Application of Composite Drive in Innovative Design of Photovoltaic Panel Cleaning Robot Structure

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Abstract

With the rise of the photovoltaic industry, efficient and clean photovoltaic panels have become a key factor in photovoltaic power generation. In response to the limitations of manual cleaning, this article explores the application of composite driving in the innovative design of photovoltaic panel cleaning robots, and proposes a design scheme of a composite driving photovoltaic panel cleaning robot with "planetary wheel+rubber wheel+suction cup" to achieve efficient and non-destructive cleaning of the surface of photovoltaic panels. Adopting a modular design concept, the cleaning robot is divided into multiple parts, including a composite driving walking mechanism, a cleaning mechanism, and a control system. The walking mechanism utilizes a composite driving method to achieve stable walking of the robot in different terrains and tilt angles; The cleaning mechanism adopts a combination of front rotating edge brushes, anhydrous cleaning devices, and rear rotating mops to effectively remove dust and dirt on the surface of photovoltaic panels; The control system can achieve intelligent control of robot walking and cleaning processes by sensing real-time environmental information through sensors. The simulation results show that this hybrid driven photovoltaic panel cleaning robot has good walking stability, not only improving cleaning efficiency and reducing costs, but also achieving non-destructive cleaning of the photovoltaic panel surface.

Keywords

Composite Drive; Photovoltaic Panel Cleaning Robot; Structural Design; Drive Control; Modular Design.

1. Introduction

To promote the development of photovoltaic power generation technology, both domestic and international efforts have been made to invest research resources in improving the performance and safety of photovoltaic systems [1-3]. The diverse potential and research progress of photovoltaic technology in improving energy efficiency and promoting sustainable development have been demonstrated in areas such as ecosystem restoration [4], capacity estimation methods [5], and environmental optimization models [6]. Currently, photovoltaic panel cleaning robots [7-10] are divided into three types: single row, cross row, and portable. The technology of single row robots is mature [11-12], such as Ecoopia Company in Israel; Cross row robots are often used in distributed power plants due to terrain and other limitations; Portable robots, such as products from Japan's Sinfonia company, have strong adaptability and can be used for irregular layouts. Although China's photovoltaic industry is developing rapidly, module cleaning and maintenance are still in the initial

ISSN: 2414-1895 DOI: 10.6919/ICJE.202512_11(12).0015

stage, and most of them still use manual cleaning. In order to improve efficiency, domestic enterprises have begun to develop cleaning robots, such as the single row robot of Nanjing Suonengduosi Company [13], the car cleaning robot of Chongqing Taichu [14], and the on-board robot of Shenzhen Chuangdong Technology [15]. However, these robots still face issues such as large volume, complex cross row mechanisms, and short battery life, and need to consider issues such as water scarcity, the impact of installation angles on motion, and damage to photovoltaic panels during cleaning processes [16]. This article proposes an innovative solution to the existing problems, which is a self-propelled photovoltaic panel cleaning robot driven by a combination of planetary wheels, rubber wheels, and suction cups. It is suitable for cleaning medium and large photovoltaic panels and uses anhydrous cleaning and lithium battery power supply. It can automatically clean pollutants such as dust and sand, which is expected to solve the current problem of photovoltaic panel cleaning.

2. Structural Design of a Hybrid Driven Self-Propelled Photovoltaic Panel Cleaning Robot

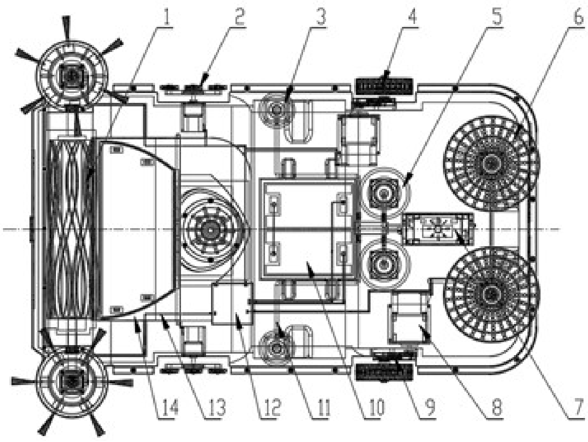

Fig. 1 Overall structure of a hybrid driven self-propelled photovoltaic panel cleaning robot

In the design process of a hybrid driven self-propelled photovoltaic panel cleaning robot, it is necessary to fully consider the technical requirements for achieving stable and efficient cleaning work on the surface of the photovoltaic panel [17]. Its main technical requirements include: adapting to changes in the tilt angle of photovoltaic panels from 30° to 60°, using anhydrous cleaning methods to protect the environment, and ensuring that the overall size is small, the structure is compact, and the weight is light for easy operation and transportation. In terms of walking mode, the robot combines wheeled and suction cup modes to adapt to photovoltaic panels with different surfaces and tilt angles. In addition, the robot is powered by lithium batteries, ensuring the continuity and convenience of cleaning operations.

The overall structural design of a composite driven self-propelled photovoltaic panel cleaning robot includes multiple key parts such as a composite driven walking mechanism, cleaning mechanism, and adsorption mechanism. Figure1 shows the overall design schematic of a composite driven self-propelled photovoltaic panel cleaning robot, detailing the layout and functions of each component. Here, 1 is the main cleaning mechanism assembly at the front end, including 1 active cleaning wheel and 2 cleaning edge wheels; 2 is a planetary gear; 3 is a small vacuum suction cup; 4 is the active rubber wheel; 5 is a vacuum suction cup; 6 is a rotating cleaning mop at the rear end; 7 is a miniature vacuum pump; 8 is a DC deceleration motor; 9 is a small gearbox; 10 is the main power supply lithium battery; 11 is a suction cup that controls the trachea; 12 is the circuit control board; 13 is the control wire; 14 is the vacuum box and fan.

The photovoltaic panel cleaning robot adopts high-efficiency lithium batteries and integrates a multi suction cup vacuum adsorption mechanism. It constructs a negative pressure environment through a micro vacuum pump to ensure stable adsorption and improve work safety and stability. The mobile system integrates DC deceleration motor and differential motor to achieve flexible turning and free movement, adapting to various photovoltaic panel layouts. The cleaning module includes a front double-sided brush, a main rolling brush, and a vacuum system, which work together to efficiently remove dust. The vacuum cleaner has a strong collection effect, achieving a clean and closed cycle. For stubborn stains, equipped with a rear mounted double rotating mop, combined with cleaning agents for deep cleaning, to restore the transparency and power generation efficiency of the photovoltaic panel.

2.1 Design of Composite Drive Walking Mechanism

In the design of a self-propelled photovoltaic panel cleaning robot, the walking mechanism is a key component that significantly affects the overall performance. Given that the surface of the photovoltaic panel is composed of tempered glass, the walking mechanism needs to have a lightweight and compact structure to reduce surface pressure, as well as the ability to cross installation gaps. Therefore, we adopt a composite drive scheme of "planetary wheel+rubber wheel". The rear wheel design includes 2 active rubber wheels, equipped with a DC reduction motor and a small reducer to ensure stable driving force and friction. The front wheel design utilizes two driven planetary gears and a front DC motor to achieve differential steering, crossing the gap and high drop of photovoltaic modules, and achieving obstacle crossing function. This design meets special needs, improves adaptability and practicality, and provides strong support for the cleaning and maintenance of photovoltaic panels.

2.1.1 Selection of Drive Motor

After research, it has been found that the current movement speed of similar photovoltaic panel cleaning robots on the market is 10-20m/min [18]. Therefore, the maximum movement speed of the photovoltaic panel cleaning robot is set to 20m/min. additionally, since the diameter of the active rubber wheel is designed to be 140mm, the rotational speed of the active rubber wheel can be determined by Eq.1:

$$n = v/(2\pi r) \tag{1}$$

In Eq.1, n is the rotational speed of the active rubber wheel, r/min; v is the robot's movement speed, m/min; r is the diameter of the active rubber wheel, m.

There are:

$$n = v/2\pi r = 20/(\pi \times 0.14) = 45\ r/\min$$

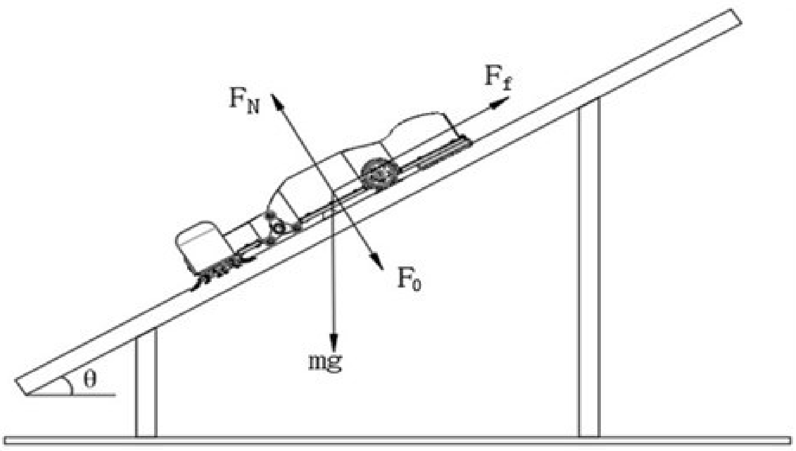

Fig. 2 Force analysis of photovoltaic panel cleaning robot

ISSN: 2414-1895 DOI: 10.6919/ICJE.202512_11(12).0015

According to the overall design of the photovoltaic panel cleaning robot, the overall weight of the robot is about 65kg. The robot is driven by two rubber wheels at the rear, so the driving force is mainly provided by the two DC deceleration motors at the rear. The force analysis of robots working on photovoltaic panels is shown in Figure 2.

The force analysis of the robot when stationary is:

$$F_N = F_0 + \mathrm{m}g\cos\theta \tag{2}$$

$$F_f = \mu F_N \tag{3}$$

To make the robot move upwards, it must meet the following requirements:

$$F_f = \mu(F_0 + \mathrm{m}g\cos\theta) \ge \mathrm{m}g\sin\theta \tag{4}$$

In Eq.2 to Eq.4, F_N is the support force of the photovoltaic panel on the cleaning robot, N; F_0 suction is the adsorption force generated by the micro vacuum pump, N; F_f is the friction force generated on the surface of the photovoltaic panel, N; μ is the dynamic friction coefficient between the cleaning robot and the surface of the photovoltaic panel, taken as 0.3.

When the maximum tilt angle θ of the photovoltaic panel is taken as 60 °, the required traction force for the motor is calculated as:

$$F_{\mathrm{M}} = \mu(F_0 + \mathrm{m}g\cos\theta) \ge \mathrm{m}g\sin\theta = 65 \times 9.8 \times \sin 60 = 552\mathrm{N}$$

The torque required for a single wheel of the active rubber wheel:

$$T = \frac{F_M R}{N\varphi} = \frac{522 \times 0.07}{2 \times 0.96} \approx 20Nm$$

The required power for the motor is:

$$P_0 = \frac{T_n}{9950} = 94.9W$$

According to actual requirements, the theoretical power needs to be increased by 1.1-1.3 times to obtain:

$$P = 1.2P_0 = 113.88W$$

Based on the calculated actual power of 113.88W, the Z5BLD120-24GU-30S/5GU100KB DC brushless reduction motor from Jardine Matheson can be selected as the two rear drive motors. This motor has advantages such as constant speed, high torque, and long lifespan. It is powered by a 24V DC power supply, with a rated power of 120W, a rated speed of 1500r/min, a rated torque of 4.35Nm, a working efficiency of 90%, and a rotation ratio of 10.

2.1.2 Design of Composite Drive Wheeled Walking Mechanism

In the academic research of photovoltaic panel cleaning robots, the walking mechanism is the core of their efficient and stable cleaning operations. To enhance the freedom and environmental adaptability of robots moving on the surface of photovoltaic panels, we have designed an innovative walking mechanism. The rear wheels are made of rubber material and equipped with asymmetric patterns to increase the friction coefficient and contact area with the surface of the photovoltaic panel, ensuring stable driving. The front wheels are designed with planetary gears, endowing the robot with excellent obstacle crossing ability, easily crossing the gaps between photovoltaic panel components, and solving the problem of driving interruption. This design not only ensures the stability and reliability of the robot, but also enhances its adaptability and practicality, which is crucial for the long-term stable operation of photovoltaic panels.

2.1.3 Design of Small Gearbox

In the design of a self-propelled photovoltaic panel cleaning robot, a small gearbox is a key component between the motor and the driving wheel, which not only achieves deceleration and torque increase, but also has a buffering and shock-absorbing function to protect the motor from impact and vibration. The gearbox is coordinated with a DC reduction motor, with a DC motor reduction ratio of 10. In order to achieve a reduction in speed from 1500 to 45 rpm, the total reduction ratio needs to reach 34. Therefore, the total reduction ratio i of the small gearbox set to 3.4. Adopting a two-stage gear reducer, limited by size, the gear module is uniformly set to 1. The specific parameters are: gear 1 has 20 teeth, gear 2 has 44 teeth, gear 3 has 25 teeth, and gear 4 has 38 teeth. This design not only meets the reduction ratio requirements, but also ensures a compact size of the gearbox, making it easy for the robot to integrate as a whole.

2.2 Design of Adsorption Mechanism

The design of adsorption mechanism mainly includes two parts: the selection design of vacuum suction cup structure and the selection design of micro vacuum pump.

2.2.1 Structural Design of Vacuum Suction Cups

The adsorption mechanism of the self-propelled photovoltaic panel cleaning robot is the core of its stable operation. Considering the weight limit of the robot not exceeding 65kg and the tilt limit angle of the 60 ° photovoltaic panel, we have carefully designed the adsorption mechanism. By carefully considering the size and component layout of the robot, two small (90mm diameter) and two large (130mm diameter) vacuum suction cups were selected as the main adsorption components. This design ensures sufficient adsorption while maintaining the compactness and stability of the robot structure, providing reliable mechanical support for efficient cleaning of photovoltaic panels.

2.2.2 Selection of Micro Vacuum Pump

Due to the compact size and limited installation space of the cleaning robot, it is not possible to use a large air compressor. Therefore, we chose a micro vacuum pump to generate the required vacuum environment. The pump is significantly miniaturized and lightweight, while maintaining high vacuum and high flow characteristics, ensuring fast and powerful adsorption of the robot on the photovoltaic panel. After market research and performance comparison, the Hailin Technology C60L micro vacuum pump was ultimately selected as the vacuum source to achieve stable adsorption and efficient operation of the robot on photovoltaic panels. Specific parameters: rated voltage 24V; Peak flow rate ≥26.5L/min; Average flow rate ≥17.5L/min; Relative vacuum degree≥88-kPa.

2.3 Design of Cleaning Institutions

The cleaning mechanism of the self-propelled photovoltaic panel cleaning robot adopts a waterless cleaning method in its core design [19]. The cleaning mechanism consists of a front edge brush, a rolling brush mechanism, a vacuum box, a vacuum fan, and a rear rotating drag device. This design directly affects cleaning efficiency and quality. The synergistic effect of the edge brush and rolling brush mechanism in front removes dust and dirt, and the combination of the vacuum box and fan maintains a clean environment; The rotating mop mechanism at the rear enhances the cleaning effect, ensuring thorough cleaning of the surface of the photovoltaic panel.

2.4 Selection of Lithium Batteries

The selection of lithium battery voltage is crucial in the power supply system of photovoltaic panel cleaning robots [20]. Considering the power supply needs of equipment such as DC reduction motors and micro vacuum pumps, 24V is selected as the lithium battery power supply voltage. By calculating the total power consumption of electrical equipment, including 2 drive motors, 2 edge brush motors, 2 mop motors, 1 vacuum fan motor, and 1 micro vacuum pump, it was found that the total power consumption for continuous operation for 5 hours is about 86.45Ah. Based on this, Tianneng 6-DZF-45.2 lithium battery is selected to meet the 5-hour battery life requirement, ensure work efficiency, while considering cost-effectiveness and practical application scenarios. The selected lithium battery is composed of two lithium batteries. The specific parameters of a single lithium battery are shown in Table 1. So choosing two lithium batteries for power supply can provide 24V voltage and 90.4Ah battery capacity, which can meet the power supply requirements for the normal operation of the photovoltaic panel cleaning robot.

Table 1. Single lithium battery parameter table

The name of the parameter	parameter
The model of lithium battery	6-DZF-45.2
Rated capacity	45.2Ah
Rated voltage	12V
Single weight	12.0kg
Single size	224*117*175mm

3. Design of Overall Control System

In the control system of a composite driven photovoltaic panel cleaning robot, the microcontroller precisely regulates the speed of the DC deceleration motor to control the active rubber wheels, thereby adjusting the movement speed of the vehicle body. The steering is achieved through differential operation of the DC motors on both sides of the planetary gear using a microcontroller. Meanwhile, the microcontroller controls the micro vacuum pump motor to ensure stable adsorption of the robot on the photovoltaic panel. In addition, the microcontroller drives the edge brush and mop motor to rotate for cleaning, while the main roller brush completes the cleaning work through bevel gear transmission.

3.1 Design of Pneumatic Control System

The adsorption mechanism of the self-propelled photovoltaic panel cleaning robot is composed of micro vacuum pumps, vacuum suction cups (including small and large ones), gas pipes, one-way valves and other pneumatic components. Its working principle is to extract gas from the vacuum suction cup through a micro vacuum pump, forming a vacuum environment to achieve adsorption with the surface of the photovoltaic panel. During operation, four vacuum suction cups synchronously adsorb to ensure the minimum adsorption force meets the standard, ensuring stable and safe movement of the robot. After reaching the designated position, the four suction cups are released synchronously to complete the cleaning task.

3.2 Design of Circuit Control System

The cleaning robot needs 9 motor drives to complete the cleaning task: 2 edge brush motors control the rotation of the edge brushes and adjust the speed; Two mop motors control the rotation of the rear mop to clean stubborn pollutants; Two driving motors control the speed of the active rubber wheels,

ISSN: 2414-1895
DOI: 10.6919/ICJE.202512_11(12).0015

thereby controlling the movement speed of the robot; Two steering motors achieve steering through differential motion; One vacuum suction fan motor controls the rotation of the fan to form negative pressure vacuum suction into the box.

4. Static Simulation Analysis of Composite Drive Wheel Systems

The static simulation analysis of composite drive wheel system mainly involves conducting stress analysis, strain analysis, and displacement analysis on key components such as rubber active wheels and driven planetary gears in the composite drive wheel system through Solidworks.

4.1 Static Simulation Analysis of Rubber Active Wheels

As a key load-bearing component of the walking mechanism, the driving wheel needs to meet the strength and stiffness requirements of the vehicle weight. It is composed of alloy steel wheels and rubber tires. Based on the total weight of the cleaning robot being 650N, with a load of approximately 163N per wheel, and bearing a motor shaft torque of 20 N • m, a static analysis was conducted as shown in Figure 3 to Figure 5.

The static simulation analysis of the active wheel shows that the maximum stress is 2.076e+05N/m ², the maximum strain is 8.255e-07, and the maximum displacement is 2.684e-05mm. These extreme data verify that active rubber wheels can meet the normal working requirements of photovoltaic panel cleaning robots.

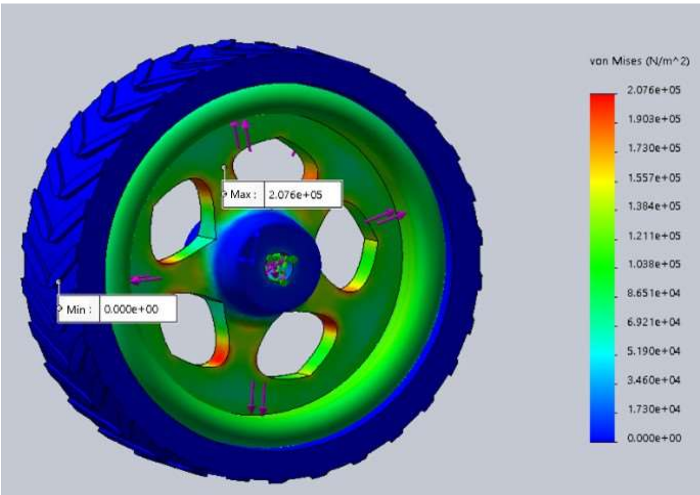

Fig. 3 Stress analysis diagram of active rubber wheel

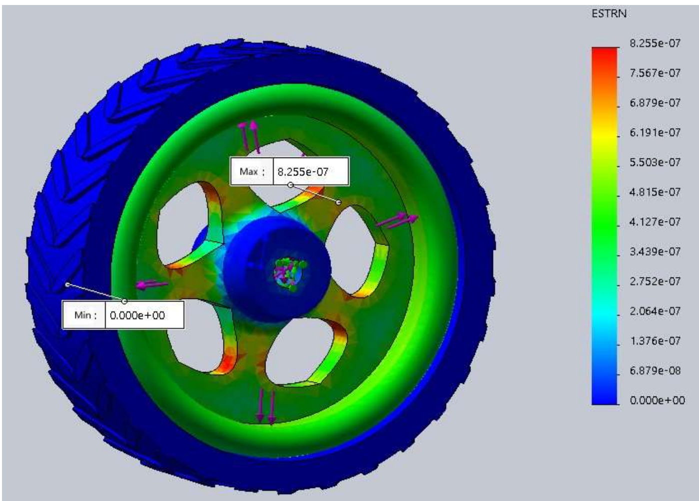

Fig. 4 Strain analysis diagram of active rubber wheel

Volume 11 Issue 12, 2025
DOI: 10.6919/ICJE.202512_11(12).0015

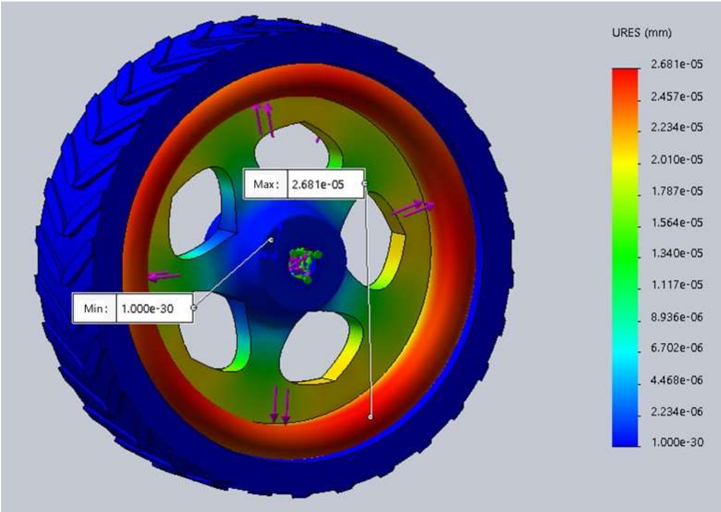

Fig. 5 Displacement analysis diagram of active rubber wheel

4.2 Static Analysis of Side Plate of Traveling Mechanism

The driven planetary gear, as a key load-bearing component in the walking mechanism, together with the driving wheel, supports the weight of the vehicle body. To achieve the obstacle crossing function, the driven wheel is designed as a planetary gear structure, consisting of alloy steel wheels and rubber tires. Under a total weight of 650N, each wheel bears a load of approximately 163N and a steering motor shaft torque of 2.5 N • m. Figure 6 to Figure 8 shows the corresponding static analysis.

The static simulation analysis of the driven planetary gear reveals that its maximum stress is 4.450e-02N/m ², maximum strain is 4.044e-06, and maximum displacement is 6.248e-05mm. These data verify that the driven planetary gear is sufficient to support the normal operation of the photovoltaic panel cleaning robot.

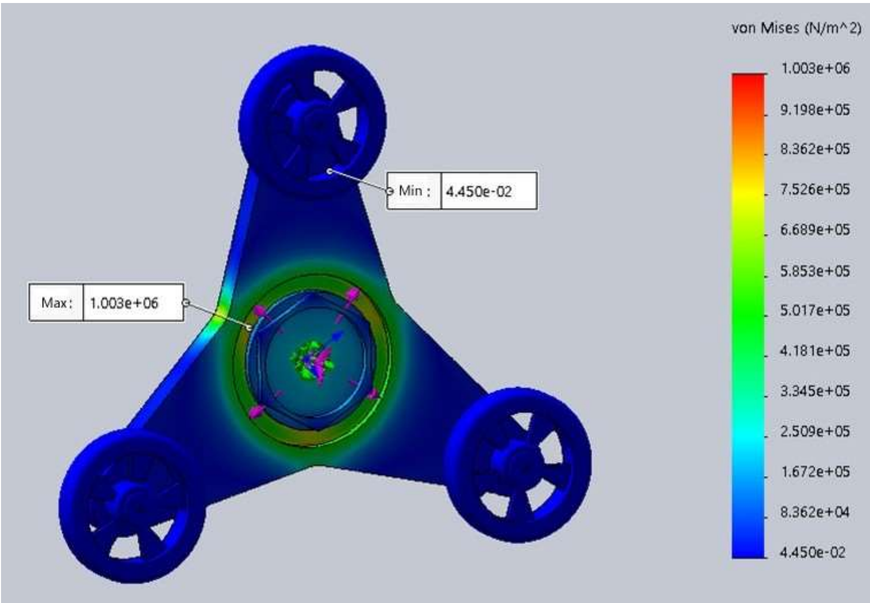

Fig. 6 Stress analysis diagram of driven planetary gear

ISSN: 2414-1895 DOI: 10.6919/ICJE.202512_11(12).0015

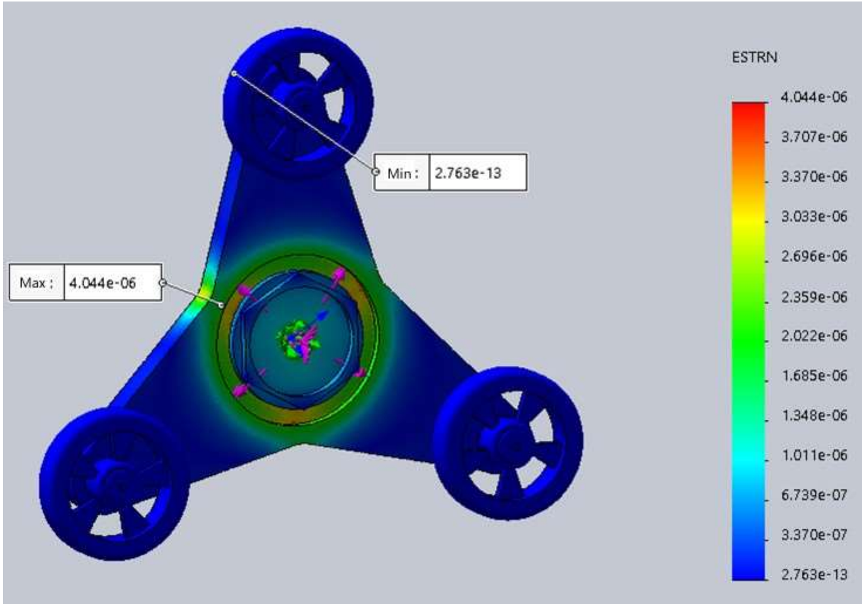

Fig. 7 Strain analysis diagram of driven planetary gear

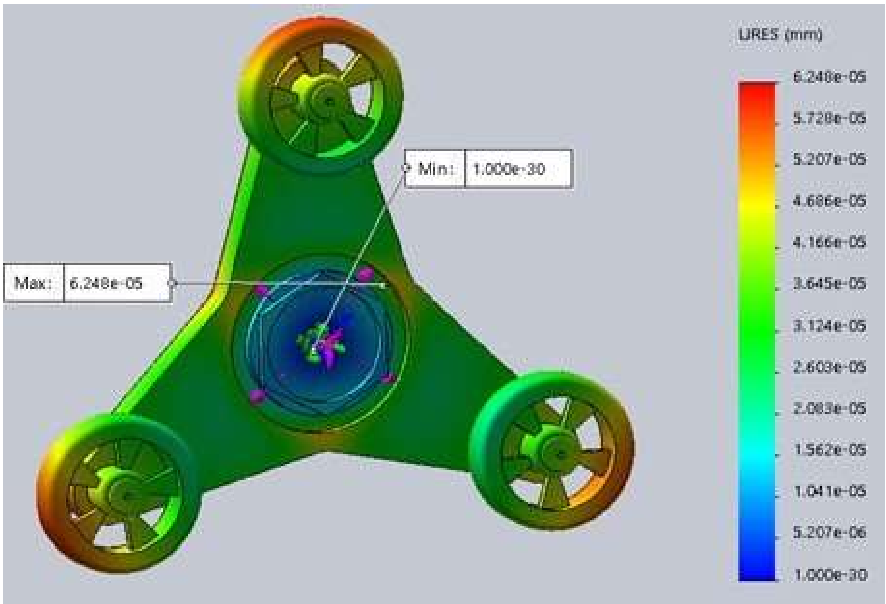

Fig. 8 Displacement analysis diagram of driven planetary gear

5. Conclusion

This study focuses on the structural design innovation of photovoltaic panel cleaning robots, deeply explores the composite driving strategy, and successfully verifies the effectiveness of the "planetary wheel+rubber wheel+suction cup" composite driving structure. The core findings include:

Firstly, the composite drive enhances the clean structure and environmental adaptability. This composite drive structure integrates the precise positioning of planetary gears, the obstacle crossing ability of rubber wheels, and the stable adsorption of suction cups, significantly improving the structural stability and operational adaptability of the robot in complex environments, ensuring stable operation in various working conditions, and providing reliable guarantees for the cleaning work of photovoltaic panels.

Secondly, the composite drive improves cleaning efficiency and non-destructive performance. By optimizing power distribution and motion control strategies, the composite driving mode promotes precise and efficient contact between cleaning tools and the surface of photovoltaic panels. This not only improves cleaning efficiency, but also reduces potential damage to the surface of photovoltaic panels, achieving efficient and non-destructive cleaning goals, reflecting the significant effect of technological innovation in improving work quality.

Thirdly, composite driving has promoted technological innovation and industry development. The composite drive technology proposed in this study has brought innovative breakthroughs to the field of photovoltaic panel cleaning, enriched design ideas, and demonstrated enormous potential in improving robot performance and expanding application scenarios. This provides strong support for technological innovation and industrial upgrading in the industry, indicating a positive trend of the industry's transformation towards intelligence and efficiency.

In summary, this study validates the superiority of composite drive structures in the design of photovoltaic panel cleaning robots, revealing their important role in improving the overall performance of robots, promoting technological innovation and industry progress. Future research should focus on the continuous optimization of composite drive technology, in order to further improve the intelligence level and operational efficiency of photovoltaic panel cleaning robots, and promote the sustainable development of the photovoltaic cleaning and maintenance industry.

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