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Design and Experimental Study of a Wind-Resistant Solar Panel Bracket with Automatic Solar Tracking

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Abstract: *To address the weaknesses of conventional fixed solar panel brackets, namely poor wind resistance and a power-generation efficiency limited by the solar incidence angle, this paper designs an integrated solar panel bracket system that combines wind-speed monitoring, graded wind resistance and intelligent solar tracking. An optoelectronic anemometer is used to acquire real-time wind-speed data, and a dual-threshold control strategy is adopted to adjust the panel tilt and to lower the panel into a protective position. Four photoresistors arranged around the panel detect the light distribution, and stepper motors drive the bracket in two dimensions so that the panel always faces the sun. A prototype was developed through three-dimensional modelling, part machining and control-system programming, and its core functions were verified by simulation tests. The results show that the bracket tracks the solar azimuth stably and remains structurally stable under low to moderate wind speeds, achieving a balance between improved power generation and operational safety. The study also reveals a limitation of structural stability under high wind speeds, which will be addressed by further structural optimization. Economic and environmental assessments indicate that the design has high engineering feasibility and sustainability.*

Keywords: *solar panel bracket; wind-resistant design; automatic solar tracking; wind speed monitoring; structural design*

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I. Introduction

With the intensification of global energy shortages and environmental pollution, solar energy, as a representative clean and renewable resource, has become a central pillar of the energy transition. Owing to its advantages of flexible installation, low transmission losses and long service life, solar photovoltaic (PV) power generation has been widely adopted in centralized power stations, building rooftops, agricultural facilities and many other scenarios.

However, most existing PV power generation systems still employ fixed brackets and suffer from two core bottlenecks in practical operation. The first is a prominent wind-safety risk. Solar panels are usually mounted on rooftops, open fields and other elevated, exposed locations, where strong winds exert large wind pressures and torsional moments on the panel surface, readily causing structural deformation, detachment or even collapse. Post-disaster reconstruction is time-consuming and costly, which seriously impairs operational reliability; typical forms of wind-induced damage are shown in Fig. 1. The second is the limited improvement of power-generation efficiency. A fixed bracket cannot dynamically adjust its angle with the solar azimuth, so the angle between the panel surface and the sunlight varies continuously with time and season, leading to significant fluctuations in received light energy and making it difficult to raise total output further.



Fig. 1 Typical forms of wind-induced damage to solar panels

In terms of China's power-generation structure, the share of clean energy increased continuously from 2016 to 2020, with solar power generation growing more than threefold and its industry scale expanding steadily; solar power has become an important component of the electricity supply system. Detailed data are given in Table 1. If the wind-safety and efficiency bottlenecks of fixed brackets could be effectively resolved, the economy and reliability of PV power generation would be further improved.

Table 1 Share of electricity generation by source in China, 2016–2020

Year	Oil-fired	Gas-fired	Coal-fired	Nuclear	Hydro	Solar	Wind	Other renewables
2016	0.17%	3.07%	67.89%	3.48%	18.80%	1.01%	3.87%	0.71%
2017	0.16%	3.07%	67.31%	3.76%	17.64%	1.78%	4.47%	0.60%
2018	0.08%	3.01%	66.49%	4.12%	16.73%	2.47%	5.10%	0.69%
2019	0.08%	3.15%	63.22%	4.71%	16.99%	5.41%	5.36%	1.08%
2020	0.15%	3.18%	60.80%	4.90%	17.50%	9.10%	6.20%	1.17%

To address the above problems, this paper proposes an integrated wind-resistant and solar-tracking panel bracket. Real-time wind-speed monitoring provides graded active protection against wind damage, while photoelectric detection enables automatic tracking of the solar azimuth, so that power-generation efficiency is improved and structural safety under extreme weather is guaranteed. The feasibility of the scheme is verified through prototype development and simulation tests. The remainder of this paper is organized as follows. Section 1 presents the research background; Section 2 reviews the state of the art and the industry pain points; Section 3 gives the overall system design and scheme selection; Section 4 describes the development of the physical prototype; Section 5 reports the simulation tests and analysis; and Section 6 summarizes the paper and outlines future work.

II. Research Background and Current Status

2.1 Market Awareness and Demand Survey

To assess market acceptance and application prospects, a questionnaire survey was conducted along the dimensions of technology awareness, demand intensity, advantage evaluation and application scenarios. The results show that although the public's overall understanding of solar power technology still needs to be improved, there is a broad consensus regarding the wind-damage problem of conventional fixed brackets, together with strong interest in the integrated anti-wind tracking scheme. Respondents generally recognized two core advantages — "excellent wind resistance that reduces equipment damage" and "automatic tracking that improves power-generation efficiency". Expected application scenarios concentrate on centralized solar power stations and residential or commercial building rooftops. Most respondents considered the technology feasible, were willing to pay a certain cost premium, and were willing to recommend it, indicating good market potential.

2.2 Limitations of Existing Technologies

A review of domestic and international research and products shows that studies on bracket wind resistance and solar tracking mostly address a single function, while integrated research remains relatively scarce. Three clear limitations can be identified. First, most studies are attached to specific application scenarios such as new energy vehicles or railway power supply and exist only as auxiliary subsystems, so there is a lack of independent bracket solutions for general scenarios. Second, some results emphasize control algorithms and simulation without being translated into physically realizable engineering products. Third, some low-cost tracking systems lack detection accuracy and fail to keep the panel perpendicular to the sunlight, limiting the resulting gain in power-generation efficiency.

Existing studies on wind-load characteristics and wind-resistance verification methods for independently supported solar panels provide a useful reference for structural design [1-2], yet research on active wind-resistance strategies is still limited.

2.3 Analysis of Practical Industry Pain Points

To clarify actual engineering requirements, in-depth interviews were conducted with practitioners in the field of PV operation and maintenance. The results indicate that the economic losses caused by wind disasters are directly related to the scale of the plant, ranging from tens of thousands to tens of millions of yuan, and that the post-disaster reconstruction period for PV panels and brackets is approximately half a year, becoming even longer if transmission equipment is damaged. The power-generation efficiency of conventional fixed brackets fluctuates markedly with season and time of day; tracking technology can effectively increase output, although the actual improvement depends on regional, climatic and other factors. In summary, an integrated bracket that combines wind protection with efficiency improvement has clear industrial demand and practical value.

III. System Design

The system functions are divided into two modules, wind protection and intelligent tracking, and the mechanical structure and the control system are deeply integrated to realize the operating logic of "tracking for efficiency under normal conditions, safety first under extreme wind".

3.1 Wind-Resistance Schemes and Selection

Two candidate schemes were proposed and compared with regard to the wind-resistance requirement.

Scheme 1: streamlined deflector for drag reduction. A streamlined fairing is mounted outside the bracket, and force sensors detect the wind direction and pressure; a servo rotates the fairing so that it directly faces the incoming wind, thereby reducing drag. This scheme requires no change in the panel posture, but its response to changes in wind direction is slow and its protective effect under strong wind is limited.

Scheme 2: dual-threshold retraction based on wind speed. A wind-speed sensor monitors the ambient wind speed in real time and two protection thresholds are set. When the wind speed reaches the first threshold, a servo rotates the panel to a horizontal posture to reduce the windward area; when it rises further to the second threshold, a lifting mechanism lowers the panel to a protected position, further reducing the wind load. This scheme has a clear response logic and provides a more significant protective effect under strong wind.

Comparing protection effect, response speed and implementation difficulty, Scheme 2 was selected as the final wind-resistance scheme, since the graded protection strategy balances normal operating efficiency with safety under extreme wind. Two typical working postures are shown in Fig. 2.

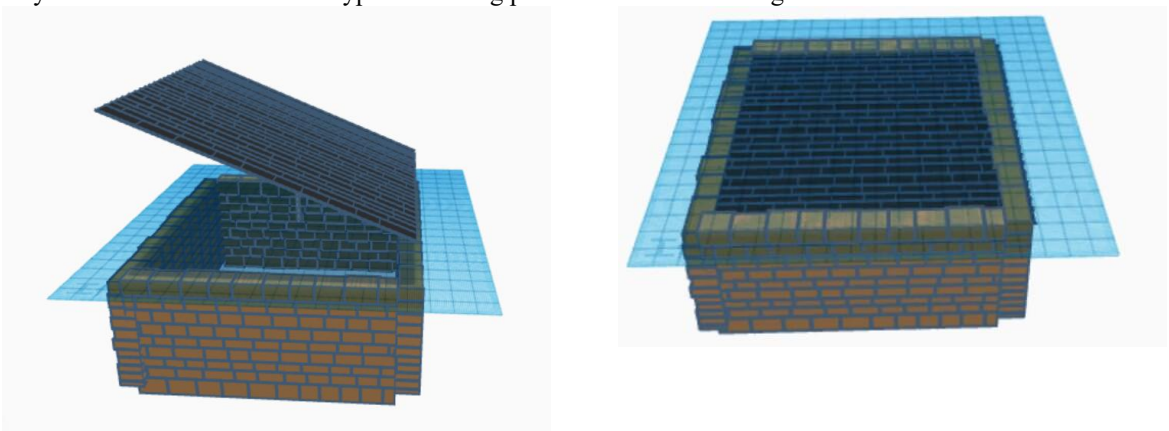


Fig. 2 Schematic of the bracket working postures
(a) tracking posture under normal conditions; (b) retracted protective posture under extreme wind

3.2 Solar-Tracking Schemes and Selection

Two candidate schemes are likewise proposed for solar tracking.

Scheme 1: satellite-positioning trajectory tracking. Satellite positioning provides geographic location and time information, and a solar-trajectory algorithm calculates the solar altitude and azimuth angles, on the basis of which motors adjust the panel angle [5]. This scheme is accurate but costly, and it depends on satellite signals, which limits its adaptability.

Scheme 2: four-direction photodetection tracking. Photoresistors fitted with shading baffles are installed around the panel to form a four-direction light-detection unit; by comparing the voltages of the four photoresistors the relative solar azimuth is determined, and stepper motors adjust the bracket angle so that the panel directly faces the sun [7]. This scheme is low in cost, simple in structure and requires no external signals, making it suitable for most outdoor scenarios. The layout of the four-direction detection unit and its detection circuit are shown in Figs. 3 and 4, respectively.

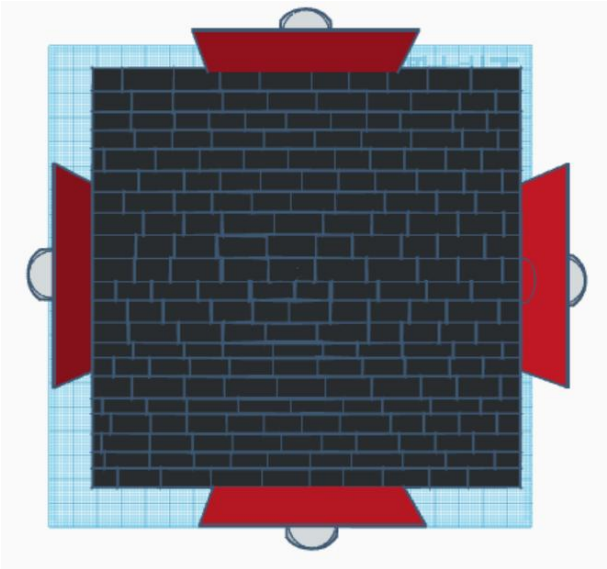


Fig. 3 Layout of the four-direction photoresistor detection unit

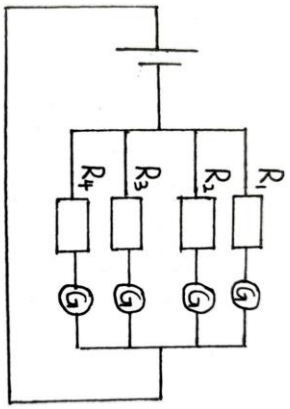


Fig. 4 Circuit diagram of the photodetection unit

Considering cost, reliability and application scenarios, Scheme 2 was adopted. An intermittent detection strategy is used, with light sampling and angle adjustment performed every 30 minutes, so that accuracy is ensured while system energy consumption is reduced.

3.3 Overall Operation Logic of the System

The system takes "safety first with efficiency taken into account" as its control principle and treats the wind-speed measurement as the highest-priority input. Under calm or low-wind conditions, the tracking action is executed every 30 minutes so that the panel remains perpendicular to the incident light, maximizing the received light energy. When the wind speed reaches the first threshold, tracking is interrupted and the panel is rotated to a horizontal posture to reduce the windward area and the wind pressure. When the wind speed rises further to the second threshold, the secondary protection is triggered and a lifting mechanism lowers the panel to a protected position, fundamentally reducing the risk of structural damage caused by wind loads. Once the wind speed falls back into the safe range, the system automatically restores the tracking state step by step, thereby enabling continuous and safe operation under unattended conditions.

IV. Prototype Development

On the basis of the above design, a physical prototype of the bracket system was developed in four stages: three-dimensional modelling, structural fabrication, sensor calibration and control-system development.

4.1 Three-Dimensional Modelling

SolidWorks was used for three-dimensional modelling and assembly verification. The overall structure consists of four main modules: a wind-speed measurement module, a rotation module composed of three stepper motors, a solar panel support module and an external housing. Structural optimization was applied to the key load-bearing parts, and standard mounting interfaces for sensors and motors were reserved, ensuring assembly feasibility and interference-free motion at the design stage. The overall three-dimensional model of the bracket is shown in Fig. 5 and its key functional modules are shown in Fig. 6.

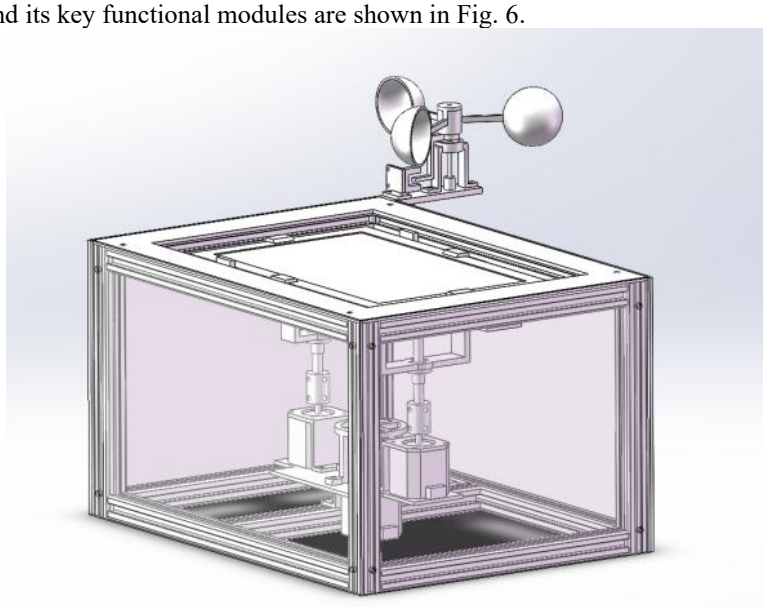


Fig. 5 Overall three-dimensional model of the solar panel bracket

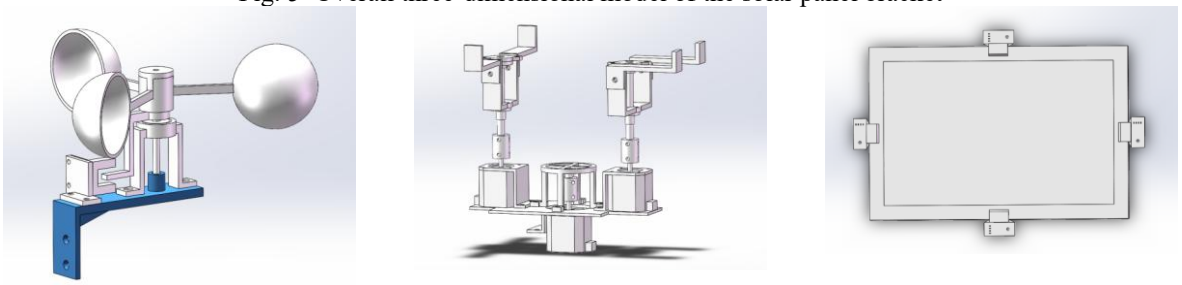


Fig. 6 Three-dimensional models of the key functional modules
(a) wind-speed measurement module; (b) rotation module; (c) solar panel and photoresistors

4.2 Part Fabrication and Assembly

A combination of 3D printing and laser cutting was employed for the non-standard structural parts. Components with complex curved surfaces — the solar panel support module, the stepper motor bracket, the wind-speed module housing and the photoresistor brackets — were produced by 3D printing, whereas regular plate-type parts such as the rotation bracket, the diamond-shaped fixing base and the external housing were fabricated by laser cutting.

After fabrication, step-by-step assembly and commissioning were carried out in the order "main frame — drive motors — detection sensors — solar panel". The assembly of each stage is shown in Fig. 7.

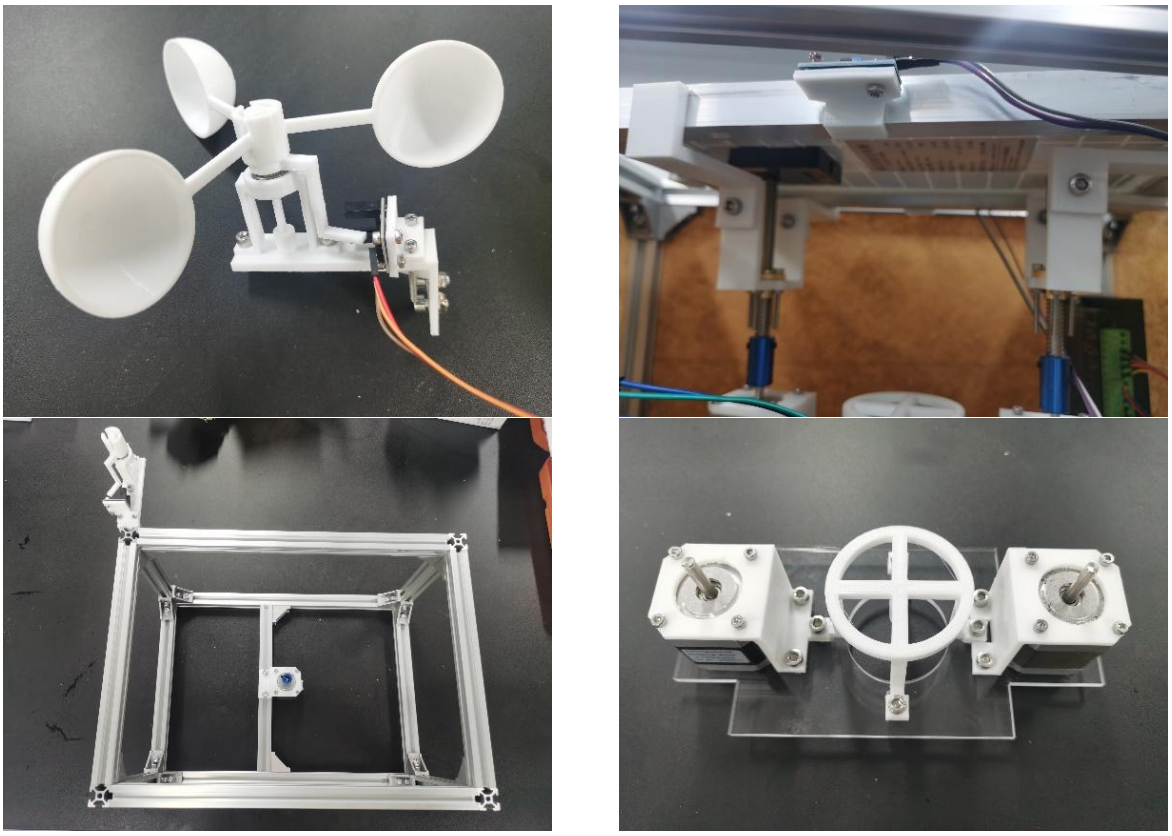


Fig. 7 Fabrication and assembly of the parts
(a) installation of the wind-speed measurement module; (b) installation of the solar panel support frame; (c) frame assembly; (d) motor installation

4.3 Sensor Selection and Calibration

Two types of core sensors are used to detect wind speed and illumination respectively. Before installation, test circuits were built on breadboards to verify data acquisition, as shown in Fig. 8.

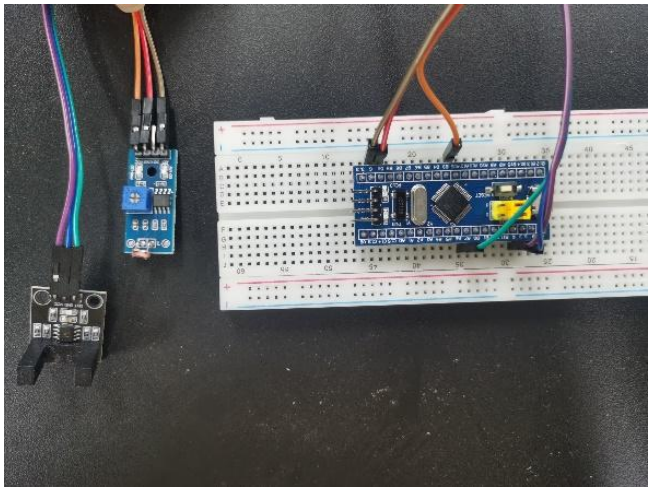


Fig. 8 Data-acquisition experiment for the two types of sensors

Optoelectronic wind-speed sensor: rotating cups drive a grating, and a photoelectric sensor outputs a pulse train. The sensor returns a digital voltage of 0 V or 5 V, indicating whether an obstacle is present near the direction faced by the emitter. The microcontroller counts through its digital input pins and combines the count with the corresponding time interval to obtain the rotational speed, which is then converted into the real-time wind speed. Its output is a digital signal, giving a fast response and strong anti-interference capability.

Photoresistor sensors: four units are evenly distributed around the solar panel and worked with shading baffles to distinguish directions. The resistance of a photoresistor varies with light intensity and is converted by

a voltage-divider circuit into an analog voltage of 0–5 V, which is acquired by the ADC peripheral of the microcontroller, thereby indirectly yielding the light intensity in each direction and thus determining the relative solar azimuth. The actual installation of the two sensor types is shown in Fig. 9.

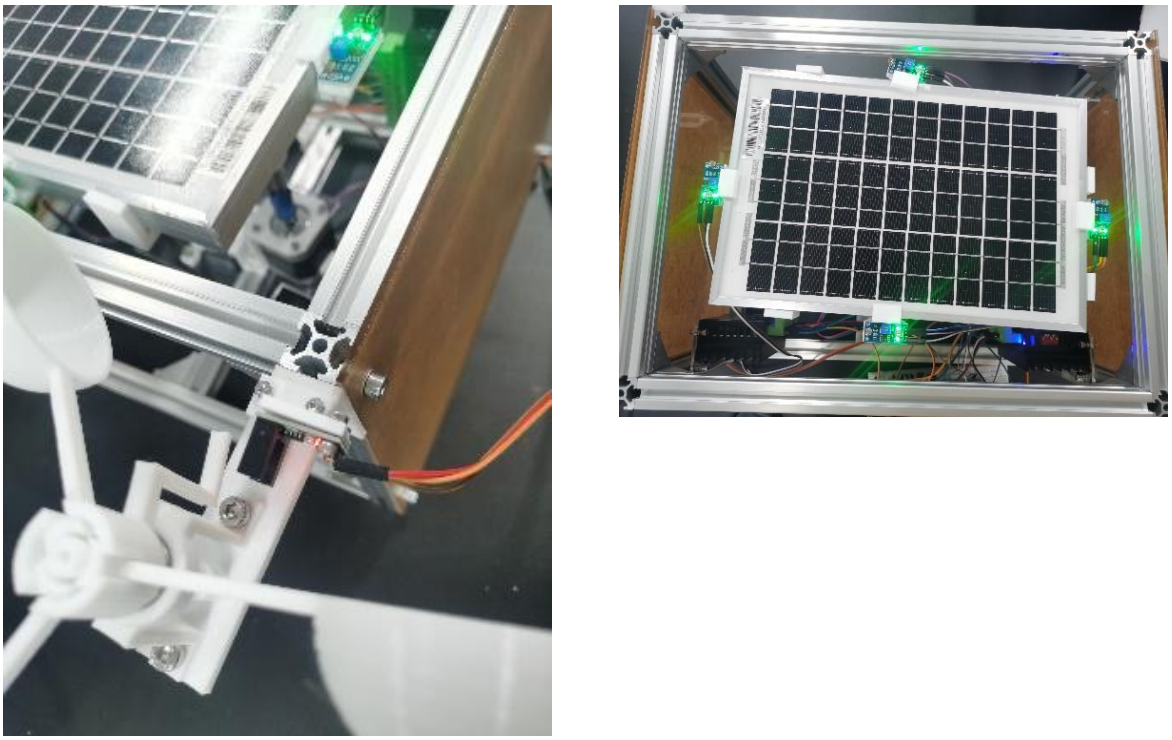


Fig. 9 Sensor installation
(a) optoelectronic sensor; (b) photoresistor

4.4 Control System Development

The system is built around an STM32 microcontroller, and the control program is developed in KEIL. It mainly comprises three functions.

(1) Peripheral initialization: the ADC acquisition channels, stepper motor drivers, pulse input capture and serial communication are initialized, and startup self-test information is output to ensure correct hardware operation, as shown in Fig. 10.

```
int i = 0;
int time = 0;
char Temp_buf[4];
Adc_Init();//初始化ADC1。启用通道0 1 8 9
Motor_Init();//初始化电机123
Key_Init();//初始化输入捕获，选用PA8
uart_init(115200);
printf("GET good!\r\n");
```

Fig. 10 Hardware peripheral initialization program

(2) Wind-speed detection and wind-resistance control: input capture acquires the pulses of the wind-speed sensor and computes the real-time wind speed; according to the preset threshold logic, control signals are output to drive the motors that adjust the panel tilt and height, thereby realizing graded wind protection, as shown in Fig. 11.

```
while (1)
{

    if(Key_GetNum() == 0)
    {
        KeyNum++;
    }

    if(KeyNum == 10)
    {
        MotAngle1 = -MotAngle1;
        MotAngle2 = -MotAngle2;
        MotAngle3 = -MotAngle3;

        Motor1_Turn_Angle_New(MotAngle1);
        Motor2_Turn_Angle_New(MotAngle2);
        Motor1_Turn_Angle_New(MotAngle3);
        MotAngle1 = 0;
        MotAngle2 = 0;
        MotAngle3 = 0;
        KeyNum = 0;
        flag = 0;
```

Fig. 11 Wind-speed measurement algorithm

(3) Tracking control algorithm: the four photoresistor voltages are sampled periodically, the solar azimuth deviation is determined by difference calculation, and two-dimensional rotation motors are driven until the four light intensities converge, which completes the tracking action, as shown in Fig. 12.

```
if((Guangming_ADC[2] - Guangming_ADC[3]) > 100)
{
    MotAngle3 = MotAngle3 + 100;
    Motor1_Turn_Angle_New(100);
}
else if((Guangming_ADC[2] - Guangming_ADC[3]) < -100)
{
    MotAngle3 = MotAngle3 - 100;
    Motor1_Turn_Angle_New(-100);
}
```

Fig. 12 Solar-tracking control algorithm

4.5 Finished Prototype

After the modelling, fabrication, assembly and program debugging described above, the finished prototype of the bracket system was obtained. An aluminium profile frame forms the main body, an adjustable-tilt solar panel is mounted on the top, photoresistors are arranged around the panel, and the wind-speed monitoring module together with the stepper motor drive unit is installed on the side. The overall structure is compact with clear module boundaries, facilitating subsequent maintenance and functional expansion. The finished prototype is shown in Fig. 13.

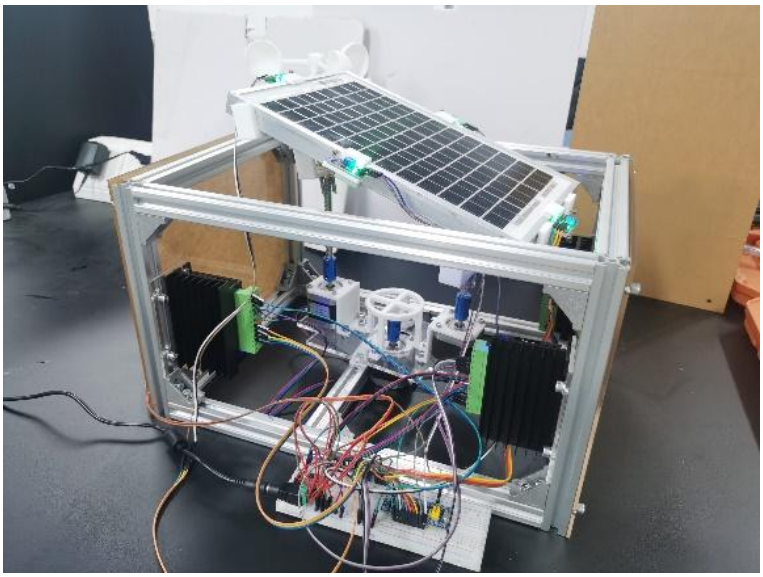


Fig. 13 Finished prototype of the solar panel bracket

5 Experimental Tests and Analysis

To verify the functional feasibility of the bracket system, a simple test platform was built and simulation tests were carried out for the tracking function and the wind-resistance function respectively.

5.1 Solar-Tracking Test

Manual shading was used to simulate the change of the solar azimuth, and tests were performed in both the vertical elevation direction and the horizontal azimuth direction, as shown in Fig. 14. During the tests, the system automatically adjusted the panel angle according to the change in light distribution so that the panel always faced the direction of strongest illumination, verifying the effectiveness of the tracking function. Repeated trials gave consistent results, indicating that the tracking function has good repeatability.

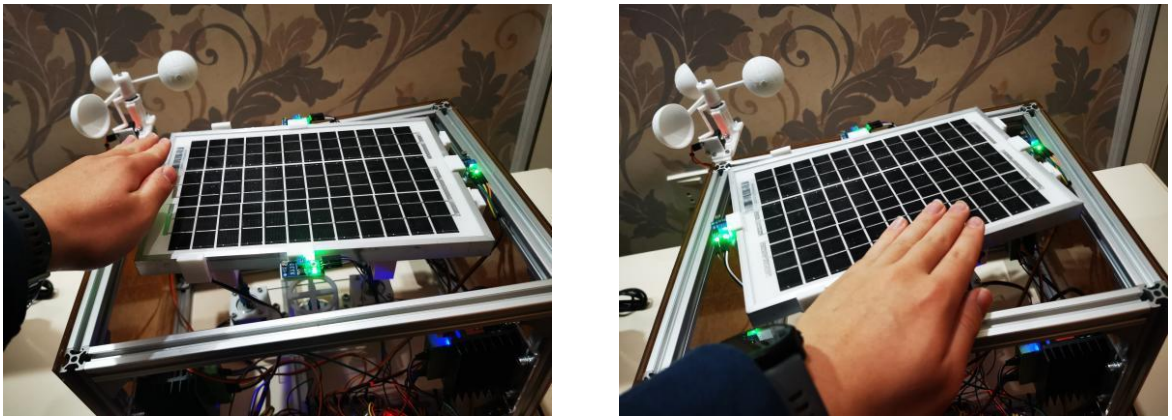


Fig. 14 Simulated solar-tracking test
(a) test in the vertical direction; (b) test in the horizontal direction

5.2 Wind-Resistance Test

The wind-speed module was manually rotated back and forth to simulate incoming wind of different intensities, so as to test the graded protection logic of the system, as shown in Fig. 15. The results show that when the simulated wind speed reached the first threshold, the system automatically drove the panel to rotate to a horizontal posture to reduce the windward area; when the wind speed rose further to the second threshold, the system triggered the secondary protection and completed the retraction action. The correctness of the wind-resistance control logic was verified, and the device operated stably under simulated low to moderate wind speeds.

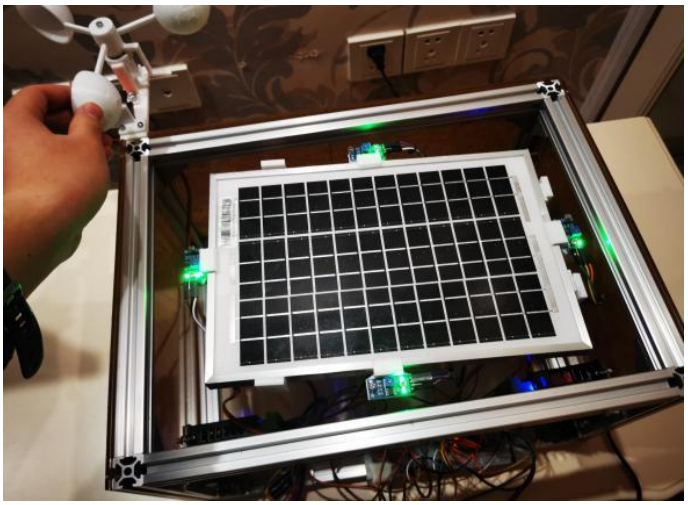


Fig. 15 Wind-resistance test

5.3 Summary of the Tests

Taken together, the two tests show that the proposed wind-resistant solar-tracking bracket is feasible in principle and stable in function, and that it achieves the intended solar tracking and graded wind protection. Nevertheless, the tests also revealed that the current prototype exhibits considerable vibration under simulated high wind speeds, leaving room for improvement in structural rigidity; further optimization of the mechanical design is therefore required.

VI. Conclusions and Future Work

To address the key pain points of conventional solar brackets, this paper designed a solar panel bracket system integrating wind protection and intelligent tracking, and completed scheme selection, prototype development and functional verification. The results show that the bracket can effectively track the solar azimuth and improve the received light energy, and that through the dual-threshold graded protection strategy it ensures structural safety under low to moderate wind speeds, combining practicality with reliability. Economic and environmental assessments show that the scheme has controllable costs, conforms to the direction of clean energy development, and possesses high promotional value.

At the same time, this study has certain limitations. The wind-resistance grade of the current prototype is limited and its stability under high wind speeds is insufficient, and the tracking accuracy is affected by the layout of the photoresistors and by ambient stray light, leaving room for optimization. Future work will proceed in three directions: first, optimizing the mechanical structure of the bracket to improve structural stability and the wind-resistance grade under high wind speeds; second, improving the tracking algorithm and incorporating time-trajectory correction to raise tracking accuracy; and third, further optimizing component selection to reduce the overall system cost and promote engineering application.

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