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Structural prowess in solar panel cleaning: A comparative study of robotic designs

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Abstract: Automated solar panel cleaning robots have emerged as a solution to mitigate the adverse effects of dust accumulation on solar panels, which can impede energy production. However, concerns persist regarding the potential long-term damage to panels and the efficiency of cleaning methods. This research focuses on various automated cleaning robots, evaluated with a primary emphasis on their structural design and its impact on cleaning efficiency and safety. The robots are assessed based on their cleaning motion time and the load stress exerted on photovoltaic (PV) panels. To evaluate structural integrity, Ansys simulations are employed to assess the strength of solar panels and frames under the loads exerted by different robot types. Furthermore, the cleaning motion of the robot is simulated using SolidWorks, with predefined pathways. The results of this study highlight the crucial role of structural design in the context of solar panel cleaning robotics. Specifically, single axis robot is identified as a standout performer, exerting only 4% stress on PV panels among the considered 4 types of robots in comparison with the maximum stress applying robot and exhibiting the fastest cleaning motion of 38 seconds only for the specified panels which is 4 times faster than other compared robots. These insights provide valuable guidance for further advancements in the design and operation of automated solar panel cleaning systems, emphasizing the significance of structural considerations in enhancing the overall efficiency and effectiveness of these robots.

Keywords: Automated solar panel cleaning, structural design, cleaning efficiency, load stress

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1. Introduction

Sustainable energy are the forms of energy which are drawn from sources that are expected to exist perpetually (Henrick, 2010). An essential component for sustainable development is energy (Allen et al., 2016). Due to the negative impact on the environment, the use of fossil fuels and perishable natural resources of energy need to be reduced in an intellectual way (Bhowmik et al., 2020). The selection of an optimum green energy source is a considerable challenge (Iddrisu & Bhattacharyya, 2015; Janeiro & Patel, 2015), since some of the sustainable energy technologies are expensive and often require extensive construction and careful maintenance because of using lots of moving parts (Ellabban et al., 2014; Stigka et al., 2014.; Soonmin& Taghavi, 2022). Solar panels have become an indispensable source of clean and sustainable energy by harnessing the power of the sun. However, their efficiency and power output can be significantly compromised by the accumulation of dust and debris on their surfaces. Research in Egypt recorded a reduction of up to 25% in PV output was noted over a two-month period and 40% after one year (Ndapuka, 2015). To address this issue, the use of automated solar panel cleaning robots has gained prominence as a practical solution (Hashim et al., 2019; Sarode et al., 2023). While these robots offer the promise of maintaining optimal panel performance, there are concerns regarding potential damage to the solar panels, especially if the cleaning process is not executed with precision (Mondal & Bansal, 2015).

The structural design of solar panel cleaning robots is pivotal to the overall success of their mission to maintain panel efficiency. This design not only determines the robot's ability to access and clean the entire surface of the panels but also affects the potential stress the robot exerts on the photovoltaic (PV) panels during the cleaning process (Zhou & Chen, 2022). Such mechanical stress can lead to undesirable consequences, including micro-cracks and long-term degradation, which reduce the lifespan and performance of the panels (Köntges et al., 2011). Therefore, a comprehensive evaluation of various structural design parameters and their influence on cleaning motion and load stress is imperative. Several previous studies considered the impact of mechanical structure and design. Researcher Shengzan and his team divided solar panel cleaning robots into two categories which are tracked and trackless (Yan et al., 2020). While this research was mostly focused on aesthetics and functional design, the stress analysis or time analysis was not conducted in depth. Research by Nowat and Noppadol did focus on cleaning time but did not compare several types of robots in the time study (Ronnaronglit & Maneerat, 2019).

The present research goes beyond mere cleaning efficiency to address the intricate interaction between the structural design of cleaning robots and the power performance of solar panels, seeking to optimize both aspects in harmony.

In the pursuit of structural design excellence, this study employs advanced simulation tools and experiments to assess the cleaning robots' impact on solar panel structures and performance. Ansys, a renowned finite element analysis software, is utilized to conduct a rigorous strength analysis of the solar panels and their supporting frames under various robot-induced loads (Nguyen et al., 2021). Furthermore, the cleaning motion of the robots is meticulously simulated using SolidWorks, allowing for precise evaluation of their movements and interaction with the panel surfaces (Hashem & Abdelwahab, 2021; Jain & Singh, 2022). These simulation methods facilitate a detailed examination of the stress distribution across the panel's surface and its subsequent implications for structural longevity.

This research delves into the intricate details of structural design considerations for solar panel cleaning robots, with a focus on addressing these challenges and optimizing the efficiency and effectiveness of automated cleaning processes. The outcomes of this research hold significant promise for the advancement of automated solar panel cleaning systems. Not only will our findings contribute to minimizing the potential damage to solar panels during the cleaning process, but they will also lead to more efficient and cost-effective solar panel maintenance. The structural design of solar panel cleaning robots is a critical factor in ensuring the long-term efficiency and effectiveness of solar panel maintenance. Through a rigorous assessment of structural parameters, load stress, and cleaning motion, this research seeks to provide a comprehensive framework for the optimization of solar panel cleaning systems. The results of this study have the potential to guide further improvements in the design and operation of these robots, contributing to the broader goals of clean energy generation and sustainability.

2. Materials and methods

Cleaning of solar panels could be done in several diverse ways. The most easily available method would be physical cleaning by using human workers and hand-held cleaning material. The main problem of using human workers for the cleaning is that the process would be slow compared to automated machine cleaning. Also, such methods could be risky in terms of the possibility of solar panel damage as well as worker health deterioration. Because of the fragility of solar panels, they can be damaged due to human error of the worker. The health issue of the worker could be caused by the scorching heat present at solar farms. Since solar farms are established where the solar irradiance is high, the plant area is usually hot. Also, the height of solar panels possesses the hazard of falling. The human labor cleaning is more practical for small scale solar energy conversion plant usually used for house or small factory (Derakhshandeh et al., 2021). Different alternatives for solar panel cleaning are presented by Table 1. The advantages and disadvantages are also stated of those respective methods. Robotic cleaning among all the cleaning solutions holds a special place since it is suitable to make an intelligent robotic solution and improve it with new research.

Table 1. Comparison of various solar panel cleaning methods.

Cleaning methods	*Advantages*	*Disadvantages*
Manual cleaning (Smith et al., 2013)	Easily available. The initial cost was incredibly low. No or minimal setup equipment required	Slow compared to automated cleaning in the case of large plants. Risk of damage. Expensive eventually.
Natural cleaning by rain and wind (Kazem et al., 2020; Smith et al., 2013)	No resources or cost required.	Highly unpredictable. No control over cleaning.
Forced air flow (Assi et al., 2012; Li et al., 2021)	Could reuse rejected air from Air-Conditioner.	Not practical for large solar plants, especially in isolated area
Electro-dynmic screen (EDS) (Biris et al., 2004; Dahlioui et al., 2023; Mazumder et al., 2011)	No moving parts required. Suitable for space exploration.	Consumes electrical energy at a high voltage. Not practical for solar plant
Chemical cleaning solution (Kazem et al., 2020)	Different solutions could be used. Surface stress as in tension or extra load on the surface could be avoided.	Solutions could be expensive. Sometimes could scatter solar irradiance and thus obstruct energy generation.
Passive cleaning by dust repellent coating Click or tap here to enter text.(Kong & Mohd Jamil, 2014; Thongsuwan et al., 2022)	Preventive method. No moving parts involved.	The coating needs to be renewed over time. Pre-processing required. Might impede solar irradiance.
Robotic automated cleaning solution (Khadka et al., 2020; Parrott et al., 2018a)	Fast cleaning. Comparatively cheap overall cost.	High initial cost. Several rotating parts.

Types of robots

Robotic solutions with several types of mechanical configuration are currently available for use in solar panel cleaning. Cleaning using cleaning robot functions to ensure that the efficiency of solar power generation to electricity by making sure the surface of solar panel is kept clean without putting manual labor at risk.

A single axis robot can move linearly in only one dimension. Moreover, tracked wheel solar panel cleaning robot implements motor driver used to run the cleaning robot on the surface of solar panels. Commonly, this kind of solar panel cleaning system uses H-bridge electronic circuit in function to switch the polarity of a voltage applied to a load. In robotics and other applications, electronic circuits are frequently utilized to allow DC motors to go forward and backward. Omnidirectional mobile robot is a famous mechanism in the cleaning process with a low cost and plain design. This robot is not limited to conducting the cleaning process on rotation and translation motion however it would be able to drive towards any direction and to rotate simultaneously (Taheri & Zhao, 2020). The frame aided two axis cleaning solar system will pivot with two degrees of rotation to monitor the sun's direction throughout the day. Because of its two degrees of freedom, the rollers may not only rotate around its axis but also turn around the axle with the cylinder. Table 2 tabulates comparison of advantages and disadvantages of different cleaning robots.

Table 2. Comparison of advantages and disadvantages of cleaning robots.

Types of cleaning robot	Advantages	Disadvantages
Single-axis	The robot is very simply, it will moves back and forth daily without human intervenion is needed.	The capital expenditure is extremely high. Commonly it is used for dry cleaning only.
Tracked wheel robot	The tracks are simple to put together, and tracked vehicles have more surface area to work.	Robots on continuous tracks travel at a slower speed than robots on wheels because there have more friction and a complex mechanical system.
Frame assisted 2 axes	The robot is easy to fabricate and low-cost for maintenance.	Many mechanical components and mechanisms are involved in the systems like as wheels, bearing, and fasteners.
Omni drive	It is light and simple. The number of wheels can be varied.	Motion can be bumpy, sensitive to nonsmooth terrain, low torque for pushing.

Characteristic of robots

For this segment, the functionality of the robot was determined while every option for each function in the robot was listed. The functional analysis begins with identifying the functional objective which is to clean the surface of the solar panel. Figure 1 shows commonly found 4 types of solar panel cleaning robots.

Figure 1. Commonly used robot types for solar panel cleaning (Ecoppia, 2023; Serbot, 2023; Solavio, 2023).

a) Single axis

Based on Figure 1, this design concept's main cleaning instrument is the implemented rotary brush which will be fixed under the device (Parrott et al., 2018b). To provide normal force and let the device remain in contact with the end of solar panel, robots will be placed on both end side of the solar panel. Hence, the force will be only applicable located at the end of the solar panel where the panel is supported by its frame. This device can be equipped with a water tank above solar panel, the cleaning fluid can be stored in the tank, and it can be flowed to the surface of the panel using gravitational force. In terms of motion, the cleaning robot will move on one axis only. When the robot reaches the end of the solar panel, the levelling sensor will drop from the surface of the solar panel to the frame of the panel. This robot will move backward from the panels to continue the cleaning process.

b) Omni drive

Referring to Figure 1, omni drive robot robots exhibit distinct cleaning ways compared to the design mentioned above. This design uses a vacuum and sponge that are fixed under the device as the cleaning media. For locomotion, this concept uses a random moving system which has similarities with the working mechanism of the automated vacuum cleaner in the household. Besides, this system is applied to an infrared obstacle sensor during the cleaning process. In terms of force application, the weight of the robot will be acting to the surface of the solar panel. Hence, it results in more stress on the surface of solar panels. Osoji Solar, is one such type of small solar panel cleaning robot which is used in swarm configuration like an ant colony (Patil et al., 2017).

c) Tracked wheel

Based on Figure 1, this design concept is like the second design using the same cleaning mechanism and direction movement. However, this design uses the tracked wheel for the operation of the robot. The tracked wheel uses continuous tracks such as soft belts or steel wires in running on the road or any surface. In terms of applied force on structure, the weight will be directly imposer on to the surface of the solar panels (SERBOT, 2023).

d) Frame assisted 2 axes

Figure 1 showcases an innovative design concept that incorporates a rotary brush fixed underneath the device. In this concept, two high-friction wheels are utilized to facilitate the vertical movement of the brushes along the y-direction within the assisted frame. Additionally, a rotary wheel is positioned on the side of the robot, allowing it to move horizontally along the x-axis. The length of the rotary brush restricts the robot's movement to only two pathways. There is some such robotic solar panel cleaning system which include two motorized rails where one rail provides horizontal motion, the other rail moved vertically to sweep one area of the solar panel array like frame assisted 2-axis robot illustration in Figure 1 (Anderson et al., 2010). But for this system to work properly, multiple solar panels need to be aligned in an array which will require a lot of solar panels in a longer row and require a large flat ground surface which is often not easily found in countries like Malaysia since it is a hilly country.

3. Result and analysis

The CAD models of the robot and panels were imported into motion SolidWorks 2022, and Ansys for load and motion simulation analysis. The experimental cleaning process was conducted on the solar panel testbed to obtain a comparison of before and after cleaning.

Robotic systems with various mechanical configurations are now available for use in solar panel cleaning. However, the length of cleaning tools used in those robots are often constrained by their structure. For example, the maximum width of a tracked wheel robot can be 1.2 meters (SERBOT, 2023). Whereas the maximum width of a single axis robot could be more than 5 meters (vmaxpower). For this research, the maximum size applicable on a 2m x 1m solar panel was considered. The omni wheel robot and frame assisted robots usually have brush size less than 1 meter (Ecoppia). Figure 2 (a) below shows the free body diagram analysis for diverse designs. To simulate the load, a mesh was created on the PV surface using Ansys 2022. The span angle center of the meshing was set to coarse meshing, while the remaining parameters will be set to their default magnitudes. It is evident from Figure 2 (a) that single-axis robots & frame-assisted robots apply force at the two ends of the testbed where the reactive force is also acting in the opposite direction. This causes the lowest stress on the PV panels. On the other hand, the applied force from the onmi-wheel robots and the tracked wheel robots could act on the middle of the solar panels which is comparatively far from the PV frame and far from reactive force. Thus, the stress on PV panels will be comparatively higher by these two robots.

Figure 2 (b) depicts a complete meshing model. Within the model, the solver has successfully divided the components into small finite elements. Referring Figure 2 (b), the meshing part of the frame will be more critical than the panel.

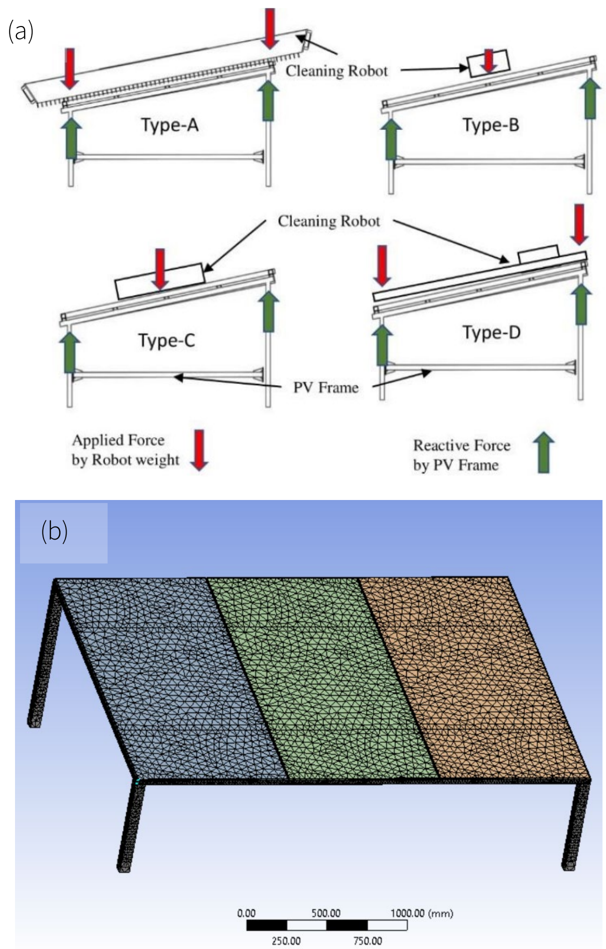

Figure 2. To design analysis (a) shows acting stresses on frame by 4-types of PV cleaning robots; (b) shows frame design with solar panels for finite element analysis in Ansys software.

The solar panel used for this experiment was from JinkoSolar (JKM470M-7RL3-V). The boundary condition was fixed on the PV frame as a fixed support, indicated by the blue color. There was a total of four frames supporting the PV. The material used for the solar frame is structural steel. The density of the steel is 7850 kg/m3 and it has a tensile yield strength of 2.5 〖×10〗^8 Pa. Silicon is the most common material used in solar cells to enhance the conversion of light into electricity, making it more efficient. According to the material property in the SolidWorks software, the density of the solar panel is 2600 kg/m3 and it has a tensile yield strength of 1.65 〖×10〗^8 Pa which matches the research by Naser (2018). Table 3 presents the estimated weight inputs of the robot on the PV component, which were collected from online resources (ECOVACS, 2024; Multifit, 2024; NOCCA, 2024; SolarCleano, 2024). It is evident that omni drive robot is the lightest, while tracked wheel robot is the heaviest. The loads of single axis robot and frame assisted 2-axis robot will act on the frame of the solar panel, while omni drive robot and the tracked wheel robot will exert forces on the solar panel directly as shown previously in Figure 2(a).

Table 3. Estimated weight of 4 types of robots.

Types of robots	Weight (kg)	Force (N)	Force acting	Brand of robot
Single axis robot	45	441.5	Frame structure	SolaKleen (Multifit, 2024)
Omni drive robot	18.70	183.48	Solar face structure	Ecovacs Deebot X1 omni Dex11-omni (ECOVACS, 2024)
Tracked wheel robot	85	833.85	Solar face structure	SolarClea n o F1A (SolarClea no, 2024)
Frame assisted 2-axis robot	35-60 (Selecte d)=60	588.6	Frame structure	Nocca S100 (NOCCA, 2024)

The main objective will be to focus on cleaning motion. In choosing the robot type, different options available need to be understood first. Figure 3 depicts the four types of mobile robot structures with the expected cleaning motion. For motion-related aspects, the design of all the robots will be created using CAD model and import into SolidWorks motion.

In the simulation process for the motion, the motion path will be setup using Solidworks. In addition, Solidworks will also be one of the options for motion planning. The robots' pathways will be initially drawn out on Solidworks 3D views, as shown in Figure 3. After that, the speed of the animation robot in Solidworks 2022 was analyzed.

The strength analysis of the solar panel and the stand frame aims to demonstrate the capability of distinct types of automated cleaning robots to determine which ones generate the least amount of stress when operating on the solar panel surface. This analysis focuses on evaluating the ability of different cleaning robot models to effectively perform cleaning tasks on solar panels without causing any structural damage to the PV frame. After completing all the preprocessing steps using Ansys, the data and results of the simulation are solved and obtained for total deformation, equivalent stress shown below. Based on the result, the total deformation, maximum equivalent stress, and equivalent elastic strain of four different robots which are single axis robot, omni drive robot, tracked wheel robot and frame assisted 2-axis robot had been obtained and shown below in Figure 4 and 5.

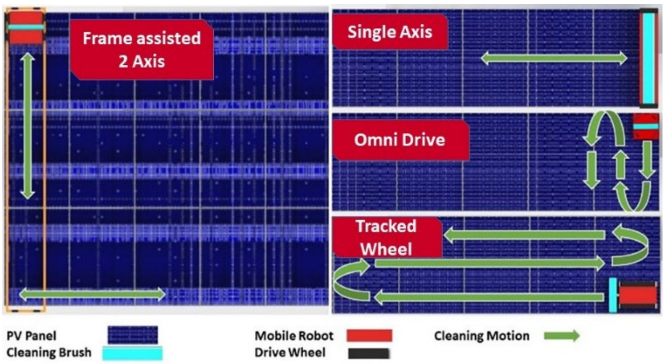

Figure 3. Cleaning motions of several types of PV cleaning robots in simulation.

Simulation analysis & load analysis

The load on single axis robot and frame assisted 2-axis robot is applicable to the structural frame, and stress occurs only at the frame part. Meanwhile, the load of omni drive robot and tracked wheel robot are acting towards the solar panel which giving a lot of stress on panels which is will damage easily of PV panels (Gabor et al., 2018).

A stress analysis is being conducted in this project to observe the maximum equivalent stress that is being applied to the solar panel. The summary of finite element method results is tabulated in Table 4. In structural analysis, deformation results can be added into the system to determine the total deformation of the panel frame and PV modules.

Total deformation is the deformation results related to the model in three coordinates (X, Y and Z). For the results of the maximum deformation, tracked wheel robots tend to show the highest deformation which is 0.0095421 mm compared to other robots. However, single axis robot displays a lowest deformation among others which is 2.6482 〖×10〗 ^(-7) mm. Hence, greater deformation in tracked wheel robot means greater force applied.

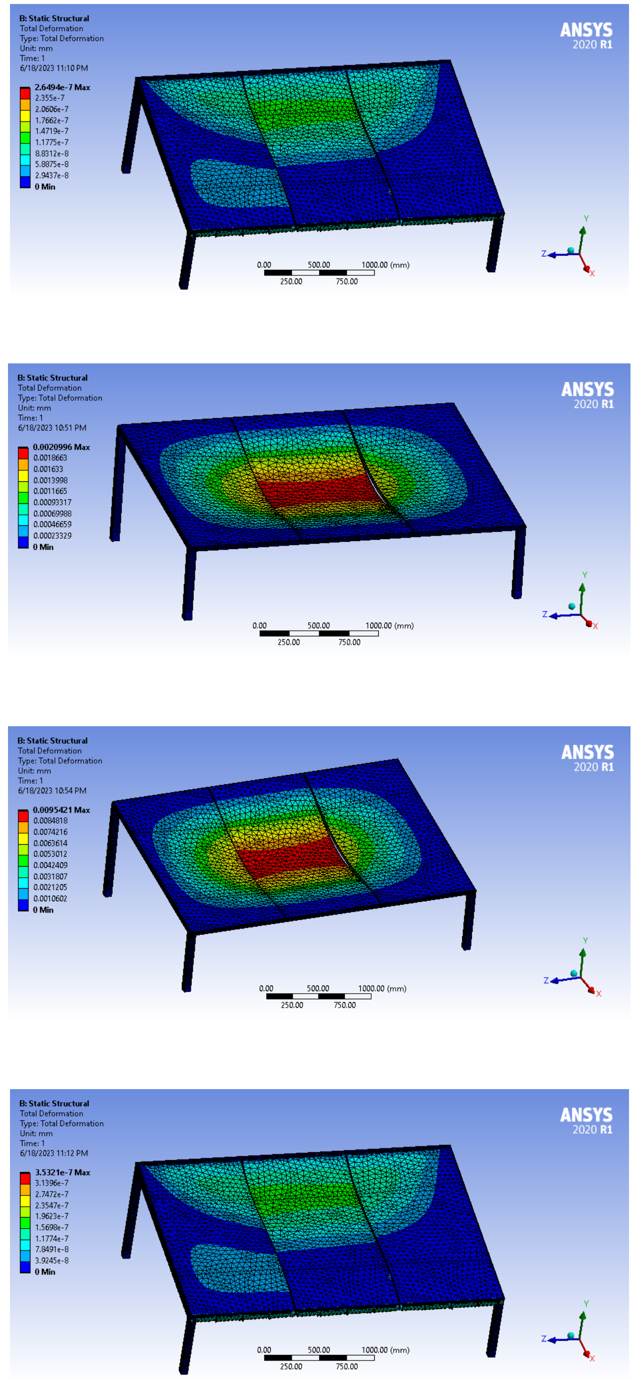

Figure 4. Analysis of the single axis robot, omni drive robot, tracked wheel robot & frame assisted 2-axis robot's total deformation.

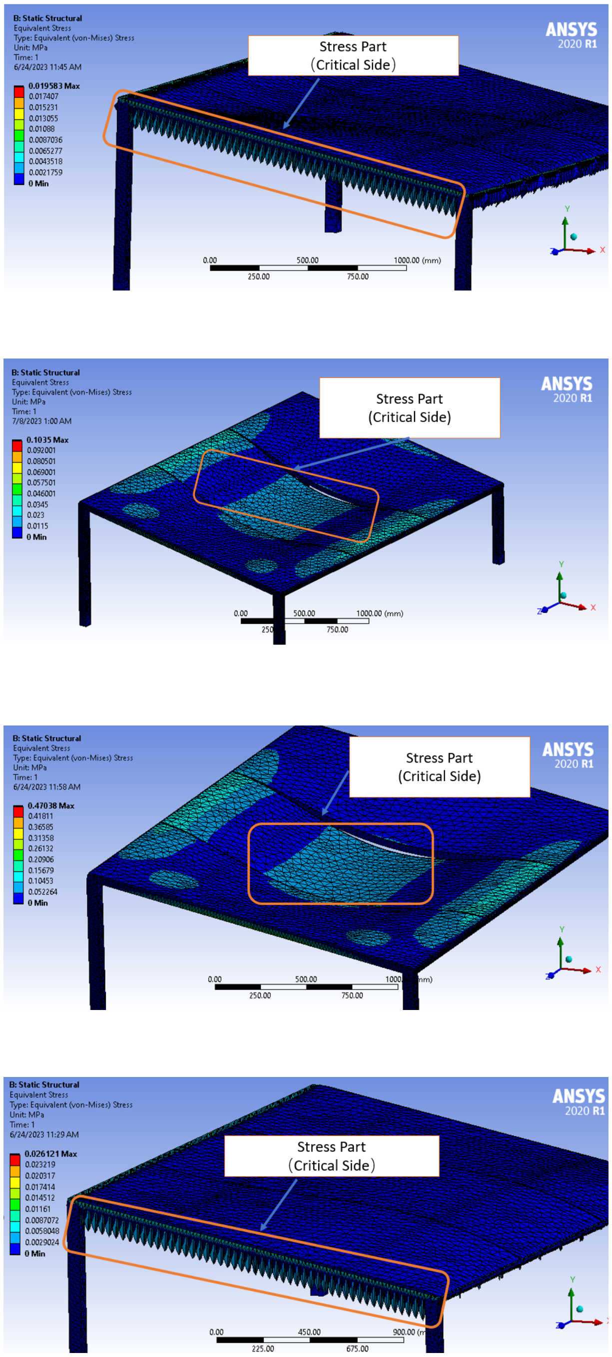

Figure 5. Analysis of the single axis robot, omni drive robot, tracked wheel robot & frame assisted 2-axis robot's critical part occurs on frame.

In addition, the maximum equivalent stress of single axis robot is the lowest with the magnitude of 0.019585 MPa. The maximum equivalent stress obtained in FEA in tracked wheel robot is the highest which is 0.47038 MPa. In conclusion, single axis robot was found to be the most suitable choice for placing on the PV module for cleaning, as it had the least impact on the entire system.

Table 4. Summarize simulation results of load analysis.

Types of Robots	Stress (MPa)		Deformation (mm)		Reaction Force (N)	
	Min	Max	Min	Max	Min	Max
Single axis robot	0	0.019585	0	2.6494×10^{-7}	0	441.5
Omni drive robot	0	0.1035	0	0.0020996	0	183.48
Tracked wheel robot	0	0.47038	0	0.00095421	0	833.85
Frame assisted 2-axis robot	0	0.02611	0	3.53×10^{-7}	0	588.6

Motion analysis

In this case, linear motion analysis was conducted on a pathway that was designed in the earlier stages. Table 5 depicts the moving direction of four different robots.

Table 5. Moving direction of four different robots.

Types of robots	Moving direction	Brand of robot	Author/Reference
Single axis robot	Moving x-axis (One-direction)	SolaKleen	(Parrott et. al. 2018b)
Omni drive robot	Moved cyclic around	Ecovacs Deebot X1 omni Dex11-omni	(Kolb, 2022)
Tracked wheel robot	Moving curved direction	SolarClean o F1A	(SolarCleano, 2024)
Frame assisted 2-axis robot	Moving x-axis, y-axis (2-direction)	Nocca S100	(NOCCA, 2024)

a) Single axis robot

Figure 6 illustrates the linear velocity against time for single axis robot for complete cleaning. Single axis robot has a breadth that corresponds to the width of a single line of solar panels, making them the largest in terms of brush size. Since the brush spans the entire width of the panels, these robots can clean solar panels in a single-dimensional motion, resulting in minimal cleaning time with only 38 seconds.

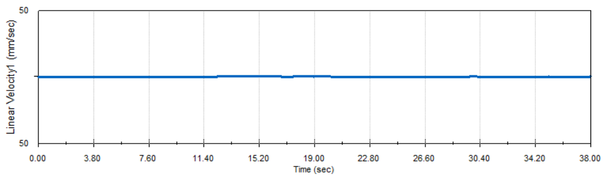

Figure 6. Linear velocity against time for single axis robot for complete cleaning.

As referred to the Figure 7, single axis robot is moving at a constant velocity of 50 mm/sec. Simultaneously, the acceleration of the robot is zero, indicating that there is zero for acceleration or deceleration since there is no requirement for a changing direction of cleaning.

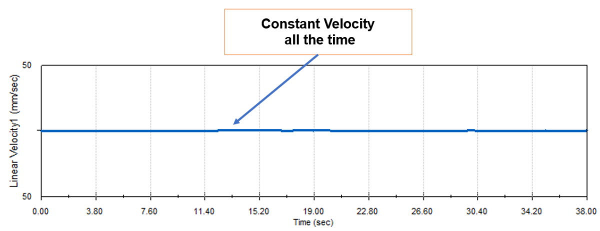

Figure 7. Details of the motion graph for single axis robot complete cleaning.

b) Omni drive robot

Based on Figure 8, the omni drive robot takes 162 seconds to complete the cleaning. Omni drive robots were omni-drive mobile robots that are compact in size, but the length of their cleaning brush is limited by their size. These robots must move in a snake-like manner to clean the solar panel, requiring two-dimensional motion as they move across the breadth of the panel and then laterally along its length. As a result, this approach is slower than a single axis robot.

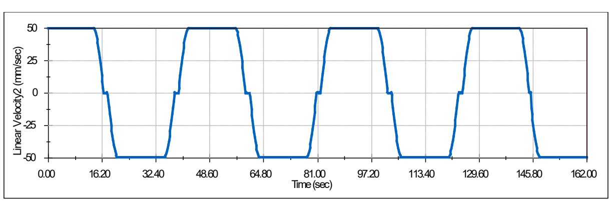

Figure 8. Linear velocity against time for omni drive robot to complete cleaning.

However, Figure 9 shows the details of the motion graph, which displays several critical points in the movement of omni drive robot. At 13.56 seconds, the robot starts decelerating as it approaches the corner. Then, at 16.76 seconds, the robot comes to a rest at the corner to change direction, indicated by a negative sign. Afterward, the robot starts accelerating in the opposite direction at 18 seconds until 21.12 seconds. Next, the robot begins to decelerate again at 35 seconds as it starts changing the direction of cleaning. The robot took a rest when near to the comer which at 38.4 seconds. Then, at 36.25 seconds, the robot accelerates in the positive direction to continue the cleaning. This process continues repeatedly until the entire panel cleaning is completed

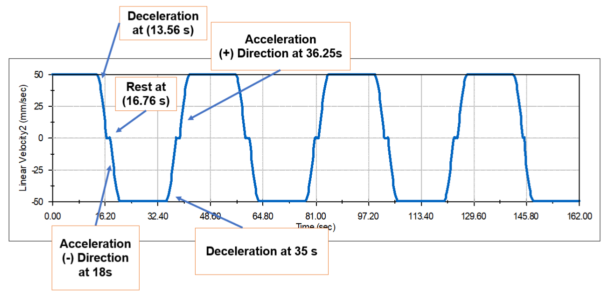

Figure 9. Details of the motion graph for omni drive robot complete cleaning.

c) Tracked wheel robot

Referring to Figure 10, the tracked wheel robot takes 155 seconds to complete the cleaning. Tracked wheel robot mobile robots typically feature a large, powerful driving system to travel across the solar panels, with the brush attached to the front. However, the robots are omnidirectional which require them to move in a snake-like manner. The time will be much slower.

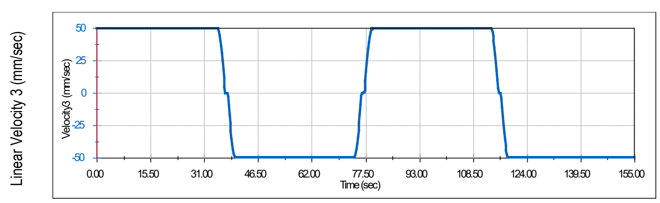

Figure 10. Linear velocity against time taken for tracked wheel robot complete cleaning.

Referring to Figure 11, initially, the robot moves at a constant velocity of 50 mm/sec. At 34.96 seconds, it begins decelerating as it approaches the corner. By 37.76 seconds, the robot's velocity decreases to zero as it prepares to make a U-turn and change direction for cleaning. Subsequently, at 40.12 seconds, the robot continues in the opposite direction with a linear velocity of 50 mm/sec. Meanwhile, at 74.28 seconds, the robot starts decelerating in a different direction until 76.56 seconds. It then comes to a complete stop momentarily before accelerating again at 77.36 seconds, but with the positive direction. This process is repeated until the cleaning process is completed.

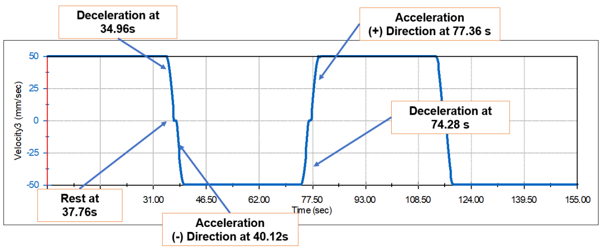

Figure 11. Details of the motion graph for tracked wheel robot complete cleaning.

d) Frame assisted 2-axis robot

Based on Figure 12 the frame assisted 2-axis robot takes 145 seconds to complete the cleaning. Frame assisted 2-axis robot was typically used in large solar farms where more than two solar panels are connected in a single line. These robots have an additional frame on top of the solar panel frame that directs them along the width of the solar panel. After cleaning along the breadth, the frame moves along the length, and the process is repeated. Hence the cleaning style quite similar with omni drive robot as well like snake styles

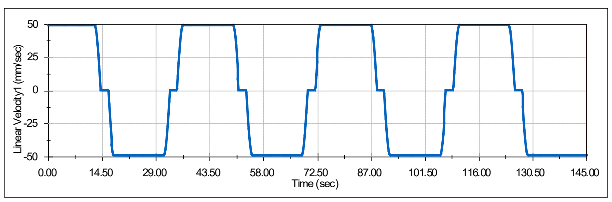

Figure 12. Linear velocity against time taken for frame assisted 2-axis robot complete cleaning.

Figure 13 provides a detailed motion graph illustrating the key moments in frame assisted 2-axis robot's movement. Initially, frame assisted 2-axis robot maintains a constant linear velocity of 50 mm/sec. At 12.64 seconds, it gradually decelerates while approaching a corner. Subsequently, at 14.20 seconds, the robot changes its motion to clean in a different direction. As a result, from 14.52 seconds to 17.76 seconds, Frame assisted 2-axis robot accelerates in the negative direction by maintaining a steady velocity of -50 mm/sec. Afterwards, at 31.2 seconds, the robot initiates a deceleration in the negative direction. It reaches the corner precisely at 32.8 seconds and commences acceleration in the positive direction at 35.8 seconds. This entire process repeats cyclically until the completion of the PV panels cleaning task.

According to the results from Table 6, single axis robot is clearly the quickest to complete cleaning among the cleaning robots. This is because single axis robot only goes in one direction along the x-axis only. On the other hand, omni-drive robot, tracked wheel robot, and frame assisted 2-axis robot move in a snake-like pattern, resulting in a lengthier cleaning time. Lastly, tracked wheel robot takes the longest time since it moves horizontally first, then vertically, resulting in a longer pathway.

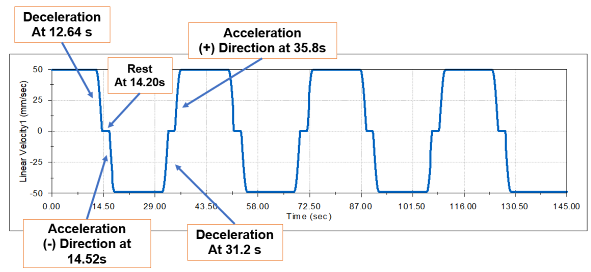

Figure 13. Details of the motion graph for frame assisted 2-axis robot complete cleaning

Table 6. Summarize simulation results of motion analysis.

Types of robots	Moving time (s)	Speed (mm/s)
Single axis robot	38	50
Omni drive robot	162	50
Tracked wheel robot	155	50
Frame assisted 2-axis robot	145	50

4. Conclusions

In conclusion, the selection of an appropriate robot type is crucial for efficient solar panel cleaning, aiming to minimize energy loss due to maintenance. Four types of mobile robot structures were explored, each with its unique advantages. Single axis robot robots, characterized by a width matching a single line of solar panels and a large brush size, demonstrated exceptional cleaning efficiency with minimal stress on the panels. In contrast, omni drive robot robots, employing omni-drive technology, which is challenging to deploy on slanted solar panels, exhibited a slower but gentler cleaning motion. Tracked wheel robot robots, equipped with a robust drive system and high-pressure water jet capabilities, addressed specific cleaning challenges, albeit imposing considerable weight stress on the solar panels. Frame assisted 2-axis robot robots, suitable for large solar farms, featured a guided frame for efficient cleaning across multiple panels. The study revealed that, considering both cleaning speed and stress on solar panels, Single axis robots stood out as an optimal choice for swift and effective cleaning. The three other types of robots had comparatively smaller cleaning tools and had to rotate and turn to cover the entire area to clean. This made those three types of robots slower than the single-axis robot. The importance of proper cleaning methods was emphasized, as timely removal of dust and residues enhances power generation efficiency and extends panel durability. Single axis robot consistently demonstrated superior performance, with the lightest stress on PV modules (0.019585 MPa) and the fastest cleaning time (38 seconds), contributing to increased energy efficiency. The selection of the ideal robot type depends on specific solar farm goals, with Single axis robot robots emerging as a compelling choice for those prioritizing fast cleaning and reduced maintenance time. Hopefully, this research would help solar farm operation and maintenance organizations to carefully choose the proper type of robot which could benefit their labor-intensive manual cleaning of solar panels. The reduction of cleaning duration can allow the solar panels to provide higher output with higher efficiency for longer time. Investigating the long-term effects of automated cleaning methods on the structural integrity and performance of PV panels in real-world conditions using all diverse types of robots could offer valuable insights for further optimization. Furthermore, exploring advancements in material science and robotics technology to enhance the durability and effectiveness of automated cleaning systems would be beneficial. Lastly, considering the potential integration of smart sensors and artificial intelligence algorithms to optimize cleaning pathways and adapt to varying environmental conditions could further improve the overall performance of solar panel cleaning robots

Conflict of interest

The authors have no conflict of interest to declare.

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