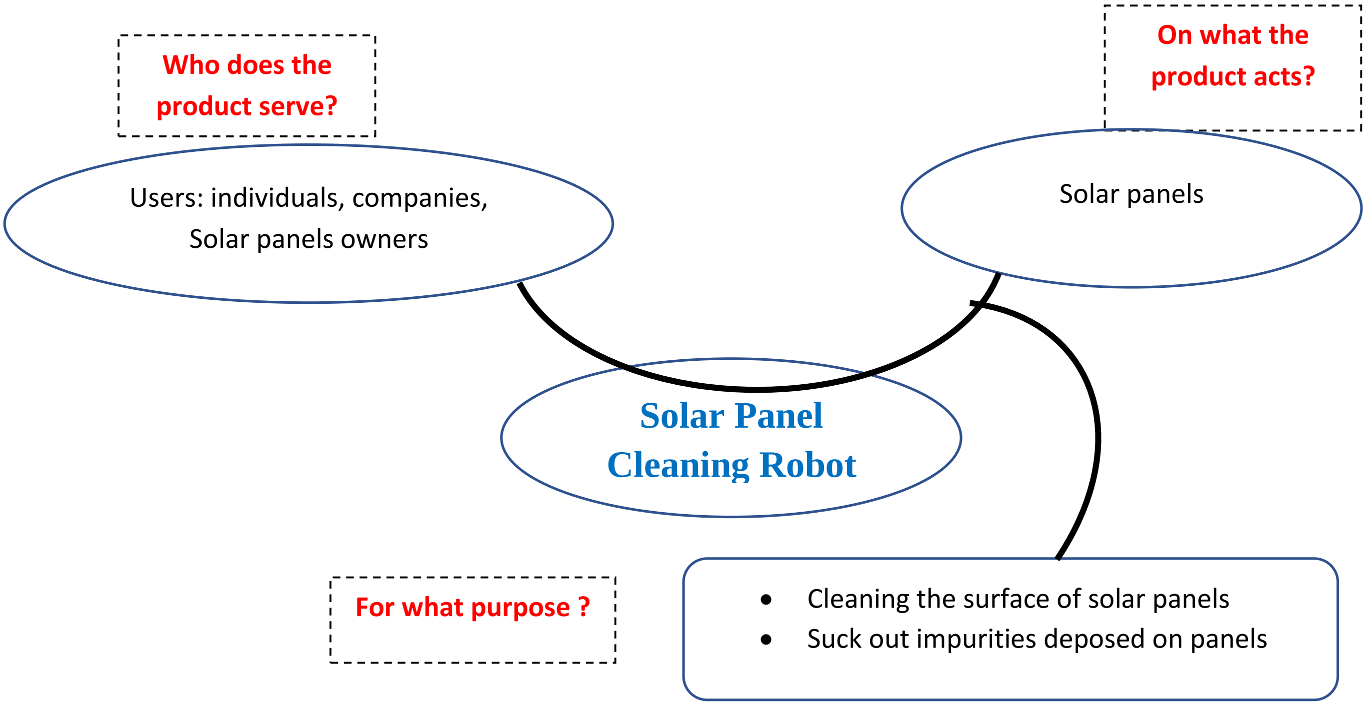


Figure 22. *Need diagram of the desired product*

5.2.2 Identifying service functions

Among objectives of external functional analysis is to **i**dentify the interactions between the solar panel cleaning robot and its external environment. The main tool to do this is Pieuvre diagram called also Octopus Diagram (Diagramme Pieuvre). An Octopus Diagram is a visual representation used in software engineering and system modeling. It illustrates the relationships and dependencies among various components, subsystems, or modules in a complex system. The name "Octopus Diagram" comes from the way the diagram resembles an octopus with multiple arms connected to a central body. In order to establish this diagram, we follow the subsequent Steps:

a) **Identify External Elements**: List all external entities interacting with the system.
b) **Identify Functions**: Determine the primary functions the system must perform in relation to these external entities.
c) **Draw the Diagram**:

Central node represents the system (solar panel cleaning robot).
Surrounding nodes represent external entities.
Arrows show the interactions (functions) between the system and external entities.

The established Octopus diagram is given by figure 3.2.

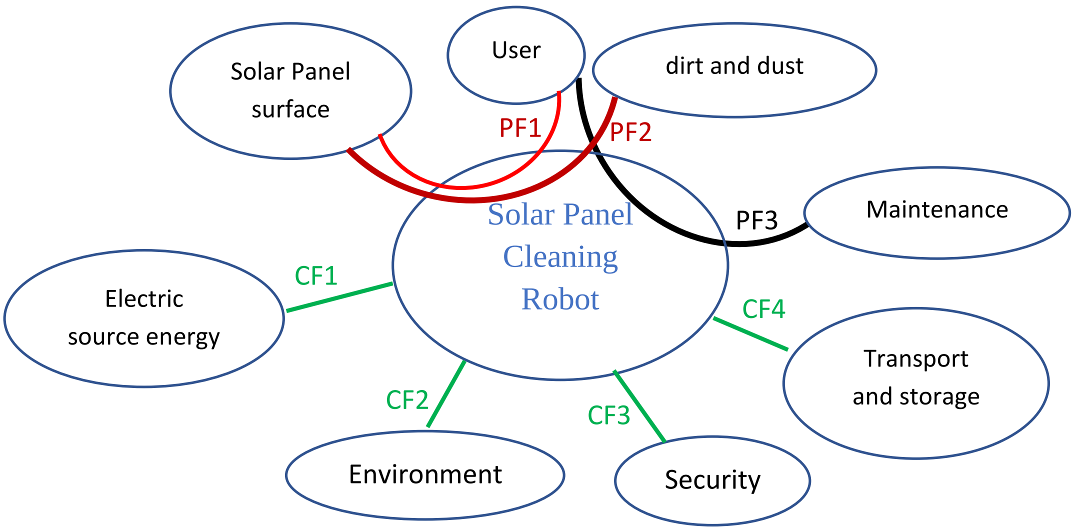


Figure 23. *Octopus Diagram of the solar panel cleaning robot*

The Principal Functions PF represent functions rendered by the product to meet a need, they are listed in table 3.1.

Table 1. *Principal Function of the cleaning robot.*

Designation	Description
PF1	Allow the user to clean the solar panel surface
PF2	Allow the user to remove/isolate dirt and dust
PF3	enable the user to carry out routine maintenance operations

The Constraint Functions CF (or service function) regroup the set of Functions allowing to adapt the product to its environment, they are given in table 3.2.

***Table 2**. Service Functions of the cleaning robot*

Designation	Description
CF1	Use electric power from appropriate source
CF2	withstand the environment in which the solar panel is installed (weather, desert, …)
CF3	comply with safety standards
CF4	can be moved and stored when not in use

Base on the above functionnal analysis, it is possible to establish the following Use case diagram

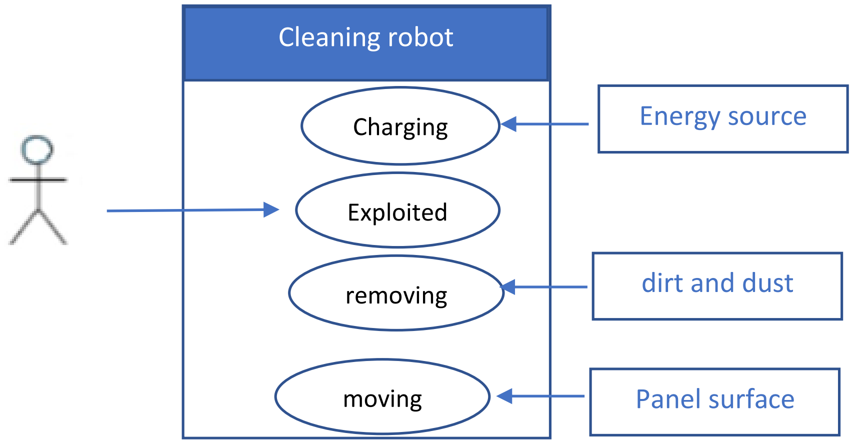


***Figure 24.** Use cases of the robot*

5.3 Internal functional analysis

When designing or studying an object, an internal functional analysis is used to show the technical functions and associated technical solutions. the design or study of an object, a functional analysis is carried out.

● Technical functions are the internal functions that enable a technical object to to perform its main function (use). A technical function is always expressed by an infinitive verb followed by a complement.

● Technical solutions are the components or elements that enable the technical functions to be carried out. technical functions.

In the internal functional analysis, we convert the service functions into technical functions, meaning that we have to look for technical solutions that will enable us to realize the service functions already identified. This can be done using different diagrams such as FAST, SADT, or the Systemic functional diagram. Systemic functional analysis is presented in the form of a functional diagram, which links the service function, technical functions and technical technical solutions. It takes place in 2 stages for the design or analysis of a technical object. For design, we identify the technical functions and then search for the correspondin solutions that are based on the specifications specifications. For the analysis, we isolate the object's components, then associate each component with the technical function it performs.

5.3.1 FAST diagram

A fist simple FAST

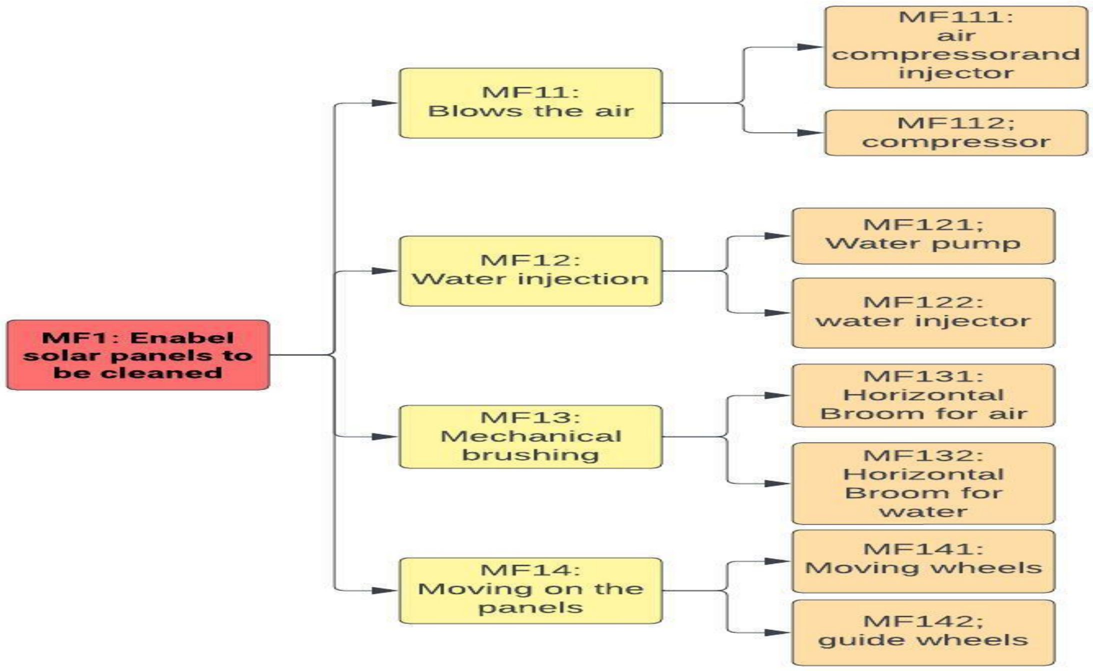


Figure 25. *Primary FAST diagram*

However, after deep analysis of existing solutions, we established a more developped Fast diagram as follows corresponding to our octopus diagram.

FAST diagram detailed

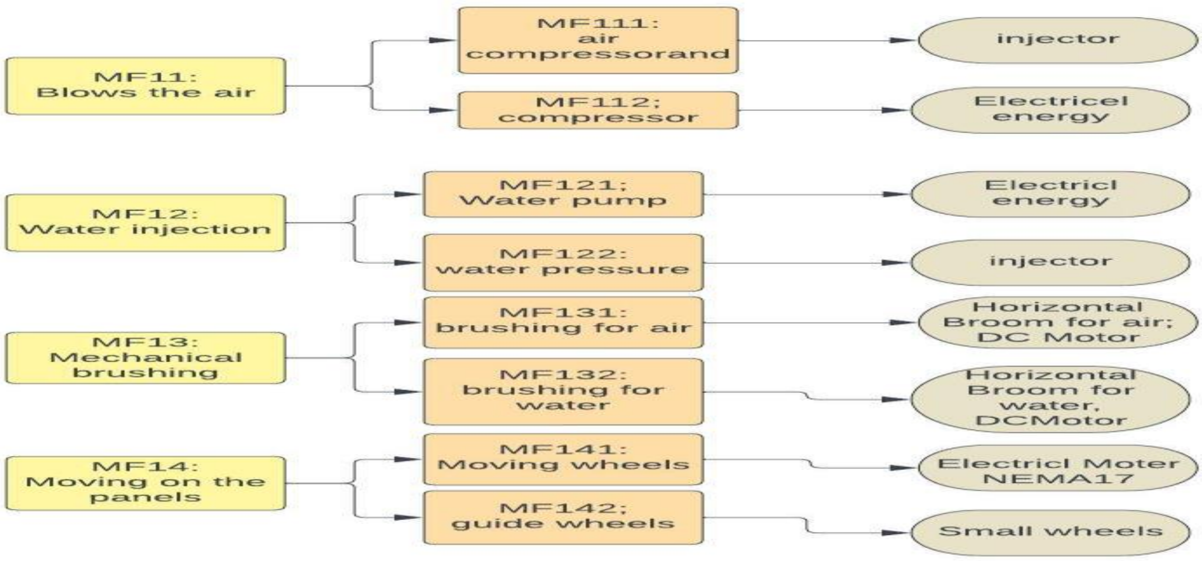


Figure 26. *FAST diagram detailed*

5.3.2 SADT Diagram

The purpose of SADT diagram is to provides a structured representation of the system's components and their interactions. Based on the fact that solar panel cleaning robots typically have the following components:

- Treads or Wheels: Allow the robot to move across the surface of solar panels.
- Roller Brushes: Clean the panels by wiping off dirt and grime.
- Water Tank: Stores water used for cleaning (in models that use water).
- Water Sprayer: Sprays water onto the panels for cleaning purposes.

The interactions between these components involve the movement of the robot across panels (treads/wheels), the cleaning action (roller brushes), and the application of water (water tank and sprayer) for those models that use water for cleaning. These components work together to maintain the efficiency of solar power production by keeping the panels clean.

A simple SADT Diagram for our system is proposed in figure 3.5.

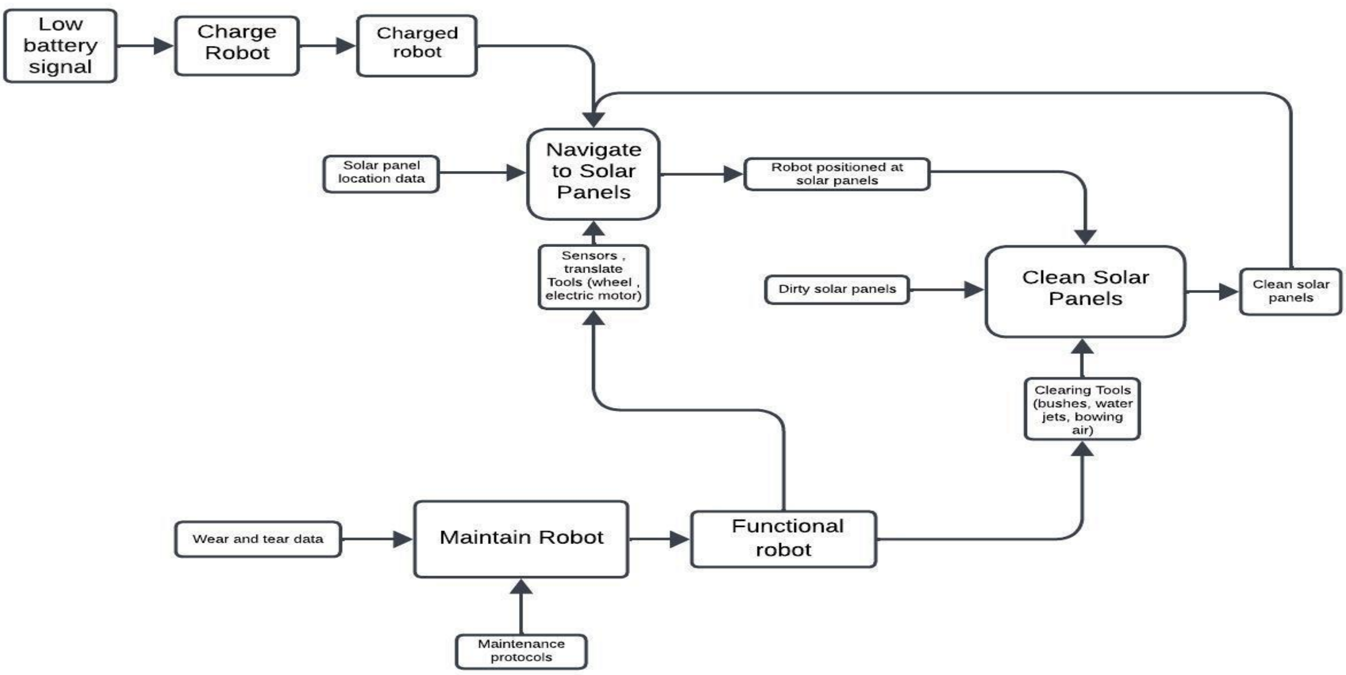


Figure 27 . *simple SADT Diagram*

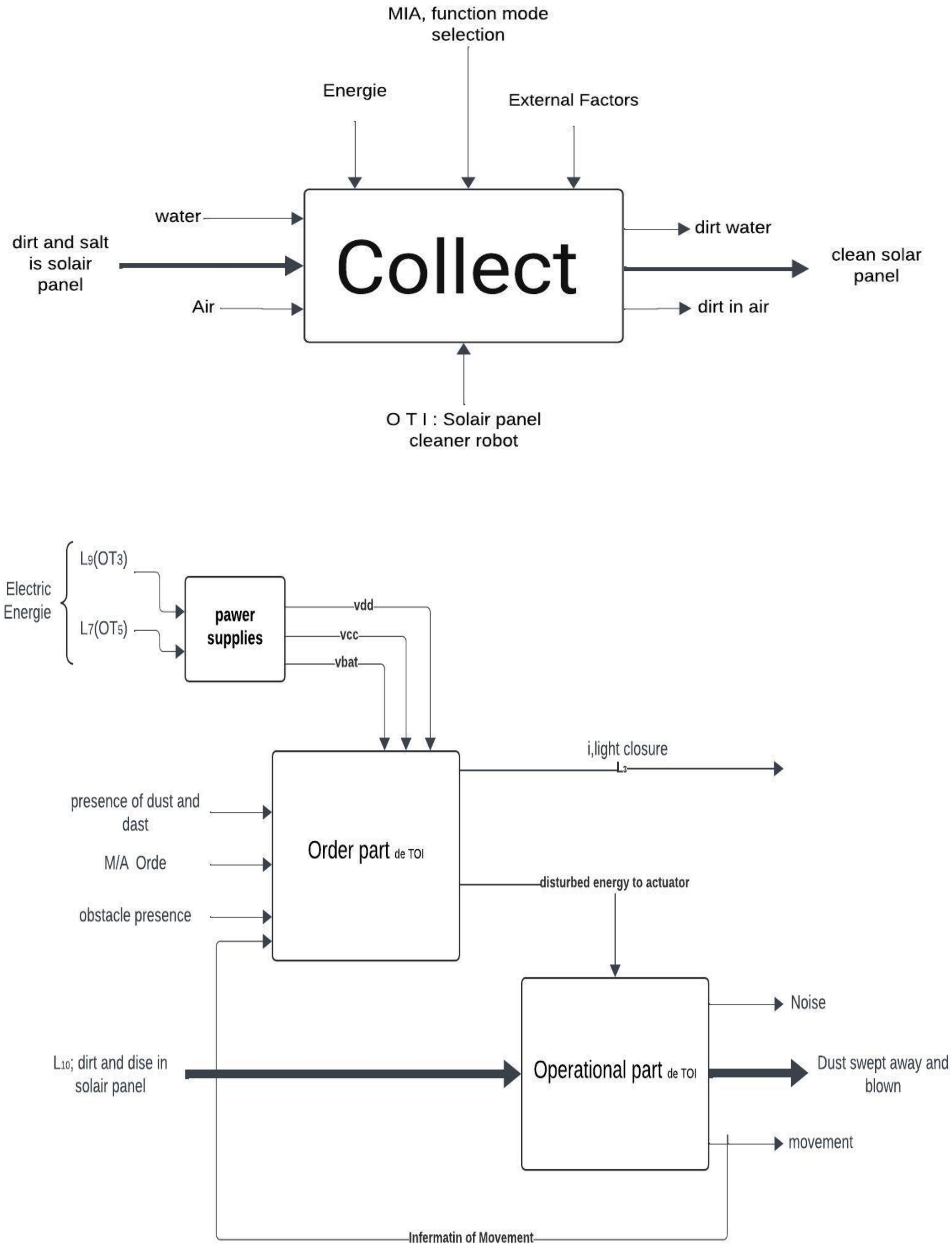


Figure 28. *Primary SADT diagram*

5.4 Requirement Specification

5.4.1 . Purpose

This document outlines the functional requirements, constraints, success criteria, and budget/planning considerations for the development, manufacturing, and deployment of the SYSTEM solar panel cleaning robot.

5.4.2 Functional Requirements

The SYSTEM is a semi-autonomous mobile robot capable of independently navigating and cleaning solar panel arrays. The following key functionalities are essential:

- Streamlined Cleaning: This robot simplifies panel maintenance by automatically cleaning along a pre-defined path, requiring occasional human oversight for optimal performance.
- Navigation: The robot employs a robust navigation system to efficiently traverse solar panel arrays, avoiding obstacles and ensuring complete surface coverage.
- Water Management: The robot utilizes water conservation techniques during the cleaning process. Water recycling or recovery systems should be incorporated for optimal efficiency.
- Cleaning Performance: The robot demonstrates a quantifiable cleaning performance metric, capable of cleaning a defined area of solar panels per unit time.
- Operational Autonomy: The robot operates for a predetermined duration on a single battery charge.

5.4.3 Constraints

The design and development of the SYSTEM robot adhere to the following constraints:

- Weight: The robot’s weight must be minimal to ensure it does not exert excessive pressure or cause damage to the solar panels.
- Weather Resistance: The robot must be operational in diverse weather conditions, including sunlight, rain, snow, and wind.
- Safety: Safety is paramount. The robot design must prioritize safe operation, eliminating any risks of falling or causing damage to the solar panels or surrounding environment.

5.4.4 Success Criteria

The success of the SYSTEM robot will be measured against the following criteria:

- Cleaning Efficiency: The robot effectively removes dust, dirt, and debris from solar panels, demonstrably improving their energy production output.
- Durability: The robot is designed for a specified operational lifespan with minimal maintenance requirements.
- Ease of Use: The robot is user-friendly, allowing for simple installation, programming, and operation.

5.4.5 Budget and Planning

A comprehensive cost estimate for the development, manufacturing, and maintenance of the SYSTEM robot shall be established.

A detailed project timeline outlining the design, testing, and production phases of the robot must be developed.

5.5 Conclusion

By conducting a thorough external and internal functional analysis and defining the main and constrained functions, we can ensure the solar panel cleaning robot is designed effectively to meet all operational requirements. The use of functional analysis tools such as the Octopus Diagram, SADT Diagram, and FAST Diagram provides a structured approach to understanding and documenting these functions comprehensively. In the next chapter we are going to expose the effective design process of our robot and discuss our realization.

Chapter 4: Design and Implementation of the Robot

Chapter 4: Design and Implementation of the Robot

6.1 CAD of the Robot (Sub-assemblies, Full Assembly)

Computer-Aided Design (CAD): is the process of digitally creating design simulations of real-world goods and products in 2D or 3D, complete with scale, precision, and physics properties to optimize and perfect the design – often in a collaborative manner – before manufacturing. [56]

6.1.1 Sub-assemblies:

6.1.1.1 Rear Section (Driving and Control Unit)

Primary Function: Responsible for propelling the robot forward and housing the main electronic components.

Sub-Components:

1. Motors:

Left Motor: Drives the left wheel.
Right Motor: Drives the right wheel.

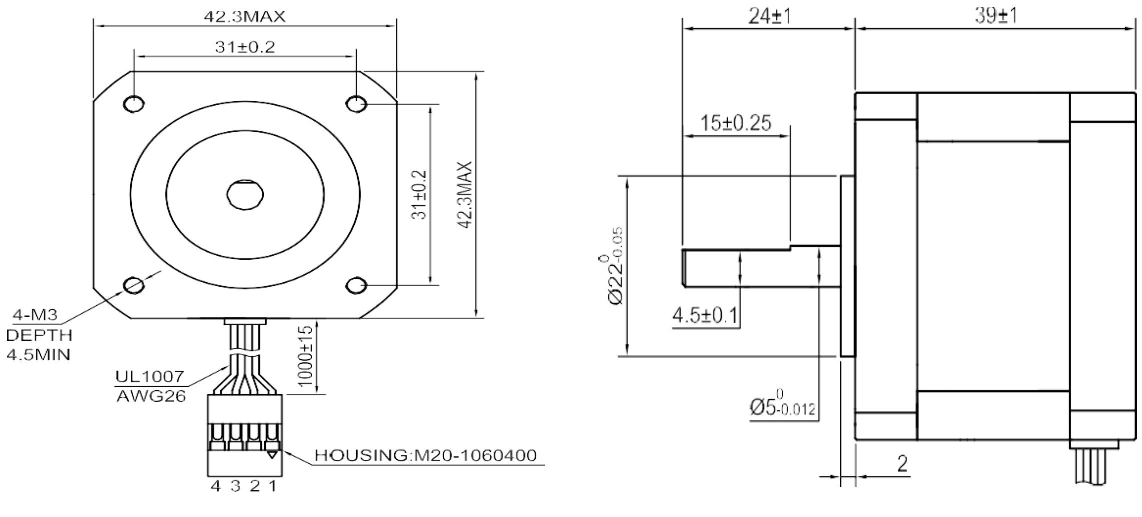


Figure 29. *Motor Nema 17*

6.2 Electronic Components:

Control Board: Manages the robot's operations and sensor data.

6.2.1 Arduino

The Arduino Mega 2560 board is a microcontroller board based on an ATmega2560

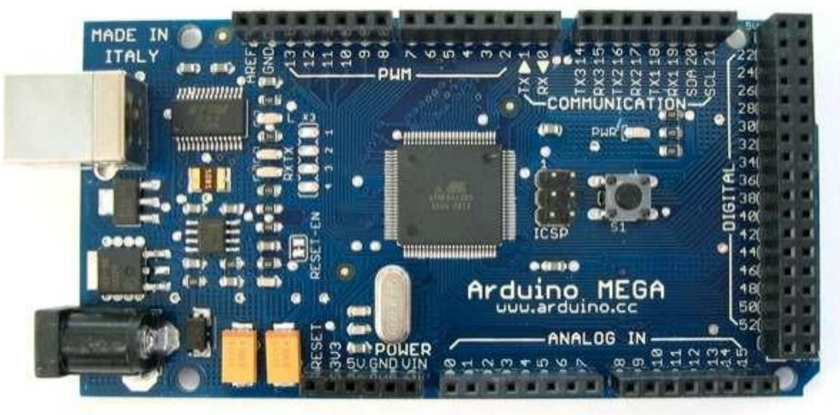


Figure 30. *View of the Arduino Mega 2560 module.*

6.2.2 Sensors:

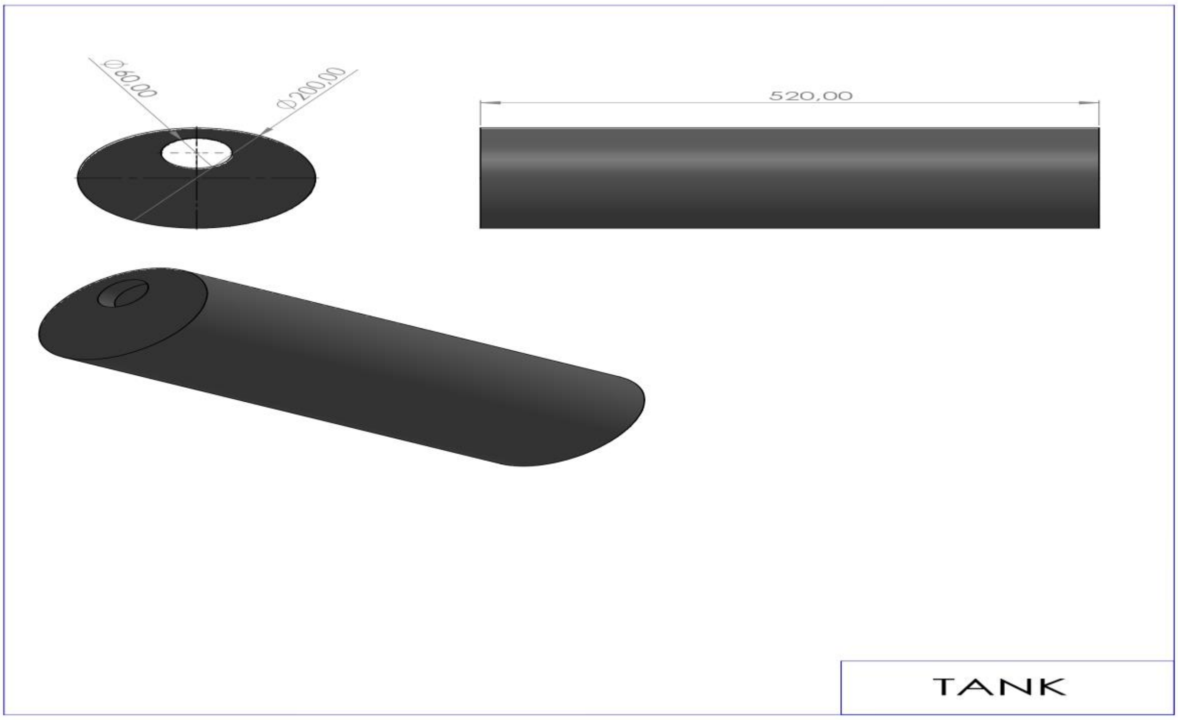
Detect obstacles, measure dirt levels, and provide feedback on the robot's environment and condition.

Figure 31. *View of the GP2D15 digital sensors*

3. Other Components:

6.2.3 Water Tank:

Cylindrical Shape: Efficient use of space and even distribution of liquid weight. Includes inlet and outlet ports for filling and dispensing the liquid, which would connect to the micro pump.



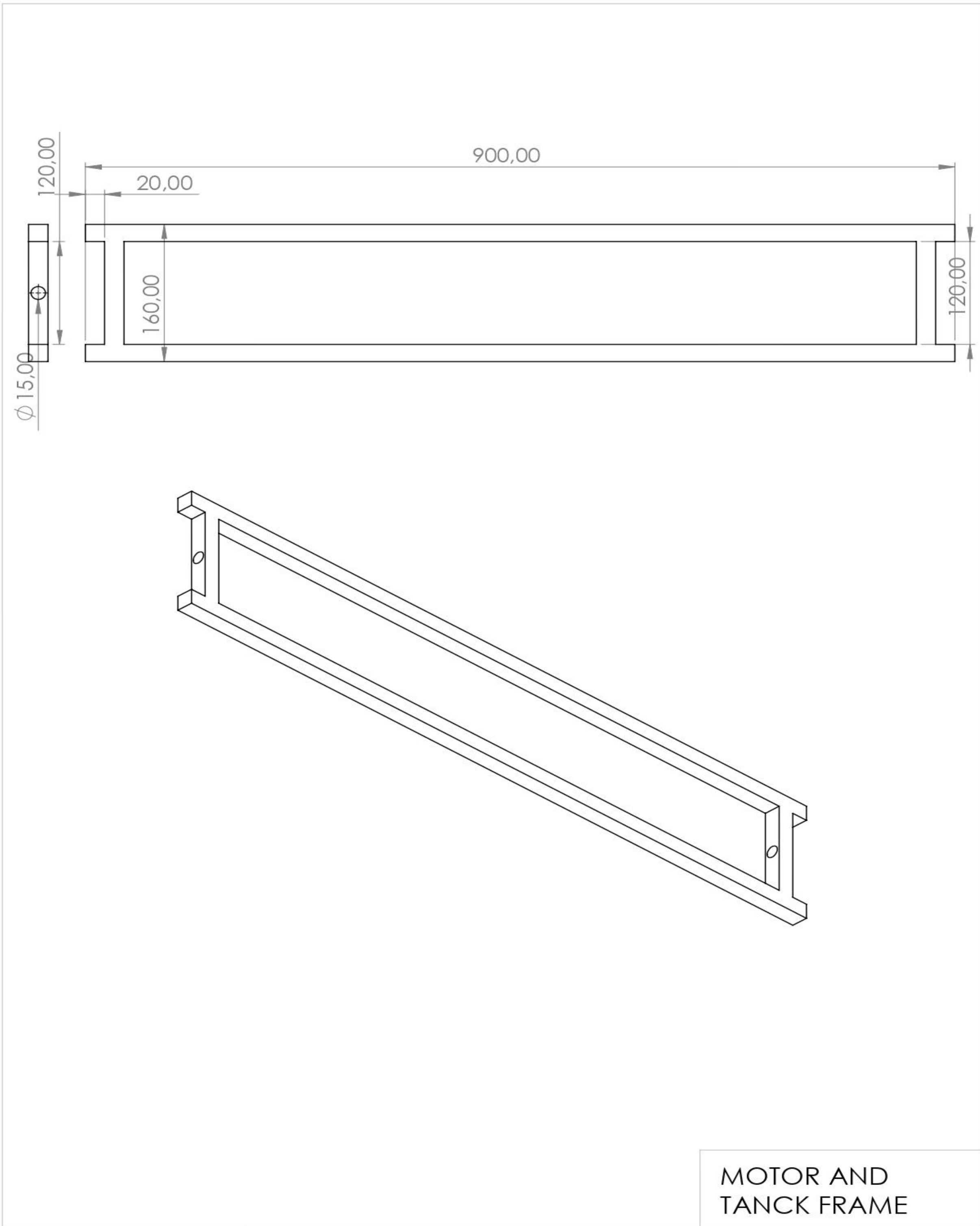
6.2.4 Water pump:

A micro pump in the context of a solar panel cleaning robot is a small, often compact pump used to circulate cleaning fluids such as water or a cleaning solution.

Figure 32 *View of the Micro Pump*

6.2.5 **Chassis Frame:**

The structural framework that supports and protects the components.

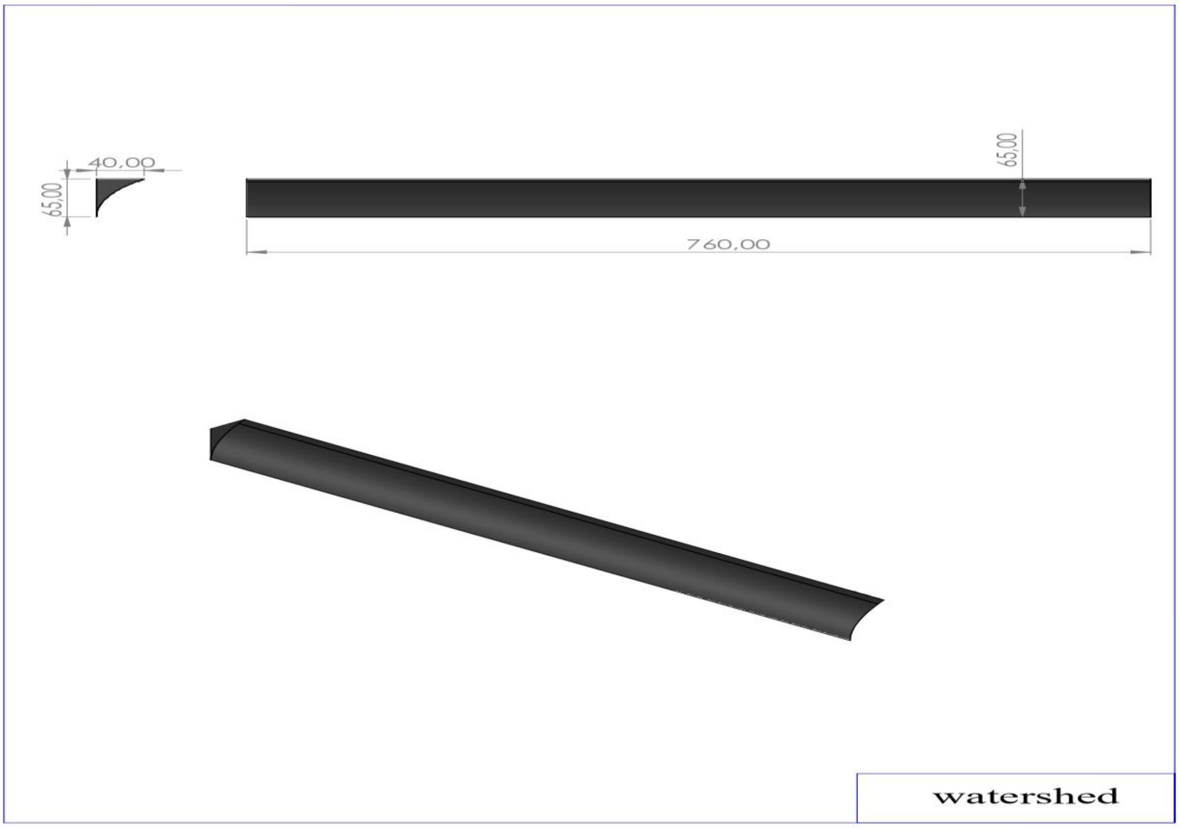

900,00
20,00
120,00
160,00
120,00
∅15,00
MOTOR AND
TANCK FRAME

6.2.5.1 Front Section (Cleaning Mechanism)

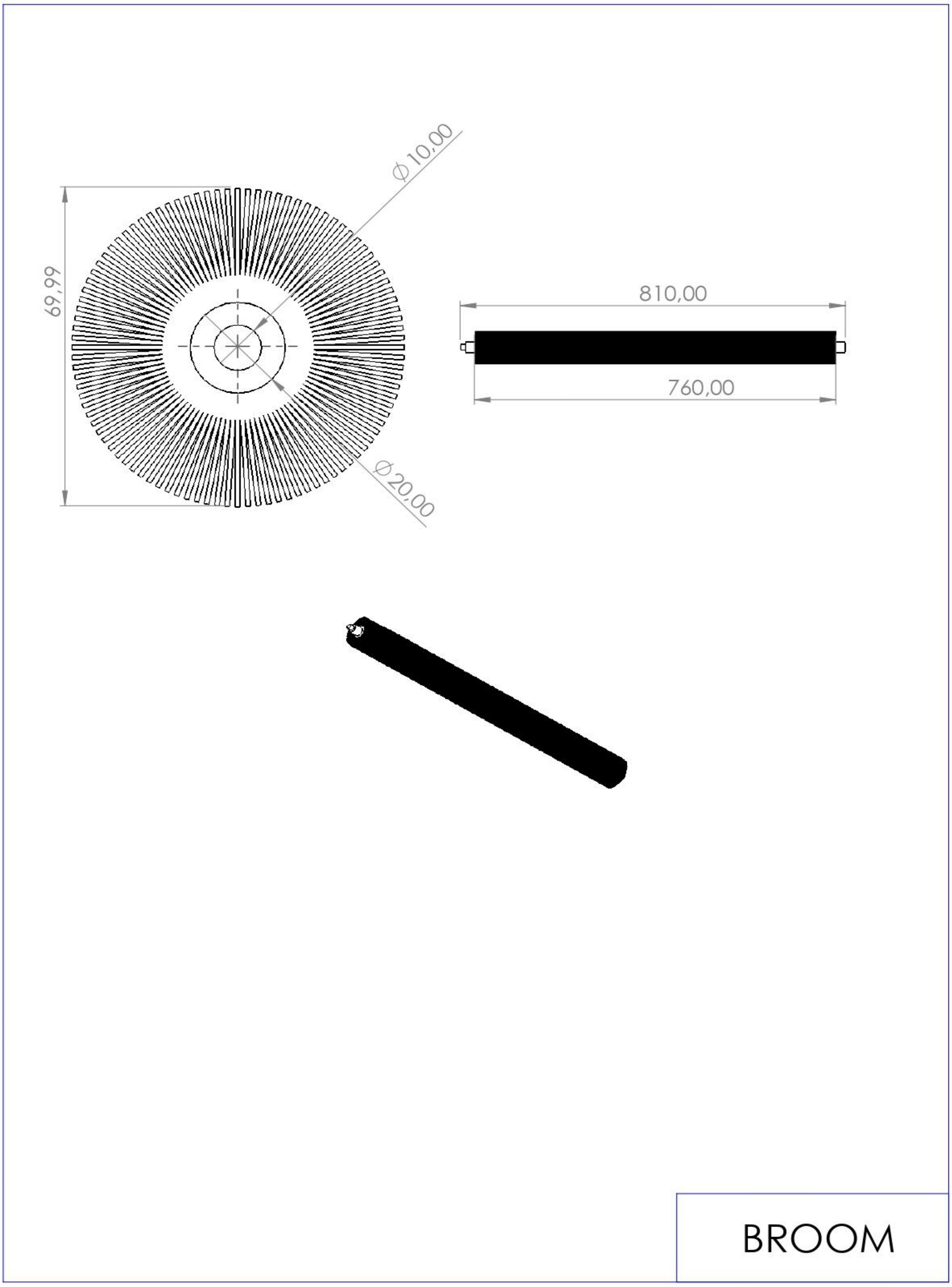
Primary Function: Responsible for the actual cleaning of the solar panels.
Sub-Components:
1. **Brushes:**

Figure 33 *Brush*

6.2.5.2 Watershed:



6.2.5.3 Brooms:



6.2.5.4 DC Motor:

Figure 34 *DC motor*

A DC motor is an electrical motor that uses direct current (DC) to produce mechanical force. The most common types rely on magnetic forces produced by currents in the coils. Nearly all types of DC motors have some internal mechanism, either electromechanical or electronic, to periodically change the direction of current in part of the motor. [57]

6.2.5.5 Injectors:

Water Injector: Sprays water onto the panels to loosen dirt.
Air Injector: Blows air to remove loose debris and dry the panels.

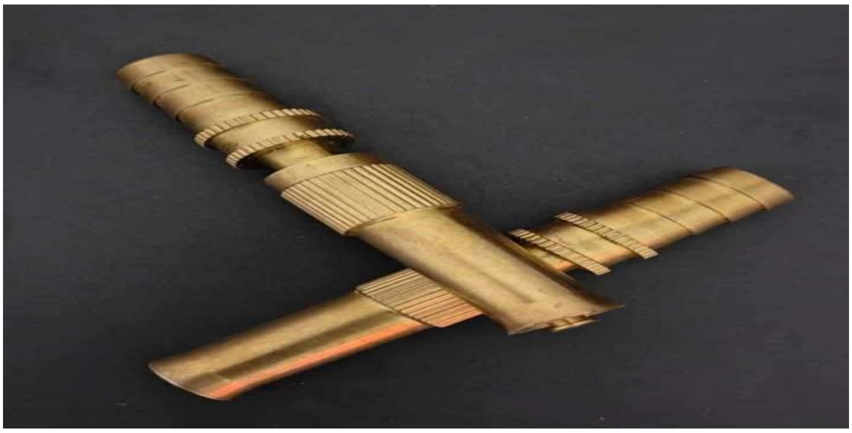


Figure 35*. View of the Injectors*

Both types of injectors are typically controlled by the robot's electronic system and can be adjusted for flow rate and direction. The design of these injectors is crucial for ensuring efficient and thorough cleaning of the solar panels.

6.2.5.6 Air Blower:

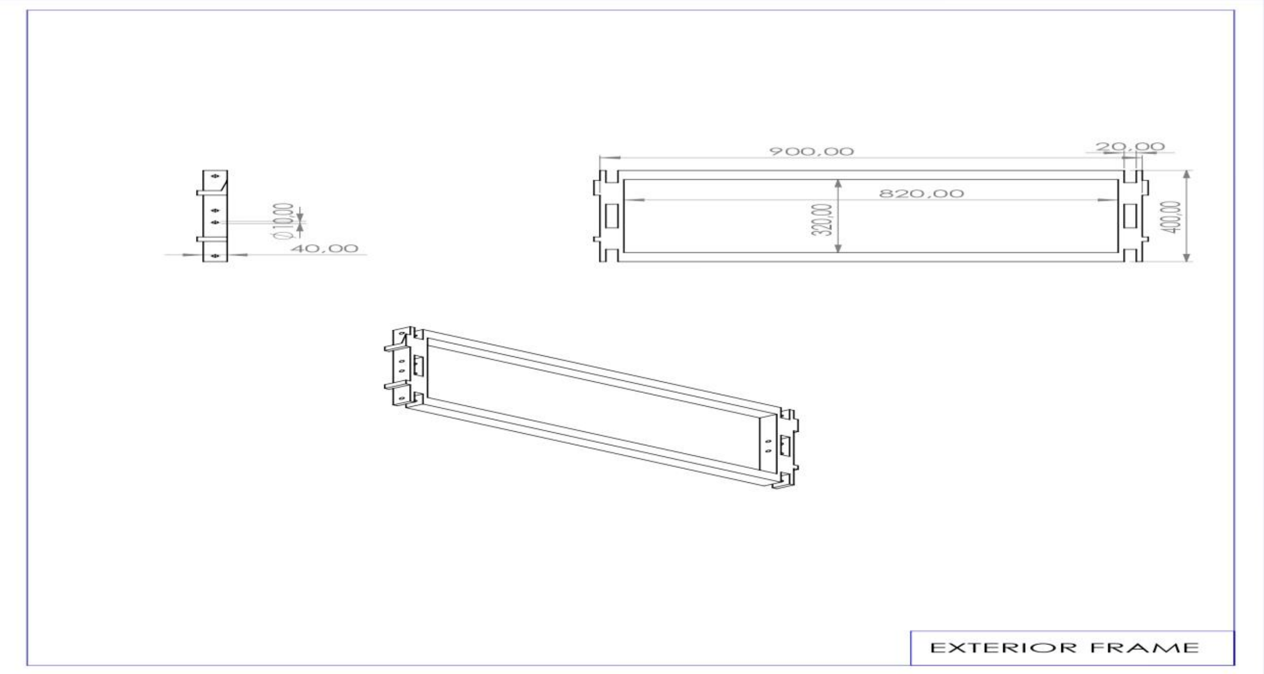
Using a car inflator, typically designed to inflate tires, as an air blower for a solar panel cleaning robot is an innovative idea. Here's how it could work:

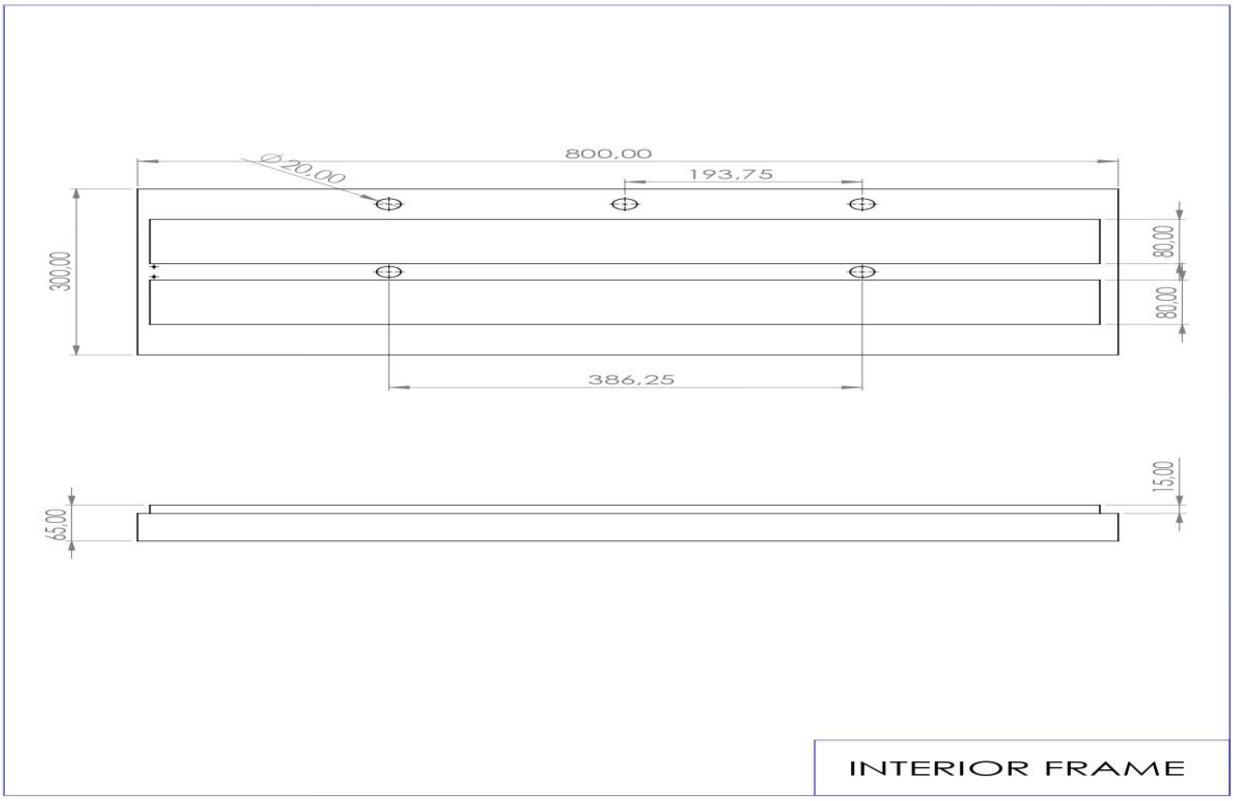
Figure 36. *View of the air blower*

6.2.5.7 Chassis Frame:

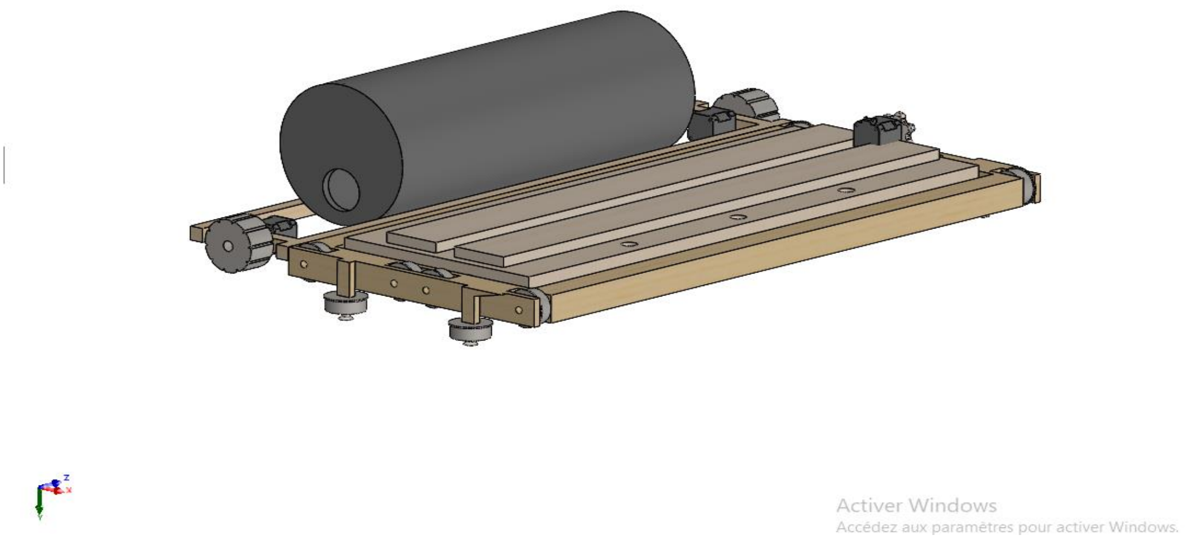
The structural framework that supports and integrates the cleaning components.

- The first part it's the exterior frame
- The second part it's the interior parts

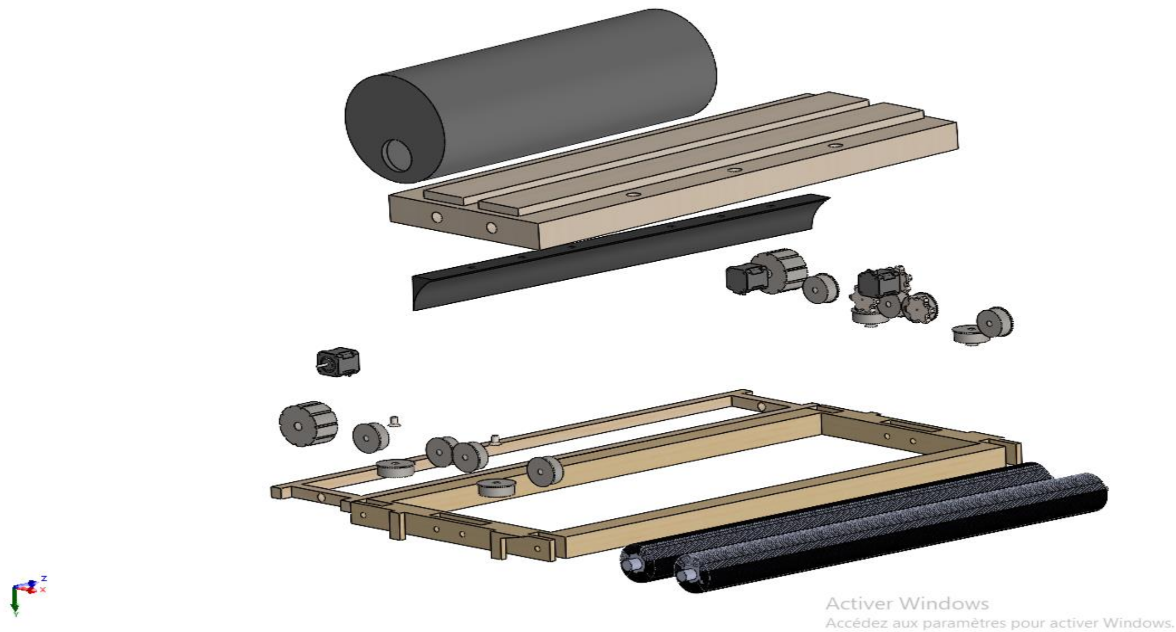




6.2.6 Full Assembly:



Exploded views:



6.3 Dimensioning Key Elements

Dimensioning Key Elements: The dimensions for the main components of the robot. Include:

- Measurements and sizes of key parts such as the chassis, wheels, brushes, motors, and sensors.
- Specifications for components like voltage, current, torque for motors, and pressure for pumps.
-

Table 3 *Dimensioning Key Elements*

Components	Dimensions and Specifications	Notes
Chassis	90 cm x 60 cm x 20 cm	Material: Wood
Wheel	Diameter: 25mm / 60mm	Material: polyurethane
Broom	Length: 760mm	Material: plastics
Motor	Voltage: 12 V	NEMA 17
Sensor	Range: 2cm	Mounted on front
Tank	Volume: 15.7 L	Material: plastic

6.4 Electrical and IT Parts

- Electrical System: The power sources and wiring diagrams:

6.4.1 Power supply:

For the power supply, we are going to need a fairly powerful one mainly to support the load of the motors. Each motor consumes about 5W, which gives us 15W for a setup with 3 motors. We used a 12V 5A power supply (about 60W) which is more than sufficient for our machine.

Figure 37 *A power supply 12V 5A*

6.4.2 Wiring Diagram:

Motor with Arduino

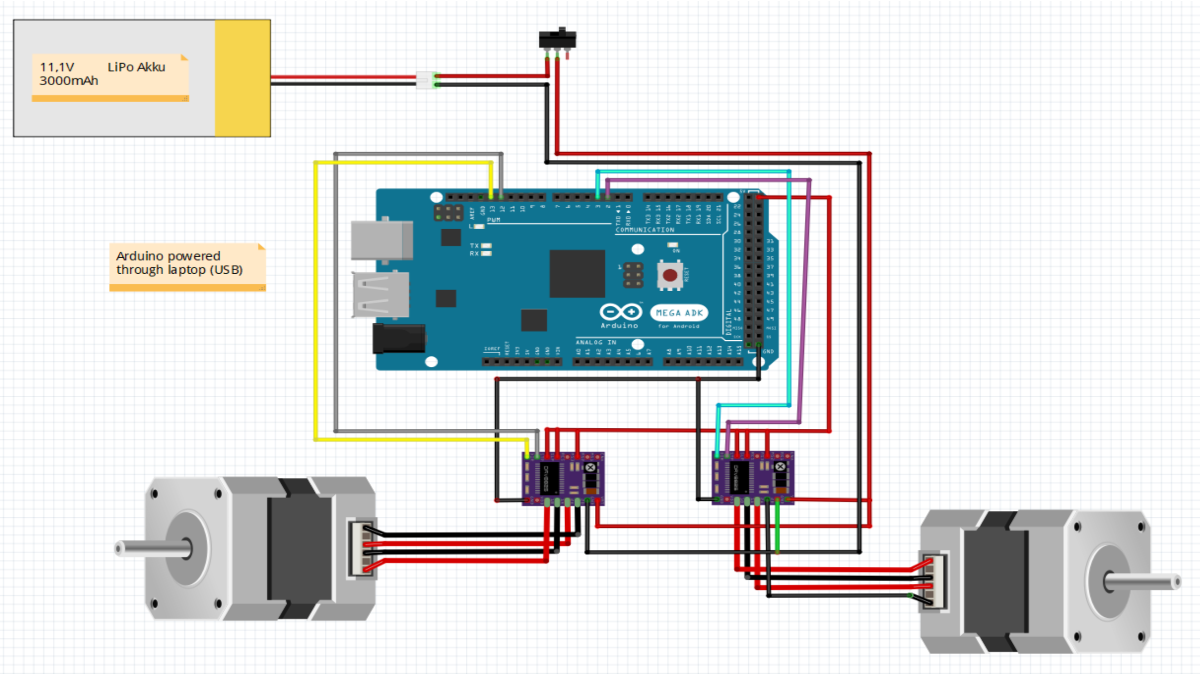


Figure 38 *Wiring Diagram*

6.4.3 Software Flowchart:

The Arduino language can be extended through C++ libraries, and those wishing to understand the technical details can transition from Arduino to the AVR C programming language on which it is based.

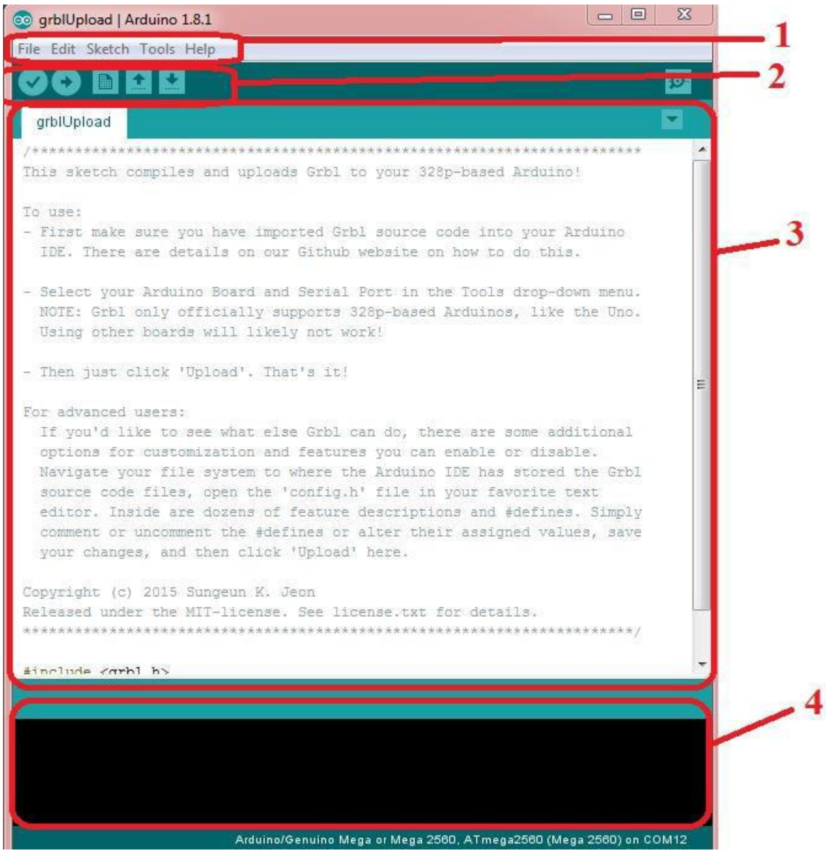


Figure 39 *The Arduino software (IDE)*

- Frame number 1: these are the configuration options of the software
- Frame number 2: it contains the buttons used to program the Arduino board
- Frame number 3: this block contains the program
- Frame number 4: it displays error messages

6.5 CONTAINTE

To simulate the stress constraints on the mobile part of a robot with a pressure of 15 kg, you would need to consider several factors:

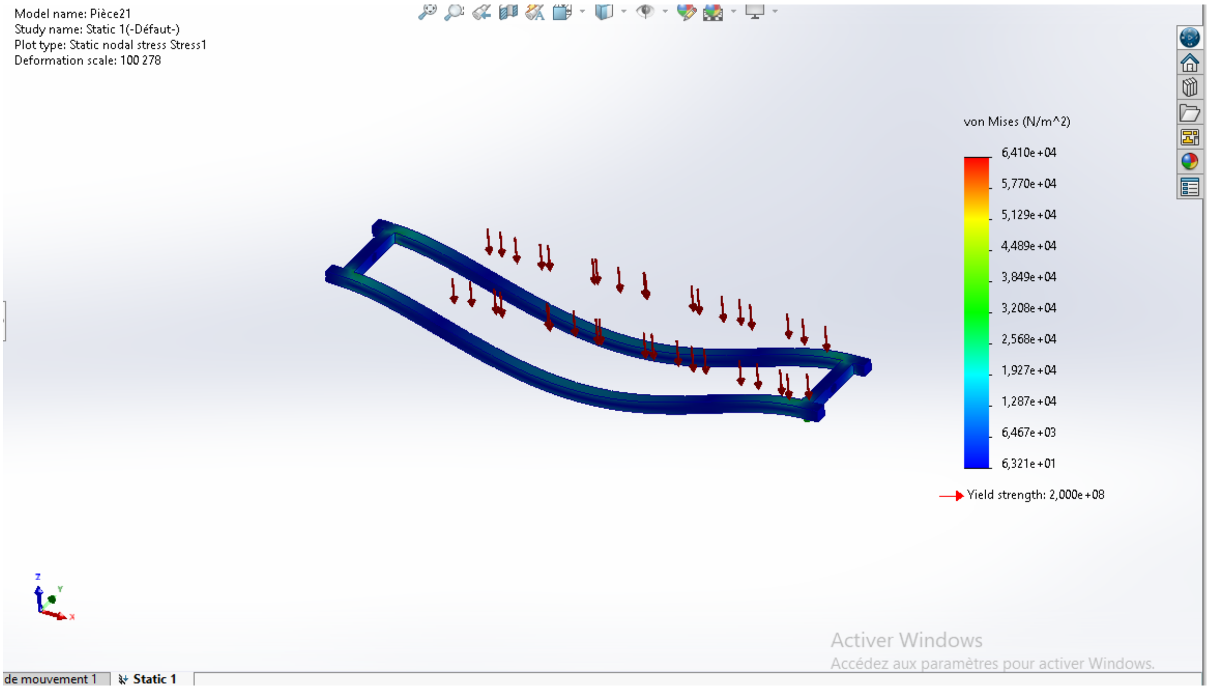


Figure 40. View of the Simulation of externel function

- Material Properties: The strength, elasticity, and durability of the materials used in the mobile part.
- Design Geometry: The shape and size of the mobile part, as well as how the pressure is applied.
- Load Distribution: How the 15 kg pressure is distributed across the mobile part.

This type of simulation is usually performed using computer-aided engineering (CAE) software, which can model the physical properties and predict how the part will react under stress. If you have access to such software, you can input the design parameters and run a finite element analysis to see how the part will handle the pressure.
If you're looking for more detailed guidance on setting up and running this simulation, please provide additional details about the mobile part and its context within the robot.
10 sur 30

6.6 Include Images of the Realization

Actual photographs of the robot during various stages of construction and testing:

6.6.1 Assembly process:

Figure 41 *Assembly process*

6.6.2 Testing phases:

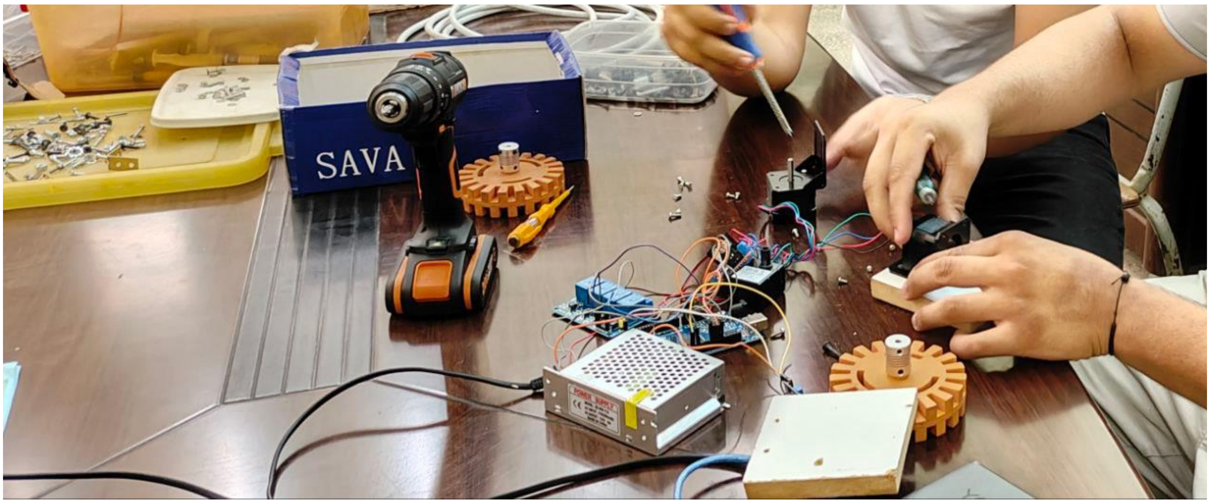


Figure 42 *Testing phases*

6.6.3 Final product:

Figure 43 *Final Product*

General Conclusion

The primary objective of this project was to design and develop a solar panel cleaning robot capable of maintaining the efficiency of solar panels by removing dust and debris. Throughout the course of this work, we have successfully addressed the critical aspects of the robot's design, functionality, and implementation.

In summary, the project involved an in-depth functional analysis, both external and internal, to determine the requirements and constraints of the system. We defined the various functions of the robot, including air blowing, water injection, mechanical brushing, and movement across the solar panels. Using functional analysis tools such as FAST and SADT diagrams, we were able to visualize and refine the operational flow and dependencies of the system components.

One of the significant achievements of this project was the successful integration of mechanical, electrical, and control systems to create a cohesive and efficient cleaning robot. The CAD models provided a clear visualization of the robot's structure, while the dimensional specifications ensured precision in the design and functionality of each component. Moreover, the development of the control algorithms and sensor integration facilitated effective obstacle detection and navigation, enhancing the robot's operational efficiency.

Throughout the development process, we encountered challenges, particularly in the synchronization of the cleaning mechanisms and movement control. These challenges were mitigated through iterative testing and optimization, resulting in a robust and reliable system.

The implications of this project are far-reaching, with the potential to significantly improve the maintenance of solar panels, thereby enhancing their efficiency and lifespan. The practical applications of this robot extend to solar farms and residential solar installations, where regular cleaning is essential for optimal performance.

Looking forward, there are several areas for future research and development. Enhancements in the robot's autonomy, including advanced path planning and machine learning algorithms for predictive maintenance, could further improve its effectiveness. Additionally, we aim to develop a fully autonomous global robot that can navigate independently across an entire solar farm, rather than being restricted to local lines of solar panels. Furthermore, designing a robot capable of cleaning all types of solar panels, including concentrated solar panels with curved surfaces, is a key objective for future iterations.

In conclusion, the development of the solar panel cleaning robot represents a significant step forward in renewable energy maintenance technology. The successful implementation of this project not only demonstrates the feasibility of automated cleaning systems but also opens the door to further innovations in the field. This work serves as a foundation for future advancements, contributing to the sustainability and efficiency of solar energy systems.

Bibliography

[1]. Vaclav Smil, *Energy and Civilization : a History*. Cambridge, Ma ; London the Mit Press, 2017.

[2]. International Energy Agency, “World Energy Outlook 2020 – Analysis,” *IEA*, 2020. https://www.iea.org/reports/world-energy-outlook-2020

[3]. G. Boyle, *Renewable energy : power for a sustainable future*. Oxford: Oxford University Press ; Milton Keynes, 2012.

[4]. REN21, “REN21,” *REN21*, Jun. 13, 2019. https://www.ren21.net/reports/global-status-report/

[5]. *Byjus.com*, 2024. https://cdn1.byjus.com/wp-content/uploads/2023/02/Sources-of-Energy.png.

[6]. Department of Energy, “Fossil,” *Energy.gov*, 2024. https://www.energy.gov/fossil

[7]. *Weebly.com*, 2024. https://hinkhousescience.weebly.com/uploads/1/5/7/4/15746562/6580472_orig.jpg?316.

[8]. “World Coal Association,” *Global Energy Monitor*, Apr. 30, 2021. https://www.gem.wiki/World_Coal_Association.

[9]. BP, “Statistical Review of World Energy,” 2020. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

[10]. BP, “Statistical Review of World Energy,” 2020. Available: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf

[11]. “Natural Sources Of Energy - Renewable and Non Renewable Resources | BYJU’S,” *Byjus.com*, 2011. https://byjus.com/physics/natural-sources-of-energy/

[12]. M. A. Green, *Third Generation Photovoltaics*. Springer Science & Business Media, 2006.

[13]. B. Guezuraga, R. Zauner, and W. Pölz, “Life cycle assessment of two different 2 MW class wind turbines,” *Renewable Energy*, Jan. 2012, doi: https://doi.org/10.1016/j.renene.2011.05.008.

[14]. “World Energy Council 2013 World Energy Resources: Hydro 5.1 5 Hydro.” Available: https://www.worldenergy.org/assets/images/imported/2013/10/WER_2013_5_Hydro.pdf

[15]. S. E. Hosseini and M. A. Wahid, “Hydrogen from solar energy, a clean energy carrier from a sustainable source of energy,” *International Journal of Energy Research*, vol. 44, no. 6, pp. 4110–4131, May 2020, doi: https://doi.org/10.1002/er.4930.

[16]. S. Mekhilef, R. Saidur, and A. Safari, “A review on solar energy use in industries,” *Renewable and Sustainable Energy Reviews*, May 2011, doi: https://doi.org/10.1016/j.rser.2010.12.018.

[17]. *Wp.com*, 2024. https://i0.wp.com/solarfunda.com/wp-content/uploads/2020/12/Solar-Panel-4.png?w=1280&ssl=1.

[18]. M. A. Green, *Third Generation Photovoltaics*. Springer Science & Business Media, 2006.

[19]. International Energy Agency, “World Energy Outlook 2020 – Analysis,” *IEA*, 2020. https://www.iea.org/reports/world-energy-outlook-2020

[20]. Greenmatch, “Types of Solar Panels (2019) | GreenMatch,” *Greenmatch.co.uk*, 2019. https://www.greenmatch.co.uk/blog/2015/09/types-of-solar-panels

[21]. M. Mani and R. Pillai, “Impact of dust on solar photovoltaic (PV) performance: Research status, challenges and recommendations,” *Renewable and Sustainable Energy Reviews*, vol. 14, no. 9, pp. 3124–3131, Dec. 2010, doi: https://doi.org/10.1016/j.rser.2010.07.065.

[22]. H. Jiang, L. Lu, and K. Sun, “Experimental investigation of the impact of airborne dust deposition on the performance of solar photovoltaic (PV) modules,” *Atmospheric Environment*, vol. 45, no. 25, pp. 4299–4304, Aug. 2011, doi: https://doi.org/10.1016/j.atmosenv.2011.04.084.

[23]. M. Nezamisavojbolaghi, E. Davodian, A. Bouich, M. Tlemçani, O. Mesbahi, and F. M. Janeiro, “The Impact of Dust Deposition on PV Panels’ Efficiency and Mitigation Solutions: Review Article,” *Energies*, vol. 16, no. 24, p. 8022, Jan. 2023, doi: https://doi.org/10.3390/en16248022.

[24]. L. El Chaar, L. A. lamont, and N. El Zein, “Review of photovoltaic technologies,” *Renewable and Sustainable Energy Reviews*, vol. 15, no. 5, pp. 2165–2175, Jun. 2011, doi: https://doi.org/10.1016/j.rser.2011.01.004.

[25]. *Springernature.com*, 2024. https://media.springernature.com/m312/springer-static/image/art%3A10.1007%2Fs40430-021-02817-9/MediaObjects/40430_2021_2817_Fig3_HTML.jpg?.

[26]. W. Hicks, “Scientists Studying Solar Try Solving a Dusty Problem,” *www.nrel.gov*, Apr. 01, 2021. https://www.nrel.gov/news/features/2021/scientists-studying-solar-try-solving-a-dusty-problem.html

[27]. K. Khandriche, “L’influence des paramètres externes sur la performance des modules PV (Salissure),” *PFE licence. Université Saad Dahlab, Blida-1*, 2017, Accessed: Jun. 21, 2024. [Online]. Available: https://www.academia.edu/40866005/L_influence_des_param%C3%A8tres_externes_sur_la_performance_des_modules_PV_Salissure_

[28]. M. Mohamed and S. Belkacem, “République Algérienne Démocratique et Populaire Ministère de l’Enseignement Supérieur et de la Recherche Scientifique MEMOIRE DE FIN D’ETUDE EN VUE L’OBTENTION DU DIPLOME DE MASTER Domaine : Sciences et Technologies Filière : Electrotechnique Spécialité : Commande Electriques. Sur le Thème : Présenté par,” Université Ahmed Draïa,Adrar,Algeria, 2022. Accessed: Jun. 21, 2024. [Online]. Available: https://dspace.univ-adrar.edu.dz/jspui/bitstream/123456789/7531/1/D%C3%A9tection%20et%20localisation%20des%20d%C3%A9fauts%20dans%20les%20panneaux%20photovolta%C3%AFque.pdf

[29]. “Google Image Result for x-raw-image:///da4e8e017b23df8674d2cf5a21f6c277877280f47358feaf0dc49079aaddfba5,” *App.goo.gl*, 2017. https://images.app.goo.gl/gEU27DsqaPRkie8D6.

[30]. “Google Image Result for https://www.epelectric.com/files/html/EPE-residential-solar-rooftop-maintenance.jpg,” *App.goo.gl*, 2024. https://images.app.goo.gl/AQN1TSjM3ytfbrSu6.

[31]. “NREL Research Finds Rain Not Enough To Wash Pollen From Solar Panels,” *Nrel.gov*, 2023. https://www.nrel.gov/news/program/2023/nrel-research-finds-rain-not-enough-to-wash-pollen-from-solar-panels.html.

[32]. “Nettoyage photovoltaïque,” *Azimuth Energies*. https://azimuth-energies.fr/nettoyage-photovoltaiques/.

[33]. “TY - JOUR AU - Patel, Shrish AU - John, James AU - Orlov, Alexander PY - 2022/05/01 SP - T1 - Innovative and Sustainable Approach to Clean Solar Panel and Increase Solar Energy Generation VL - ER - .”

[34]. Y. Liu, S. Wang, Y. Xie, T. Xiong, and M. Wu, “A Review of Sensing Technologies for Indoor Autonomous Mobile Robots,” *Sensors*, vol. 24, no. 4, pp. 1222–1222, Feb. 2024, doi: https://doi.org/10.3390/s24041222.

[35]. “Home | SolarCleano,” *solarcleano.com*. https://solarcleano.com/de/.

[36]. “Google Image Result for https://cdn.getmood.io/warehouse/dynamic/257936.jpg,” *App.goo.gl*, 2024. https://images.app.goo.gl/PoJV8j5vQjcecduy8.

[37]. “Ecoppia’s Solar Panel Cleaning Robot System Maintenance for O&M | Ecoppia,” *www.ecoppia.com*, Jun. 10, 2017. http://www.ecoppia.com/technology/.

[38]. “Google Image Result for https://eepower.com/uploads/articles/SandStorm_water-free_autonomous_robot.jpg,” *App.goo.gl*, 2024. https://images.app.goo.gl/UFouwMUhpaMJwb4aA.

[39]. E. Clark, “Sandstorm: Autonomous Sustainable Waterless Cleaning Robot for Solar Panels,” *Energy Theory*, Aug. 10, 2023. https://energytheory.com/sandstorm-autonomous-sustainable-waterless-cleaning-robot-for-solar-panels/.

[40]. “HELIOS – an automated cleaning service for solar panels,” *ART Robotics*. https://art-robotics.com/cases/helios/#:~:text=HELIOS%20is%20an%20automated%20cleaning.

[41]. “LOTUS A series,” *Greenleap Robotics*. https://www.greenleaprobotics.com/lotus-a.

[42]. L. C. Wei, “Solar Panel Cleaning Robots,” *ClimateTechReview*, Apr. 15, 2023. https://climatetechreview.com/solar-panel-cleaning-robots/.

[43]. P. Dorge *et al.*, “International Journal of Computing and Digital Systems Design and Implementation of Automatic Solar Panel Cleaning Robot.” Accessed: Jun. 21, 2024. [Online]. Available: https://journal.uob.edu.bh/bitstream/handle/123456789/5493/1571001992.pdf?sequence=1&isAllowed=y

[44]. S. Technologies, “Solar Panel Cleaning Systems and their Pros and Cons - Soilar Technologies,” Aug. 30, 2022. https://soilar.tech/solar-panel-cleaning-systems-and-their-pros-and-cons/

[45]. D. Mukherjee, K. Gupta, L. H. Chang, and H. Najjaran, “A Survey of Robot Learning Strategies for Human-Robot Collaboration in Industrial Settings,” *Robotics and Computer-Integrated Manufacturing*, vol. 73, p. 102231, Feb. 2022, doi: https://doi.org/10.1016/j.rcim.2021.102231.

[46]. “Kiaara Robotics – Automatic Solar Panel Cleaning Systems,” Feb. 16, 2023. https://kiaararobotics.com/

[47]. “Google Image Result for https://hycleaner.de/wp-content/uploads/2023/05/slide-4.webp,” *App.goo.gl*, 2023. https://images.app.goo.gl/6iPuxcq2oPNForth7.

[48]. K. Misbrener, “Solar panel cleaning devices cut grime and save cash,” *Solar Power World*, May 03, 2022. https://www.solarpowerworldonline.com/2022/05/solar-panel-cleaning-devices-cut-grime-and-save-cash/.

[49]. “Noccarc - A600 - Solar Panel Cleaning Robots - Solar Panel Cleaning Robot By Noccarc Robotics,” *energy-xprt.com*. https://www.energy-xprt.com/products/noccarc-model-a600-solar-panel-cleaning-robot-753887.

[50]. O.-G. Brad, “Solar Panel Cleaning: The COMPLETE Step By Step Guide,” *Off Grid HQ*, May 28, 2023. https://offgridhq.com/solar-panel-cleaning-guide/.

[51]. “Google Image Result for https://www.triplecleangang.uk/wp-content/uploads/2023/05/The-Solar-panel.png,” *App.goo.gl*, 2023. https://images.app.goo.gl/LNhEMEqdcHHgwFBXA.

[52]. “Google Image Result for https://i.ytimg.com/vi/lxc1Xs0CtgQ/mqdefault.jpg,” *App.goo.gl*, 2024. https://images.app.goo.gl/foFZmrudnG7xrjsW6.

[53]. A. Kantar, “Comparing Manual vs. Robot Solar Panel Cleaning Solutions,” *Nhlink.net*, Mar. 24, 2024. https://nhlink.net/manual-vs-robot-solar-panel-cleaning-solutions/.

[54]. “Solar Panel Cleaning Guide: Do’s and Don’ts for Efficiency - solarpowersystems.org,” Feb. 02, 2023. https://solarpowersystems.org/blog/cleaning-solar-panels/.

[55]. Nishant Sarode, Paras Ghugal, S. Yadav, Samiksha Dantule, and Praful Nandankar, “A comprehensive review on solar panel cleaning robot technologies,” *AIP conference proceedings*, Jan. 2023, doi: https://doi.org/10.1063/5.0127800.

[56]. C. BasuMallick, “What is CAD (Computer Aided Design)? Definition, Types, and Applications,” Spiceworks, Sep. 27, 2022. https://www.spiceworks.com/tech/devops/articles/what-is-cad/

[57]. Wikipedia Contributors, “DC motor,” Wikipedia, Jan. 21, 2019. https://en.wikipedia.org/wiki/DC_motor

1.Annexe:

```
digitalWrite(IN4_1, LOW);
break;
case 2:  // 0110
digitalWrite(IN1_1, LOW);
digitalWrite(IN2_1, HIGH);
digitalWrite(IN3_1, HIGH);
digitalWrite(IN4_1, LOW);
break;
case 3:  // 0101
digitalWrite(IN1_1, LOW);
digitalWrite(IN2_1, HIGH);
digitalWrite(IN3_1, LOW);
digitalWrite(IN4_1, HIGH);
break;
case 4:  // 1001
digitalWrite(IN1_1, HIGH);
digitalWrite(IN2_1, LOW);
digitalWrite(IN3_1, LOW);
digitalWrite(IN4_1, HIGH);
break;
}
}

void stepMotor2(int step) {
switch (step) {
case 1:  // 1010
digitalWrite(IN1_2, HIGH);
digitalWrite(IN2_2, LOW);
```

```
digitalWrite(IN3_2, HIGH);
digitalWrite(IN4_2, LOW);
break;
case 2:  // 1001
digitalWrite(IN1_2, HIGH);
digitalWrite(IN2_2, LOW);
digitalWrite(IN3_2, LOW);
digitalWrite(IN4_2, HIGH);
break;
case 3:  // 0101
digitalWrite(IN1_2, LOW);
digitalWrite(IN2_2, HIGH);
digitalWrite(IN3_2, LOW);
digitalWrite(IN4_2, HIGH);
break;
case 4:  // 0110
digitalWrite(IN1_2, LOW);
digitalWrite(IN2_2, HIGH);
digitalWrite(IN3_2, HIGH);
digitalWrite(IN4_2, LOW);
break;
}
}

void activateRelay(int cycle) {
// Deactivate all relays first
digitalWrite(relayPin1, LOW);
digitalWrite(relayPin2, LOW);
digitalWrite(relayPin3, LOW);
```

```
digitalWrite(relayPin4, LOW);

// Determine which relay to activate based on cycle count
switch (cycle % 4) {
case 1:
digitalWrite(relayPin1, HIGH);
break;
case 2:
digitalWrite(relayPin2, HIGH);
break;
case 3:
digitalWrite(relayPin3, HIGH);
break;
case 0:
digitalWrite(relayPin4, HIGH);
break;
}
}
```