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QUALIFICATION PAPER

(EXPLANATORY NOTE)

FOR THE ACADEMIC DEGREE OF BACHELOR

Title: “Control System of Solar Panel Tilt Angle”

Submitted by: student of group Ba-151-21-2-CY _____ Marharyta KOVTUN

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Kyiv 2025

ДЕРЖАВНИЙ УНІВЕРСИТЕТ «КИЇВСЬКИЙ АВІАЦІЙНИЙ ІНСТИТУТ»
Факультет аеронавігації, електроніки та телекомунікацій
Кафедра авіоніки та систем управління
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ЗАТВЕРДЖУЮ

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« _____ » _____ 2025 р.

ЗАВДАННЯ

на виконання кваліфікаційної роботи

Ковтун Маргарити Юріївни

1. Тема кваліфікаційної роботи «Система управління кутом нахилу сонячної панелі» затверджена наказом ректора від «20» березня 2025 р. № 429/ст.
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5. Перелік обов'язкового ілюстративного матеріалу: Алгоритм для розробки системи управління; Схема підключення системи; Робота системи при низькому рівні освітлення та високій вологості; Система за умови, що Сонце знаходиться нижче горизонту; Результати для фіксованої панелі; Результати для рухомої панелі з 2 осями.

6. Календарний план-графік

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2	Розробка системних вимог та вибір компонентів	22.05.2025 – 23.05.2025	виконано
3	Аналітичні розрахунки: визначення висоти та азимута Сонця	24.05.2025 – 26.05.2025	виконано
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“__-__” _____ 2025

Qualification Paper Assignment for Graduate Student

Kovtun Marharyta Yuriivna

1. The qualification paper title “Control System of Solar Panel Tilt Angle” was approved by the Rector’s order of March 20, 2025 № 429/CT.
2. The paper to be completed between: 19.05.2025 and 14.06.2025
3. Initial data for the paper: solar panel, azimuth of the Sun, elevation angle of the Sun, humidity and temperature sensor, photoresistor.
4. The content of the explanatory note: Analysis of the object of study; Development of a panel angle control system; Implementation of the control system on the Arduino platform; Comparison of the operating efficiency of a movable and fixed solar panel.
5. The list of mandatory illustrations: Algorithm for developing the control system; System connection diagram; System operation at low light level and high humidity; System provided that the Sun is below the horizon; Results for a fixed panel; Results for a movable panel with 2 axes.

6. Timetable

№	Assignment	Dates of completion	Completion mark
1	Analysis of scientific sources and justification of the research	19.05.2025 – 22.05.2025	completed
2	Development of system requirements and component selection	22.05.2025 – 23.05.2025	completed
3	Analytical calculations: solar elevation and azimuth determination	24.05.2025 – 26.05.2025	completed
4	Arduino-based system design and simulation in Wokwi	27.05.2025 – 01.06.2025	completed
5	Efficiency analysis of movable vs fixed panels	02.06.2025 – 04.06.2025	completed
6	Formatting of scientific work: introduction, conclusions, abstract	05.06.2025 – 08.06.2025	completed

7. Assignment issue date: “05” May 2025

Qualification paper supervisor _____
(the supervisor's signature)

Antonina KLIPA

Issued task accepted _____
(the graduate student's signature)

Marharyta KOVTUN

ABSTRACT

The text part of the work: 78 pages, 33 figures, 8 tables, 12 references.

Research object: the process of automated positioning of solar panels to increase the efficiency of electricity generation.

Research subject: a system for controlling the angle of tilt of the solar panel, taking into account the position of the Sun and external factors (lighting, humidity).

Research methods: mathematical modeling and optimization techniques.

Scientific novelty of the obtained results: as part of the qualification work, a concept was developed for an automated solar panel positioning control system that takes into account the current location of the Sun and current meteorological conditions. For the first time, it was proposed to adapt tracking algorithms based on astronomical calculations for a simplified control model implemented on the Arduino platform. The scientific novelty lies in the generalization of known approaches to panel orientation, which take into account not only astronomical parameters but also meteorological data obtained in real time, which contributes to increased orientation accuracy without the use of expensive sensor systems.

Practical significance of the obtained results: the proposed system can be used to create inexpensive automated solutions for orienting solar panels in private households, educational projects, or where energy resources are limited. Experiments demonstrate the possibility of effectively using inexpensive microcontrollers and standard electronic components to create energy-saving systems. The practical value lies not only in the functional system, but also in the methodology of gradual implementation of control, which can be adapted to various geographical locations.

CONTROL SYSTEM, AUTOMATION, SOLAR PANEL, TILT ANGLE.

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LIST OF ABBREVIATIONS

AC – Alternating Current;
DC – Direct Current;
DS – Daylight Saving;
ET – Equation of Time;
IDE – Integrated Development Environment;
LAT –Latitude;
LDR – Light Dependent Resistor;
LED – Light-Emitting Diode;
LL – Local Longitude;
LON – Longitude;
LST – Local Standard Time;
NREL – National Renewable Energy Laboratory;
OLED – Organic Light-Emitting Diode;
RES – renewable energy sources;
RTC – Real Time Clock;
SES – Solar Energy System;
SL – Standard Longitude;
TST – True Solar Time.

INTRODUCTION

With the growing desire for energy self-sufficiency and the transition to sustainable energy sources, the use of solar energy is becoming increasingly important. Modern technologies make it possible not only to fix solar panels in the optimal position, but also to ensure their dynamic orientation, taking into account the constant change in the position of the Sun in the sky. This makes it possible to significantly increase the efficiency of electricity generation, which is critically important in conditions of limited space for the placement of photovoltaic systems or at a low level of insolation.

The initial data for the implementation of this topic are the geographical location of the object, the parameters of the solar panel, the technical characteristics of the system components (sensors, servo motors, controller), as well as mathematical models for calculating the position of the Sun.

Automated tracking systems for solar panels are being actively implemented in the world, which are able to adjust the angle of inclination and orientation relative to the Sun in real time. Developed countries show high efficiency of such solutions in both industrial and private institutions. At the same time, in Ukraine, such technologies have not yet gained wide popularity due to their high cost or technical complexity, which makes it relevant to develop an affordable automated system that can be implemented using the popular Arduino microcontroller platform and simple sensors. The choice of the research topic is also due to its relevance for Ukraine in the conditions of war, when the transition to renewable energy sources will ensure stable energy autonomy.

The relevance of the study is due to the global transition to renewable energy sources, which helps to reduce greenhouse gas emissions and minimize the impact on the climate. The topic is relevant for Ukraine in the context of the energy crisis, the need for efficient use of solar energy is growing, because fixed solar panels do not provide maximum absorption of energy from the Sun due to its constant change of position. will reduce the need for traditional energy sources and is a promising solution for ensuring stable power supply in critical infrastructure, military and civilian facilities.

The purpose and objectives of the qualification work. The main goal of the work is to develop a solar panel angle control system that relies on predicting solar activity to ensure the maximum use of solar energy. To achieve this goal, the following tasks need to be solved:

1. To study the principle of operation of solar power plants and the influence of the position of the panel on the efficiency of generation.
2. To develop an algorithm for automatic control of the panel position depending on weather conditions.
3. To select the optimal hardware components for the implementation of the system.
4. To develop software taking into account the position of the Sun.
5. To test the system in different weather conditions.
6. To conduct a comparative analysis of the efficiency of the movable and fixed panel.

CHAPTER 1

ANALYSIS OF THE OBJECT OF STUDY

1.1. The principle of operation of solar power plants

In the modern world of rapid technical development and growth of energy consumption, the issue of environmental safety and energy independence is becoming increasingly relevant. Traditional energy sources (gas, oil, coal, etc.) have a number of significant drawbacks: they are limited, pollute the environment and increase greenhouse gas emissions that contribute to global warming. Therefore, renewable energy sources (RES) are now starting to play an important role. RES includes solar, wind, hydro and geothermal energies, which are practically inexhaustible, environmentally friendly and can significantly reduce dependence on fossil fuels that have limited reserves, which will be exhausted sooner or later. As of 2025, more than 140 countries have announced net-zero emission plans, with deadlines ranging from 2030 to 2070. The implementation of these plans is unattainable without a large-scale transition to renewable energy sources.

Among various RES, solar energy stands out as a leader, accounting for 41% in 2023. According to scientists, our Sun has the potential to exist for about five billion years. From a human perspective, the use of solar energy, which is renewable, does not involve the risk of exhaustion.

Department of ACS				EXPLANATORY NOTE			
Submitted by	Kovtun M.Y.			CHAPTER 1. ANALYSIS OF THE OBJECT OF STUDY		Page	Pages
Supervisor	Klipa A.M.					13	76
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Head of department	Tachynina O.M.						

Developments in the field of solar energy are promising given the significant growth of the renewable energy market. A study by Nova One Advisor found that the global renewable energy market was valued at US\$1.14 trillion in 2023 and is projected to reach approximately US\$5.62 trillion by 2033, with a CAGR of 17.3% during 2024-2033 (Fig.1.1) [1].

According to the study, Ukraine plans to increase the percentage of electricity production from renewable sources from 4% to 25% by 2035 [2].

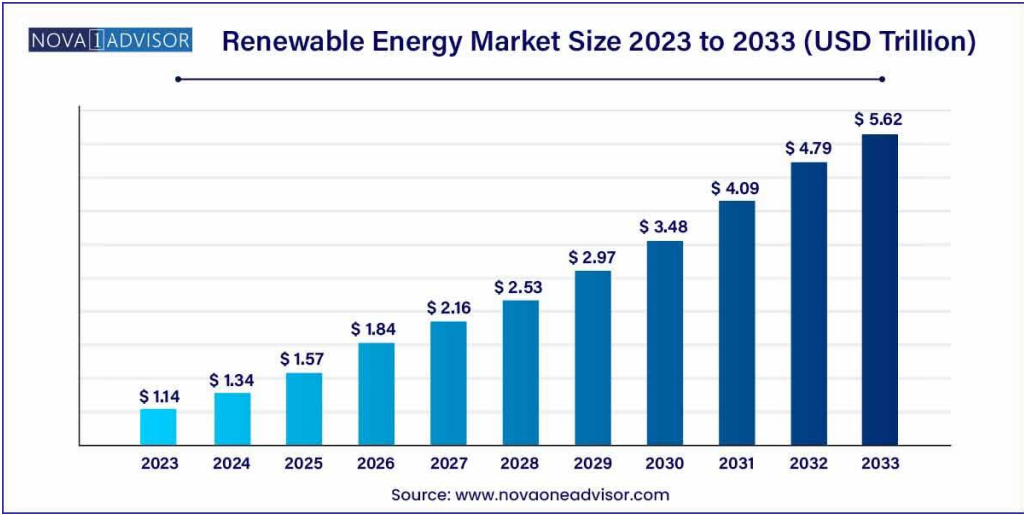


Fig.1.1. Forecast of the renewable energy market over the next 10 years

The Asia-Pacific region is the leader in the world market of energy from renewable sources (Fig.1.2), the primacy here belongs to mass installations of solar power plants in China, Japan, India and Australia. Due to its significant coastline and favorable solar radiation, this region has become home to the largest solar power plants (in particular, the Tengger Desert Solar Park).

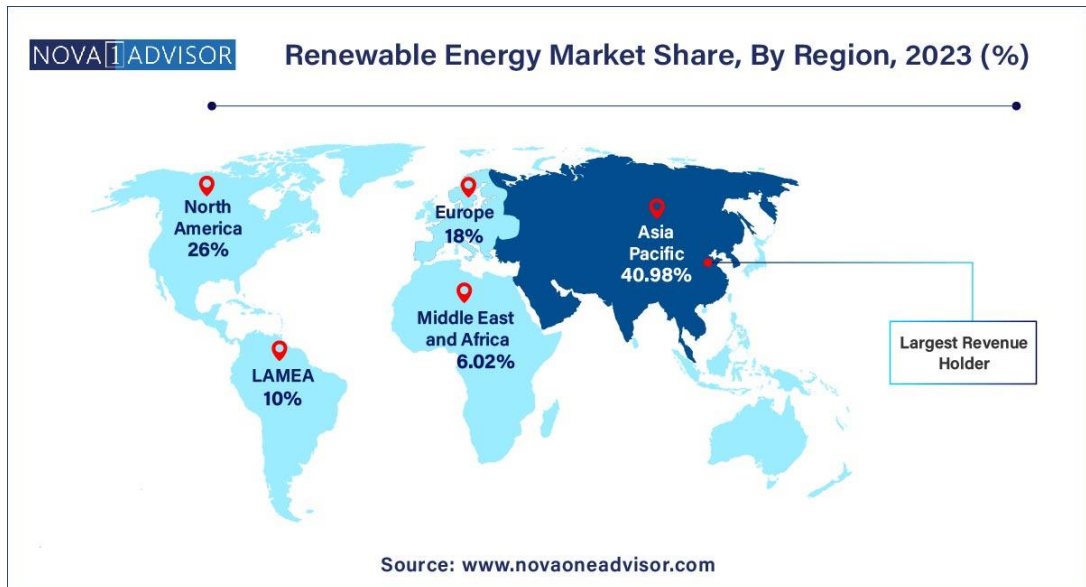


Fig.1.2. Global renewable energy market

A solar energy system (SPS) is an electricity supply system designed to supply usable solar energy through photovoltaic cells. It includes several key components, including solar panels for absorbing and converting sunlight into electricity, a solar inverter for converting DC energy into alternating current energy, as well as other mounting structures, cables and other electrical fittings for setting up the working system (Fig.1.3) [3].

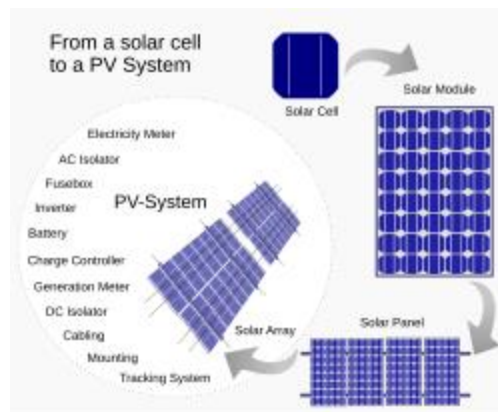


Fig.1.3. Diagram of possible components of a photovoltaic installation

A photovoltaic system for power supply to residential, commercial or industrial premises consists of a solar panel and a number of components, which are often defined as the balance of the system. System balance is power conditioning equipment and mounting structures, usually one or more DC-to-AC converters, also known as inverters,

an energy storage device, a racking system that supports a solar panel, electrical wiring and connections, and fasteners for other components.

Optionally, the system's balance may include any or all of the following: a profit-grade meter using a renewable energy credit, a maximum power point tracker, a battery system and charger, a solar tracker, energy management software, solar radiation sensors, an anemometer, or specialized accessories designed to meet the special requirements of the system owner.

Photovoltaic installations can be distinguished by a number of features: those connected to the mains and autonomous systems; integrated into buildings and located on racks. There are also household and communal systems, distributed and centralized; roof and ground; systems with sun tracking and those with a fixed angle of inclination. Additional differences may be the use of microinverters or central inverters, as well as crystalline silicon or thin-film technologies, which also take into account the features of the photovoltaic modules used.

The key component of the solar power plant is the solar panel (Fig.1.4). This is a structure mounted from photovoltaic modules, or solar cells, which are connected and protected in a frame. Sunlight hits the element, causing a complex physicochemical reaction (photoelectric effect). Each solar cell generates direct current when sunlight hits it. The more powerful the light and the more correct the angle of incidence of the rays, the greater the efficiency of electricity production.



Fig.1.4. Solar panels

The resulting direct current is usually stored in batteries or converted by the inverter into alternating current, which can be used in home or industrial power grids. For reliable

and safe operation, the solar power plant is equipped with a charge controller, protective components, and sometimes monitoring and automatic control systems.

The efficiency of solar power plants largely depends on the location, weather conditions and the correct orientation of the panels relative to the Sun. Therefore, in modern projects, tracker systems are increasingly used – mechanisms that automatically adjust the angle of inclination of panels during the day, following the Sun. This allows you to maximize the use of solar energy and increase the efficiency of the power plant.

With their environmental friendliness, renewability, and growing economic benefits, solar power plants are playing an increasingly important role in the global energy transition to clean energy sources.

1.2. Impact of panel tilt angle on power plant generation efficiency

The angle of inclination of the solar panel is one of the key parameters that directly affects the efficiency of converting sunlight into electrical energy. The amount of energy that the panel can collect during the day or year depends on the correct setting of this angle.

Since during the year the Sun changes its location in the sky: in winter it rises low, and in summer it rises high. Therefore, a fixed angle is not able to ensure the maximum use of solar energy in all seasons. That is why the introduction of a dynamic system for changing the angle of inclination (tracker system) significantly increases the productivity of the station. Studies demonstrate that automatically adjusting the angle of inclination according to the position of the Sun can increase the annual generation volume by 20–30% compared to a fixed system.

The main purpose of adjusting the angle of inclination is to guarantee the most perpendicular penetration of the sun's rays on the surface of the photovoltaic modules, which reduces light reflection and energy loss. It is possible to achieve this need for solar structures only with the use of special swivel structures with a two-axis sun tracking system, the so-called tracker systems. In the case of a fixed position of the panels, the

angle is determined depending on the latitude of the terrain and is guided by the average annual position of the Sun [4].

The solar energy tracking system tilts the solar panel throughout the day. Depending on the type of tracking system, the panel is pointed either directly at the Sun or at the brightest area of the partially cloudy sky. Trackers noticeably improve performance in the early morning and late afternoon, increasing the total amount of energy produced by the system by about 20–25% for a single-axis tracker and about 30% or more for a two-axis tracker (Fig.1.5), depending on latitude. In diffused light (i.e., under clouds or fog), tracking has little or no use. Since most concentrated photovoltaic systems are very sensitive to the angle of sunlight, tracking systems allow them to produce usable energy for more than a short period each day. Tracking systems improve performance for two main reasons. First, when a solar panel is positioned perpendicular to sunlight, it receives more light on its surface than if it were angled. Second, direct light is used more efficiently than angular light.



Fig.1.5. Two-axis solar trackers

For the coordinated operation of solar panels that change position, not only technical equipment for automatic angle adjustment is critical, but also a reasonable choice of location. Unlike fixed systems, movable panels require more space for free maneuver, which is especially important for two-axis trackers.

The best option is an open, unshaded space with minimal risk of shadow from trees, buildings or other obstacles throughout daylight hours. Even a short-term shading of a

part of the panel can lead to a noticeable decrease in the overall efficiency of the entire system. The height of objects on the horizon line should be especially taken into account, because the tracker system tracks the position of the Sun from dawn to dusk.

In addition, the terrain must be sufficiently flat or provide for installation on specially prepared structures. It is equally important to take into account the wind load - moving panels are less resistant to strong gusts of wind, therefore, in windy regions, reinforced fastening or installation of a system with the function of automatically transferring the panels to a protected position is necessary.

The advantages of solar tracking technologies depend on the parameters of solar radiation, in particular its amount and type. The main types of solar radiation are divided into direct radiant and diffuse radiation. Direct radiant radiation is sunlight that directly reaches the Earth in a straight line, while diffuse radiation is light scattered in the Earth's atmosphere and reaches the surface at different angles.

Solar trackers that track the movement of the Sun across the sky work best with direct radiation, as they can be directly targeted at a light source. But they are of little use for collecting diffuse radiation, because the latter is not concentrated in a specific direction. For example, in the eastern United States, compared to the west, there is a higher annual cloudiness. Therefore, the eastern regions receive a greater share of diffuse radiation, which reduces the effectiveness of tracking technologies, so solar panels with a fixed angle of inclination are more often used there. In the west of the country, where direct solar radiation predominates, single-axis photovoltaic panels follow the sun from east to west, thus increasing the collection of direct radiation compared to fixed-axis installations (Fig.1.6) [5].

Operable utility-scale solar photovoltaic generating units (2015)

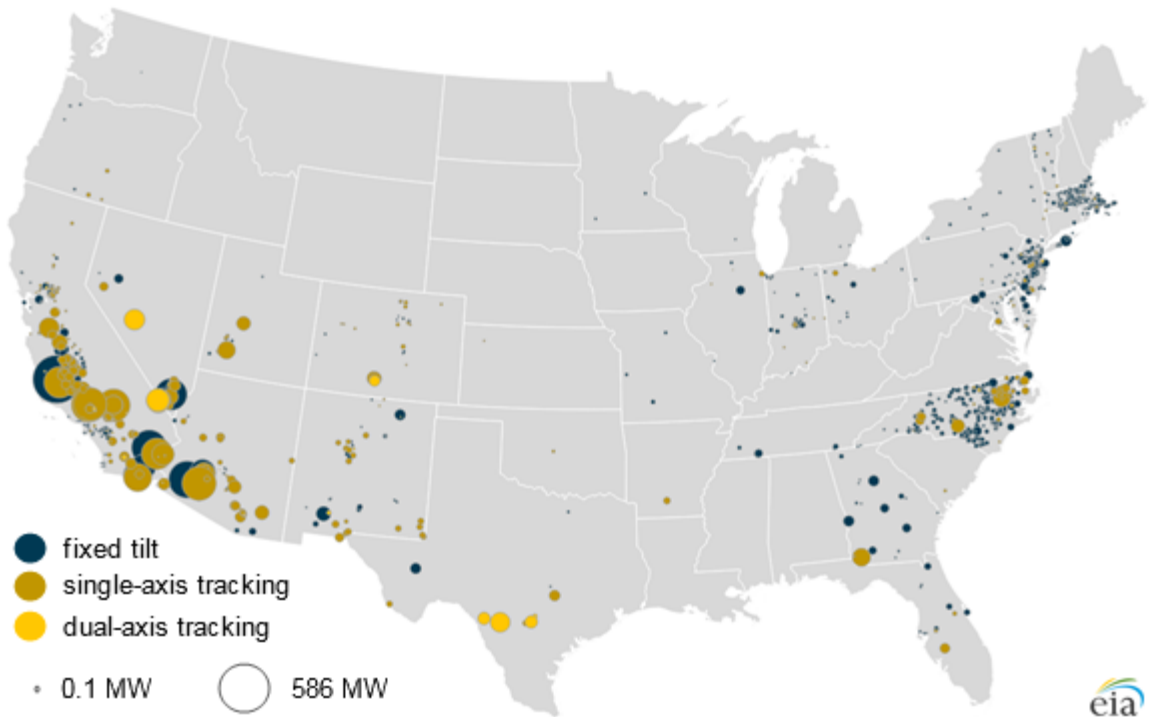


Fig.1.6. Location of solar panels in the United States

Financial aspects also have an impact on the choice between fixed mounting and the use of solar tracking technology. Fixed tilt installation is cheaper than solar panels with installation tracking technology. Single- and dual-axis tracking systems require additional installation space, and the tracking systems themselves have a higher cost. However, tracking systems, while more expensive, have the potential to produce more electricity. For example, the PVWatts calculator developed by the National Renewable Energy Laboratory demonstrated that over the course of a year, a 10-kilowatt photovoltaic system in Los Angeles, California, that uses a single-axis tracking system would produce 21% more electricity than a 20-degree fixed-tilt system. A two-axis tracking system in the same location will produce 31% more than a fixed-tilt system [6].

Therefore, the use of systems with adjustable tilt ensures the best absorption of sunlight during the day, which is especially important in conditions of unstable sunlight.

1.3. Existing methods and systems for orientation of solar panels

At the moment, there are several key strategies for setting up solar panels designed to capture solar energy the most, given the movement of the Sun in the sky. The final choice of method is determined by the climatic features of the area, the purpose of use and economic feasibility.

Fixed systems are the simplest and cheapest. They are mounted at a fixed angle, which is selected depending on the latitude. The negative side is reduced return in the morning and evening, as well as in the off-season.

Systems with seasonal adjustment of the angle of inclination allow you to change the angle of inclination manually several times a year, mostly three times: in spring, summer and winter. The optimal angles of inclination of the panel depending on the time of year are shown in Fig.1.7. This makes it possible to increase electricity production without complex technological solutions, but requires the participation of service personnel [7].



Fig.1.7. Recommendations for the angle of inclination of solar panels, depending on the season

Single-axis trackers automatically rotate the panels from east to west, tracking the movement of the Sun during the day. They make it possible to increase the efficiency of the system by 20-30% compared to fixed installations. Such systems are especially relevant in regions with intense solar radiation.

Dual-axis trackers provide the most performance because they can accurately orient the panel to the Sun at any given time, changing both the angle of inclination and the angle of rotation. They can increase electricity production by 35–45%, however, they require a higher investment, are more difficult to maintain, and have higher energy costs.

There are different types of solar trackers, differing in the mechanism of movement:

Active trackers. They use a system of motors and gears to control the movement, which is controlled manually or programmed. Single-axis active trackers have one degree of freedom and rotate from north to south or from east to west, depending on the latitude of the panel installation which changes the angle of the tracker's axes depending on the position of the sun in the sky. After determining the optimal lighting angle, the motor turns off and the sunlight collects. Usually, active trackers produce more energy and are more efficient than passive ones (discussed below), but they consume more of their own energy due to engine operation. They are more commonly used in large systems where they seek to get the most energy from sunlight; However, single-axis active trackers are also popular among home users who want to increase solar energy production without significant costs.

Passive trackers. Another main type of trackers is a passive tracking system. These trackers do not contain motors, but use the sun's heat to direct the tracker's movement. A shader/reflector system is used to direct morning sunlight to "wake up" the panel, and this can take up to an hour. However, recently they have begun to use various self-leveling schemes to install the tracker so that the panel can start working immediately after sunrise. Passive trackers are by far the most popular type in home solar systems. They are usually cheaper, require less maintenance, and provide high conversion efficiency.

Chronological trackers. These unique trackers work on the principle of the opposite rotation of the Earth, turning in the opposite direction at the same speed. The tracker contains a timer and an engine similar to an active tracker that rotates based on a predefined program that takes into account the date, time, latitude, year, and other parameters [8].

1.4. Advantages and disadvantages of automated systems

Automated solar panel orientation control systems have been an important step in the evolution from traditional fixed designs to more modern solutions that make it possible to maximize the potential of solar energy. However, like any technical innovation, such systems have their strengths and weaknesses that should be taken into account when implementing.

Advantages of automated systems:

1. Increasing the efficiency of power generation.

One of the key advantages is the ability to monitor the position of the Sun during the day and change the angle of inclination of the panel accordingly. This makes it possible to increase the amount of absorbed solar energy by 20-45% compared to fixed systems, depending on the type of tracker and operating conditions.

2. Optimization of work in real time.

Automatic systems are able to respond to changes in weather conditions (lighting, humidity, temperature), which ensures the most rational use of resources. For example, on cloudy or rainy days, the system can stop traffic, which reduces energy costs for drives.

3. Reducing the need for human intervention.

Automatic control systems work without the need for constant operator involvement. This reduces labor costs for maintenance, eliminates the risks of human error and allows remote monitoring.

4. Flexibility of settings.

With the help of microcontrollers, you can adjust the motion logic, determine the thresholds of parameters for activation, and create different operating modes — for example, daytime, economy, or test.

Disadvantages of automated systems:

1. Higher cost of implementation.

Automated systems require additional equipment — servo motors, controllers, sensors, rotation mechanisms, and more. This increases the initial costs of project implementation.

2. Complexity of design and maintenance.

With an increase in the number of components, the likelihood of breakdowns increases, which requires periodic technical inspection and repair. Also important is the need to protect electronic components from weather influences (moisture, dust, temperature extremes).

3. Electricity consumption for own needs.

Moving elements, controllers, and displays consume a certain amount of energy, which can affect the overall performance of the system, especially in conditions of insufficient sunlight.

4. Restrictions on use on difficult terrains.

In areas with uneven terrain or limited space, moving the panels can be technically difficult or require individual placement and orientation solutions.

Automated solar panel angle adjustment systems open up wide prospects for increasing the productivity of solar power plants. However, the rationality of their implementation is determined by the size of the project, climatic features, available finances, as well as readiness for technical support.

1.5. Conclusion

In this chapter, a thorough analysis of the object of study, namely the solar panel angle control system, was carried out. Based on the analysis, it has been established that current trends in the energy sector are increasingly focused on the use of renewable energy sources, in particular solar, which is environmentally friendly, free of charge and potentially inexhaustible.

The general principle of operation of solar power plants was considered: from the conversion of solar radiation energy into direct electric current, up to the possibility of its further transformation to meet the needs of consumers. Particular attention was paid to the impact of the design features of the solar installation, in particular, the angle of inclination of the photovoltaic modules, on the efficiency of electricity production. It has been demonstrated that the correct orientation of the panels relative to the Sun can significantly increase the level of electricity production during the day and year.

During the analysis, the available types of panel orientation systems were studied, ranging from simple fixed structures to automated trackers capable of changing their position in two planes. It has been found that automated solutions provide the highest efficiency, but require additional resources for implementation and support.

In addition, the advantages and disadvantages of automated systems were analyzed. Key benefits include: increased productivity, reduced need for manual intervention, and the ability to adapt to weather changes. Among the limitations are indicated: greater complexity of the system, higher cost of implementation, as well as the need for maintenance.

On the basis of the analytical review, a justified need to develop a system for controlling the angle of inclination of the solar panel was formulated. This decision is relevant in the context of improving energy efficiency, reducing the carbon footprint and introducing innovative approaches in alternative energy. In the following chapters of the work, the practical implementation of such a system based on the Arduino platform will be carried out using appropriate sensors, algorithms and visualization.

CHAPTER 2

DEVELOPMENT OF A PANEL ANGLE CONTROL SYSTEM

2.1. Statement of the problem of automatic control

One of the most important factors for increasing the efficiency of solar power systems is the automatic adjustment of the panel according to the location of the Sun. Fixed systems are set up once, which leads to a loss of solar energy, especially in the morning and evening, as well as at different times of the year. Automatic control allows you to dynamically change the angle of the panel, guaranteeing its maximum perpendicularity to sunlight throughout daylight hours.

The goal of automatic control in this project is to develop a system that, based on data from various sensors, in particular: lighting, temperature, humidity, as well as astronomical calculations of the position of the Sun (azimuth and altitude), will be able to:

- decide whether to move the panel (for example, to avoid unnecessary movement in low light or high humidity);
- calculate the optimal angles of rotation of the panel vertically (tilt) and horizontally (azimuth);
- control actuators (servo drives) for precise positioning of the panel;
- provide information to the user through the display.

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Head of department	Tachynina O.M.						

To implement an automated solar panel position control system, it is necessary to clearly outline the principles of its operation and the factors that will influence decision-making. The functioning of the system is based on data coming from several sensors. They measure the light level, air temperature, ambient humidity, as well as the current time. Based on these indicators, the system analyzes the feasibility of moving the panel in order to ensure the most effective capture of sunlight.

The system of automatic adjustment of the angle of inclination of the solar panel operates according to the following mechanism: sensors record information about the intensity of light, temperature and humidity of the surrounding space. At the same time, taking into account the current time, the position of the Sun (azimuth and altitude) is determined using the SunPosition library. In case of favorable conditions (good lighting, acceptable humidity), the system calculates the required angles of inclination and rotation of the panel and transmits this data to servo motors, which, in turn, change the position of the panel. In the evening or in adverse weather conditions, the panel remains motionless. All information is displayed on the OLED display, and also shows the status of the system (active or inactive) using a signal indicator. The algorithm for developing the control system is shown in Fig.2.1.

Let us consider the list of input and output parameters, the conditions for activating the system and the basic principles of interaction between the components of the system.

The input data includes:

1. Solar altitude and azimuth values derived from the astronomical model.
2. Light level.
3. Temperature and humidity.
4. Current time.

Output parameters:

1. Servo position (angle of inclination and rotation of the panel).
2. Status of the indicator LED.
3. Information display on OLED display.

Conditions for the functioning of the system:

1. Active state in sufficient light and permissible humidity.
2. Reaction to changes in the position of the Sun during the day.
3. Transition to an inactive state after sunset or under adverse conditions.

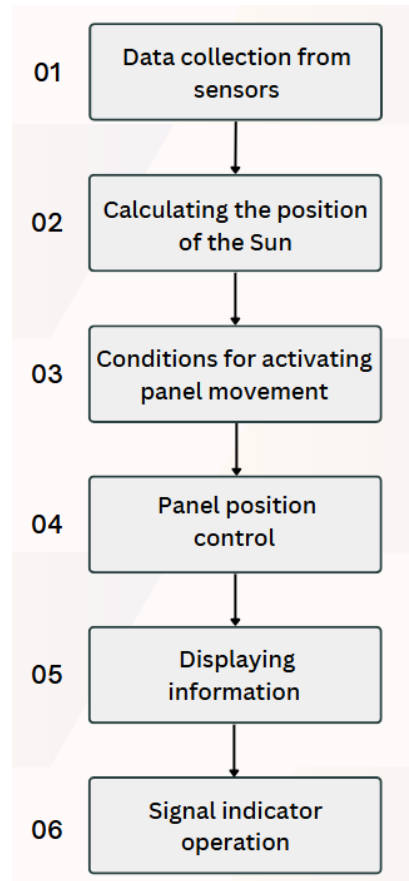


Fig.2.1. Algorithm for developing the control system

2.2. Selecting the microcontroller and main system components

When creating an automated system to control the angle of inclination of a solar panel, the key point was to select the best electronic components. Important factors were: economical use of energy, ease of embedding, functionality and the ability to simulate in the Wokwi environment. Next, each of the selected elements will be considered in detail.

Arduino UNO

The central component of the system is the Arduino Uno microcontroller (Fig.2.2). All elements interact with each other through a microcontroller. He is the coordinator of

data processing and makes decisions on the functioning of the system. With this integration, the device works adaptively, saving energy, and independently, reacting to changes in the external environment in real time. This choice is due to several factors:

- ease of programming thanks to the Arduino IDE;
- a wide range of digital and analog inputs/outputs;
- support for a large number of libraries, in particular for working with sensors, screens, servo motors.

Arduino Uno provides data processing from sensors, performs calculations using an astronomical library, and also generates control signals for the system's actuators [9].

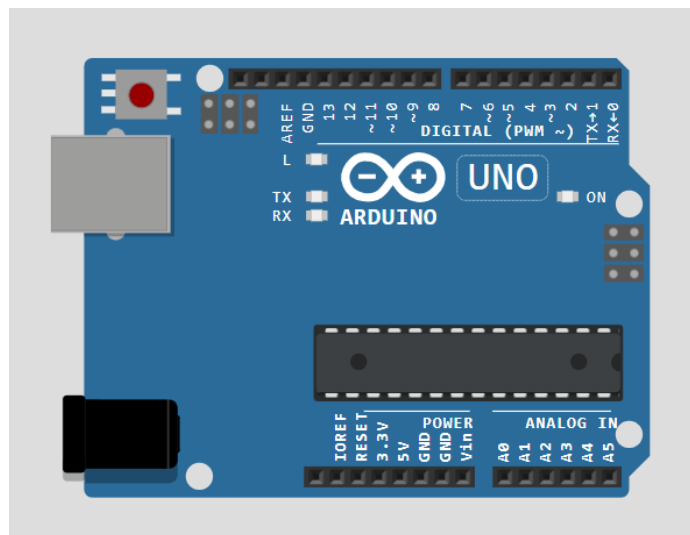


Fig.2.2. Arduino Uno microcontroller

Servo motors

Two servos are used to adjust the position of the solar panel (Fig.2.3):

- one controls the vertical inclination (angle of elevation);
- the second is by rotation horizontally (azimuth).

The servo motors have a simple control system - the angle of rotation depends on the duration of the pulse, which is great for Arduino microcontrollers. They were chosen for accuracy, compactness and sufficient power to move small panels.

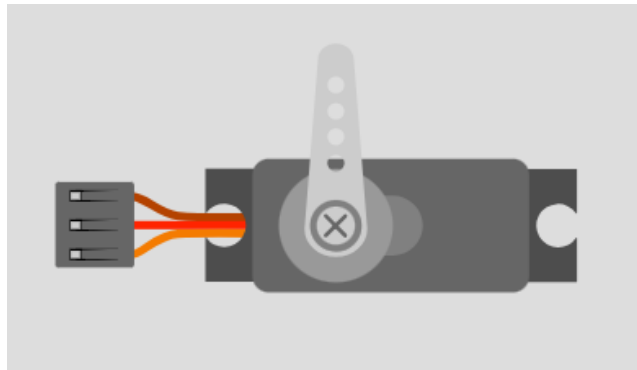


Fig.2.3. Servo motor component

DHT22

The DHT22 combined sensor (shown in Fig.2.4) allows you to read air temperature and relative humidity indicators. Its application allows you to take into account climatic conditions, in particular, to avoid moving the panel in conditions of excessive moisture, which can be dangerous for electromechanical components.

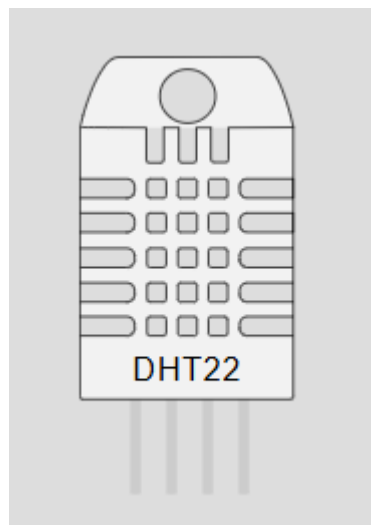


Fig.2.4. Humidity and temperature sensor

The main characteristics of the humidity and temperature sensor are discussed in Table 2.1.

DHT22 specifications

Temperature range	-40°C to +80°C
Humidity range	0-100%
Temperature measurement accuracy	±0,5°C
Humidity measurement accuracy	±2%

Photoresistor (LDR)

The photoresistor shown in Fig.2.5 is used as a light sensor, which makes it possible to determine the presence of a sufficient amount of solar radiation. In the case when the lighting intensity drops below the set value, the system does not start rotation, saving energy and prolonging the operating time of the equipment. The characteristics are shown in Table 2.2.

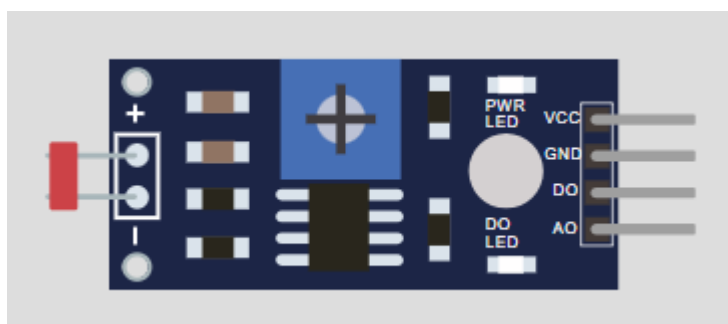


Fig.2.5. Light sensor

Table 2.2

Light sensor characteristics

Operating temperature range	-30°C to +70°C
Resistance in the illuminated state	2-5 kΩ
Resistance without lighting	250 kΩ

DS1307 RTC Module

The DS1307 real-time module (Fig.2.6) guarantees an accurate display of the time required to calculate the position of the Sun. It allows the system to operate in real time, regardless of the time it is turned on or rebooted, maintaining synchronization with the circadian rhythm. Consider the characteristics in Table 2.3.

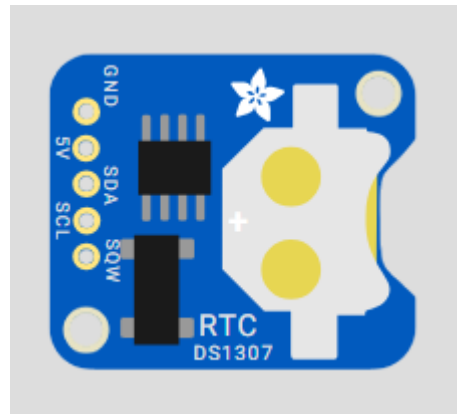


Fig.2.6. Real-time module

Table 2.3

Key features of Real-Time Module

RTC Type	I2C
Time format	24-hour or AM/PM
Supply voltage	5 V
Measurement accuracy	± 1 min/month

OLED display SSD1306

To display up-to-date data, an OLED screen is used SSD1306 (Fig.2.7), with a resolution of 128x64 pixels. It visualizes data on temperature, humidity, illumination, time, as well as calculated angles of the Sun's position, which makes it convenient for tracking the state of the system in real time. The characteristics of the display are discussed in Table 2.4.

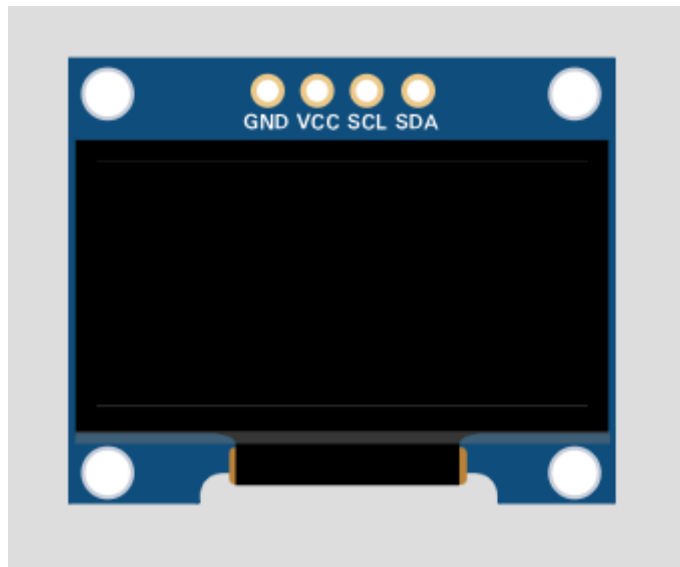


Fig.2.7. OLED display SSD1306

Table 2.4

OLED Display Specifications

Display Type	monochrome OLED
Interface	I2C
Supply voltage	3.3-5V
Extension	128x64 pixels
Contrast	High

LED and Resistor

The LED shown in Fig.2.8 acts as an indicator of the working status - it lights up when the system starts the movement of the panel. To limit the flow of current through the LED, a resistor is also added to the circuit (Fig.2.9), which protects it from burnout. The characteristics of the indicator and resistor are shown in Table 2.5.

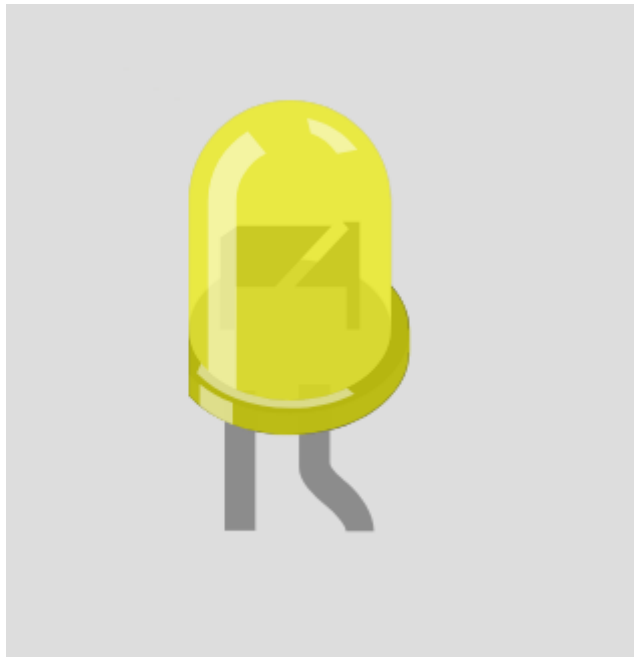


Fig.2.8. Signal indicator

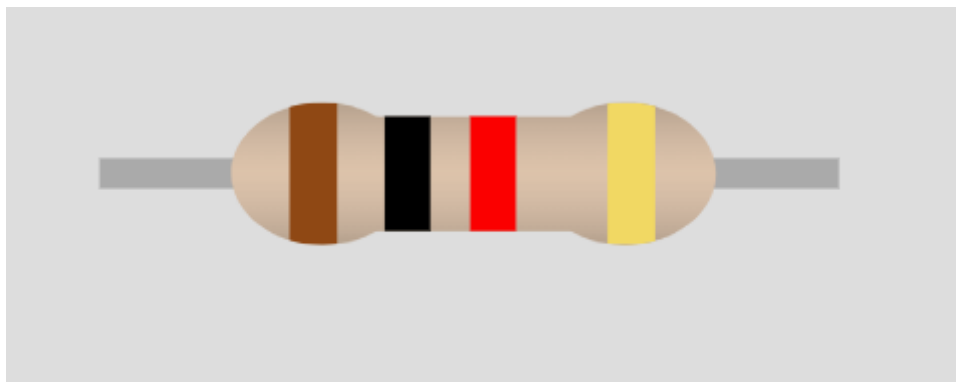


Fig.2.9. Resistor

Table 2.5

Main characteristics of LED and resistor

Led	Standard 5 mm
Color	yellow (active state)
Direct Drop Voltage	2 V
Current	20 mA
Resistor	220-330 ohms

The selected hardware component allows you to create a productive, flexible and collapsible solar panel position control system that takes into account climatic factors and astronomical calculations. All components work perfectly together, are supported in a Wokwi testing environment, and are also suitable for practical implementation.

2.3. Analytical calculation of the Sun's ascension and azimuth values

One of the most important aspects of an automated solar panel orientation system is to accurately determine the position of the Sun in the sky at a specific time. To do this, you need to calculate two main indicators: azimuth (angle relative to the north direction) and the height of the Sun above the horizon (angle of elevation). These values are used to calculate the rotation and tilt angles of the panel, which allows you to achieve the greatest efficiency in power generation.

The position of the Sun in the celestial sphere, determined for a specific latitude, longitude, date and time, is calculated using astronomical formulas or specialized libraries (for example, SunPosition.h, used in the project).

Using the following formula, it is possible to calculate the sun's elevation angle α [10]:

$$\alpha = \arcsin(\sin L \sin \delta + \cos L \cos \delta \cos h), \quad (2.1)$$

where α is the angle of elevation of the Sun;

L is the geographical latitude of the city in degrees;

δ is the declination of the Sun (depending on the day of the year);

h is the hour angle of the Sun.

The azimuth of the Sun can be calculated using the formula:

$$z = \arccos\left(\frac{\sin \alpha \sin L - \sin \delta}{\cos \alpha \cos L}\right) \text{sign } h, \quad (2.2)$$

where z is the azimuth of the Sun.

The z sign must coincide with the hour angle sign h provided by the function sign(h).

You can convert the latitude of the city to degrees using the formula:

$$L = \text{Degrees} + \frac{\text{Minutes}}{60} + \frac{\text{Seconds}}{3600}. \quad (2.3)$$

The declination of the Sun in degrees is found by Cooper's formula:

$$\delta = \delta_0 \sin \left[\frac{360}{365} (284 + N) \right], \quad (2.4)$$

where δ_0 is the inclination of the Earth's axis of rotation relative to the plane of rotation of the Earth around the Sun (equal to 23.45°);

N is the number of the day (starting from January 1).

The value of δ is positive in the summer months and negative in the winter months. $\delta = 0$ on the days of the spring and autumn equinoxes, $\delta = \delta_0$ on the day of the summer solstice and $\delta = -\delta_0$ on the day of the winter solstice.

The angle between the current projection of the sun's rays on the horizontal plane and the projection of the sun's rays to the solar south (when the sun is at the zenith $\alpha = \alpha_{\max}$) is called the hour angle. This angle is calculated by the formula:

$$h = (t + \Delta t - 12) * 15, \quad (2.5)$$

where t is the local time;

Δt determines the total amendment.

The hour angle to the south is zero ($h=0$), is considered negative before the south ($h < 0$) and positive after the south ($h > 0$).

When the Earth rotates, the hour angle h changes during the day, but the angle of declination of the δ in engineering calculations is considered unchanged.

It is convenient to determine the hour angle in terms of True Solar Time (TST). This time is different from the time that the clock shows and is determined by the movement of the sun across the sky. Obviously, it depends on the local standard time LST (Local Standard Time), that is, the time that is counted from the standard meridian SL (Standard Longitude) - the center of a given time zone. In addition, the observer is located

on his local meridian LL (Local Longitude. Due to the existence of a difference between LL and SL, it is necessary to introduce a correction to the true solar time, which is equal to $(LL - SL)/15$. Division by 15 corresponds to the fact that the hour angle increases by 15° in 1 hour.

The general formula for calculating true solar time TST is:

$$TST = LST + \frac{LL - SL}{15} + \frac{ET}{60} - DS, \quad (2.6)$$

where TST is true solar time;

LST is the local standard time;

LL is the local meridian;

SL is the standard meridian;

ET is the time correction;

DS is an adjustment for daylight saving time: 1 (from the end of March to the end of October) or 0 (at other times of the year).

The correction of time ET takes into account the unevenness of the Earth's motion along the ecliptic and the tilt of the Earth's axis. In technical calculations for ET, the following approximate formula is used:

$$ET = 9.87 \sin 2B - 7.53 \cos B - 1.5 \sin B, \quad (2.7)$$

where $B = \frac{360(N-81)}{364}$.

If we express the local time $LST = t$ in terms of the true solar time TST, we will have:

$$t = TST - \Delta t. \quad (2.8)$$

The total correction is determined by the formula:

$$\Delta t = \frac{LL - SL}{15} + \frac{ET}{60} - DS. \quad (2.9)$$

Let us make analytical calculations of the rise and inclination of the Sun at 14:00 on June 18, 2025 in accordance with the previous formulas.

The latitude of Kyiv is $50^{\circ}27'$, longitude $-30^{\circ}31'25''$. Let us convert the latitude and longitude of the city of Kyiv into degrees according to the formula 2.3:

$$L = 50 + \frac{27}{60} + \frac{0}{3600} = 50.45^{\circ};$$

$$LL = 30 + \frac{31}{60} + \frac{25}{3600} = 30.52^{\circ}.$$

Let us calculate the declination of the Sun using formula 2.4:

$$\delta = 23.45 \sin \left[\frac{360}{365} (284 + 169) \right] = 23.41^{\circ}.$$

Time correction is calculated according to formula 2.7:

$$ET = 9.87 \sin 2 * 90^{\circ} - 7.53 \cos 90^{\circ} - 1.5 \sin 90^{\circ} = 0 - 0 - 1.5 * 1 = -1.5;$$

$$B = \frac{360(169 - 81)}{364} = 87.03^{\circ} \approx 90^{\circ}.$$

Using formula 2.6, let us calculate true solar time:

$$TST = 14 + \frac{30.52 - 30}{15} + \frac{-1.5}{60} - 1 = 13.01.$$

That is, the true solar time is 13:01 with local time of 14:00.

Using formula 2.9, we calculate the total correction:

$$\Delta t = \frac{30.52 - 30}{15} + \frac{-1.5}{60} - 1 = -0.99.$$

Using formula 2.8, let us calculate local time:

$$t = 13.01 - (-0.99) = 14.$$

So the local time is 14:00 and is the same as what we have chosen.

The hour angle is calculated using the formula 2.5:

$$h = (14 + (-0.99) - 12) * 15 = 15.15^\circ.$$

Having all the necessary data, we will calculate the angle of rise of the Sun using formula 2.1:

$$\begin{aligned} \alpha &= \arcsin(\sin(50.45^\circ) \sin(23.41^\circ) + \cos(50.45^\circ) \cos(23.41^\circ) \cos(15.15^\circ)) \\ &= 60.50^\circ. \end{aligned}$$

Let us also calculate the azimuth of the Sun using the formula 2.2:

$$z = \arccos\left(\frac{\sin(60.50^\circ) \sin(50.45^\circ) - \sin(23.41^\circ)}{\cos(60.50^\circ) \cos(50.45^\circ)}\right) = 29.17^\circ.$$

For the afternoon:

$$\text{Azimuth} = 180^\circ + z = 180^\circ + 29.17 = 209.17^\circ.$$

The time of rise and the time of sunset occur when the angle of elevation $\alpha = 0$. The hour time that corresponds to these events, expressed in hours, is found using the following formula:

$$h_s = \frac{1}{15} \arccos(-\tan L \tan \delta), \quad (2.10)$$

where it is taken positive in the west and negative in the east h_s .

The length of daylight hours is determined by the following formula T_s :

$$T_s = 2|h_s|, \quad (2.11)$$

If you go from TST to standard local time (on the clock), then the sunrise t_{sr} and sunset t_{ss} times will be equal respectively:

$$t_{sr} = 12 - h_s - \Delta t, \quad (2.12)$$

$$t_{ss} = 12 + h_s - \Delta t, \quad (2.13)$$

Using the formula 2.10, we find the hour time:

$$h_s = \frac{1}{15} \arccos(-\tan(50.45^\circ) \tan(23.41^\circ)) = 8.11.$$

Let us calculate the length of daylight hours using formula 2.11:

$$T_s = 2|8.11| = 16.22.$$

That is, the length of the day is 16 hours and 22 minutes.

Let us calculate the time of sunrise using the formula 2.12:

$$t_{sr} = 12 - 8.11 - (-0.99) = 4.88.$$

That is, the time of sunrise will be 4:53 (because $0.88 \cdot 60 = 52.8$ minutes).

Let us calculate the time of sunset using the formula 2.13:

$$t_{sr} = 12 + 8.11 - (-0.99) = 21.1.$$

That is, the time of sunrise will be 21:06 (because $0.1 \cdot 60 = 6$ minutes).

After completing the calculations of the sunrise and sunset times for June 18, 2025, based on formulas that take into account the geographic latitude of the location, the declination of the Sun, and the hour angle, the following data were obtained: the approximate time of sunrise is 04:53 and the time of sunset is 21:06.

To establish the correctness of the calculation, a comparative analysis was performed with astronomical indicators published on the Internet (Fig.2.10). According to these data, on June 18, 2025, the Sun will rise at 04:46 in Kyiv and set below the horizon at 21:12 [11].

Середа, 18 Червня 2025

Схід Сонця **04:46**, Астрономічний опівдні: **12:59**, Захід Сонця: **21:12**, Довжина дня: **16:26**, Довжина ночі: **07:34**.

Fig.2.10. Sunrise and sunset time on June 18

The discrepancy between the calculated and real indicators is an insignificant number of minutes, which indicates the high accuracy of the mathematical methods used and the correctness of the chosen calculation methodology. This confirms the correctness of the implementation of calculations in the context of the development of a system for automatic adjustment of the solar panel.

2.4. Conclusion

Within the framework of this chapter, a concept of an automated system controlling the position of the solar panel was developed. At first, the process of creating a system capable of adjusting the orientation of the photomodule in accordance with the change in the position of the Sun in the sky during the day was determined. Input parameters such as: geographic coordinates, date, time, illumination, temperature and humidity were defined, and criteria for activating the actuator based on meteorological indicators were formulated. So, in this chapter, theoretical and engineering training was carried out to create an effective control algorithm, which will become the basis for practical implementation at the next stage of system development.

Further, the choice of the Arduino Uno microcontroller was substantiated as a reliable and affordable platform for creating a prototype of the system. The functionality of the sensors used is analyzed in detail: a photoresistor for measuring illumination, a DHT22 sensor for monitoring temperature and humidity, an RTC module for accurate timing, as well as an OLED display for displaying diagnostic information. Servos with the appropriate angle of rotation were selected for the physical positioning of the panel in two planes.

An analytical calculation of the key astronomical parameters that determine the position of the Sun at a given moment of time is performed. In particular, the elevation angle and azimuth of the Sun are calculated using trigonometric formulas that take into account the day of the year, the geographic latitude of the area, the hour angle and the declination of the Sun. The calculations were verified by comparison with astronomical data and the results obtained confirmed high accuracy and compliance.

CHAPTER 3

IMPLEMENTATION OF THE CONTROL SYSTEM ON THE ARDUINO PLATFORM

3.1. Wokwi software environment

To implement the operation of the solar panel tilt angle control system, the Wokwi software environment was used. It is a modern online platform for modeling, connecting components, programming, and virtual launches of Arduino projects without the need for real hardware. Wokwi supports Arduino (UNO, Mega, Nano), ESP32, STM32, Pi Pico, a variety of sensors, displays, servo motors, and more. The interface of the platform is shown in Fig.3.1.



Fig.3.1. Wokwi software interface

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This online platform made it possible to create a model for controlling the angle of the solar panel and clearly show the operation of the system under different weather conditions. Wokwi fully supports all the necessary components and libraries for the implementation of the project, and the platform has significantly reduced the time of development, testing, and demonstration of the system compared to the physical environment. The software provides the ability to flexibly configure parameters, which is extremely useful when developing projects of this type. In the simulation, you can manually change the values of light, humidity and temperature, this allows you to instantly check the operation of the system when external conditions change without waiting for real time.

The project has implemented a full-fledged scheme, which includes the following components:

- **Arduino Uno** as the main controller of the system;
- two **Servo** motors to control the position of the panel;
- **DS1307 RTC** real-time clock module;
- display for displaying the desired information **SSD1306 OLED display**;
- signal **LED** for visual display of the state of the Sun;
- **Resistor** to limit the current flowing through the LED;
- **Photoresistor (LDR) Sensor**;
- **DHT22** humidity and temperature sensors.

For the correct operation of the system, the following libraries were used:

- **Wire.h** – library for working with I2C (OLED, RTC);
- **RTClib.h** – library for the DS1307 real-time clock module;
- **Servo.h** – library for controlling servo drives;
- **SunPosition.h** – library for calculating the position of the Sun by date and time;
- **Adafruit_GFX.h** – library for OLED display;
- **Adafruit_SSD1306.h** – library for displaying information on the display;
- **DHT.h** – library for reading humidity and temperature.

Advantages of using Wokwi:

- online environment that does not require installation;
- creation of a control system without the use of a physical Arduino board;
- a large database of components and libraries;
- integrated time support, you can set a simulated moment of day, which is critical for checking the functioning of Sun tracking algorithms;
- the ability to instantly observe signals, internal values of variables and the operation of the system, which greatly simplifies the correction of work compared to the physical environment, in which each shift requires flashing of the controller;
- the ability to visually demonstrate the movement of servos and the operation of the system when changing the parameters of the sensors.

Therefore, the platform has become an effective tool for the implementation of this project in conditions of limited access to hardware, but at the same time, thanks to the use of Wokwi, it was possible to significantly simplify the stages of developing and demonstrating a solar panel control system.

3.2. System component wiring diagram

A scheme for connecting all the necessary components of the solar panel angle control system on the Arduino Uno platform was implemented. The connection diagram is shown in Fig.3.2.

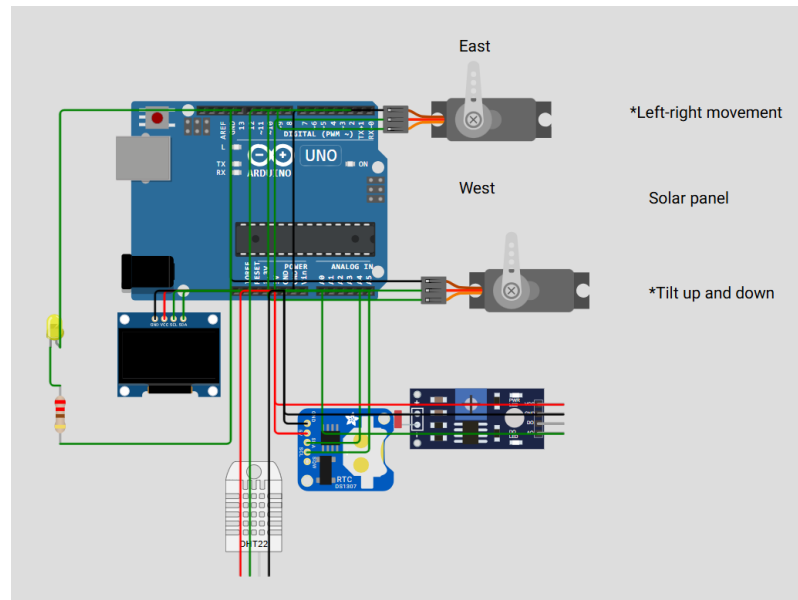


Fig.3.2. System connection diagram

Each component has a corresponding pin to connect, the main pin designations are given in Table 3.1.

Table 3.1

Basic pin notation

Denomination	Full name	Description
GND	Ground	The common "zero" point in the circuit (grounding). They are connected to it in order to have a common electrical potential
PVM	Pulse width Modulation	Used to control servo motors, LED brightness, etc
SDA	Serial data (I2C)	Data line for the I2C protocol, used to exchange information between Arduino and modules
SCL	Serial clock (I2C)	Synchronization line for the I2C protocol, determines when to transmit data bits

VCC	Voltage common collector	Positive voltage supply contact (power, in our case 5V). All components must be powered by this foam
A0	Analog 0	Analog input, reads light level
D0	Data out	Output digital data, DHT22 transmits its values through this pin
A4, A5	Analog pins	Contacts when working with I2C
D2, D13	Digital pins	Digital inputs and outputs. In our circuit, D2 reads the signal from the sensor, and D13 controls the LED

Consider connecting components to the main control device of the Arduino Uno, which processes data from sensors and generates control signals for servos.

The servoazimuth is responsible for turning the panel along the azimuth axis.

GND → GND;

V+ → 5V;

PWM → D9.

Servon-tilt is responsible for changing the angle of inclination.

GND → GND;

V+ → 5V;

PWM → D10.

DS1307 RTC Module provides an accurate real-time countdown to calculate the position of the Sun.

GND → GND;

5V → 5V;

SDA → A4;

SCL → A5.

Photoresistor (LDR) Sensor measures the level of illumination of the environment.

VCC → 5V;

GND → GND;

A0 → A0.

DHT22 A digital sensor that reads the temperature and humidity of the air.

VCC → 5V;

SDA → D2;

GND → GND.

OLED display SSD1306 is used to output information about the values of time, illumination, humidity, temperature, azimuth, and altitude of the Sun.

GND → GND;

VCC → 5V;

SCL → A5;

SDA → A4.

Signal LED is a visual indicator of system activity.

C (cathode) → r1:1 (through the resistor to GND);

A (anode) → D13.

220 Ω Resistor limits the current through the LED to prevent damage to it.

1 → C (cathode);

2 → GND.

The assembled circuit implements a fully autonomous panel orientation logic that takes into account both astronomical and climatic factors. All component interaction is carried out in real time under the control of Arduino Uno. The general principle of operation of the circuit works according to the following algorithm: the Arduino Uno microcontroller reads information about the light level from the photoresistor (LDR), temperature and humidity from the DHT22 digital sensor and the current time from the DS1307 real-time module. Further, using data on time, latitude and longitude, the program calculates the solar altitude (elevation) and azimuth (azimuth) using the SunPosition library. The system then checks for the following conditions: whether the Sun is above the horizon, whether there is enough light, or whether the humidity does not exceed 80%. If conditions are favorable, servos rotate the panel behind the Sun. If the

conditions are unfavorable or the Sun is below the horizon, the panel does not move. The current parameters are displayed on the display, the signal LED signals the state of the system, when the diode lights up – the system is active and the solar panel moves behind the Sun, when the diode is turned off – the system is inactive and the movement of servo mechanisms is suspended. Let us consider the principle of operation of the system in more detail.

Data collection from sensors

In the solar panel position control system, sensors play a critical role, which provide information about environmental weather conditions. This data is used to make decisions about the feasibility and safety of the panel's movement, as well as to calculate the orientation to the Sun.

A photoresistor is used to measure the level of illumination of the environment. Its resistance varies according to the amount of incident light, that is, in high light the resistance decreases, in low light the resistance increases. The LDR is connected to the analog input A0 of the microcontroller. A voltage divider is installed in the circuit, where the voltage is removed on the LDR. This voltage is proportional to the illumination and is read using the `analogRead()` function (more on the implementation code later). The resulting value is compared to the threshold `LDR_THRESHOLD` (600 for our system). If the light level is lower, we assume that it is cloudy outside and the system pauses the movement of the panel to avoid unnecessary movements.

The digital temperature and humidity sensor provides two key values – air temperature and relative humidity, which is especially important for monitoring the operating conditions of the solar panel. The DHT22 is connected to the D2 digital input. The data is read using the `DHT.h`. If the humidity exceeds 80%, the system blocks the movement of the panel to avoid damage due to possible rain or condensation. Temperature is used for information display.

The real-time module provides accurate time and date, regardless of the power supply to the main controller, thanks to the built-in battery. The DS1307 is connected via the I2C interface to the A4 and A5. The RTC provides the microcontroller with the current

date and time that is needed to calculate the position of the Sun. This allows the system to know when dawn or sunset comes and react accordingly.

Calculating the position of the Sun

Determining the exact position of the Sun is necessary for the correct orientation of the solar panel, which allows you to ensure maximum efficiency in collecting solar energy during the day. To do this, the program code uses a special SunPosition library, which performs mathematical calculations based on astronomical formulas. The input parameters for the functions of this library are the latitude (LAT) and longitude (LON) of the system location, the current time in Unix-time format (the number of seconds that have elapsed since January 1, 1970), and the time zone in order to adjust the local time.

Based on the above data, two main parameters are calculated:

1. The angle of elevation of the Sun shows how high the Sun is above the horizon. The value varies from 0° to 90° , at the horizon and at the zenith, respectively.
2. Azimuth of the sun (azimuth) - shows the direction of the sun relative to the north, expressed in degrees, where 0° are north, 90° - east, 180° - south and 270° - west.

These values are used to calculate the position of the servo motors that rotate the panel in the appropriate direction, the tilt angle (tilt) is determined by the height of the Sun, and the rotation angle (azimuth) is determined by its azimuth. Accordingly, our system updates the position of the panel every 10 minutes of the simulated time, ensuring constant monitoring of the movement of the Sun.

Conditions for activating panel movement

An important advantage of the solar panel angle control system is its ability to independently assess external conditions before performing movement in the direction of the Sun. This approach avoids unnecessary energy consumption by servomechanisms in situations where electricity generation is inefficient or even impossible

There are three main conditions for the system under which the activation of the panel movement is allowed:

- The position of the Sun above the horizon, the elevation value should be greater than 0° , indicating that the Sun is above the horizon. This eliminates the rotation of the panel at night.

- Sufficient level of illumination, i.e. if the illumination value exceeds the specified threshold (600 in this case), then it is considered that the Sun is actively shining and the orientation of the panel will make sense.
- Low humidity level, if the humidity is less than 80%, then servo mechanisms are allowed to be turned on. This prevents movement during rain or high humidity, which can affect the reliability of the system.

Only when all three conditions are met simultaneously, a signal is applied to the LED, which signals the active state of the system, the servos are moved to the appropriate positions to orient the panel to the Sun. If at least one condition is not met, then the system goes into an inactive state, without wasting resources on driving drives. This solution saves energy, increases system reliability and extends component life.

Panel position control

The process of controlling the position of the solar panel is based on the dynamic calculation of the coordinates of the Sun in the sky and the mechanical orientation of the panel according to these coordinates. Thanks to the use of modern computing tools and sensors, the system is able to change the orientation of the panel in real time, maximizing its exposure to sunlight.

Above, we looked at how the system obtains the lift and azimuth values using the SunPosition library, then the obtained values are converted into the corresponding values of the angle of rotation of the servo motors. This is done using the map() function – it transforms the angle of the Sun from physical coordinates into a range from 0 to 180°, which corresponds to the capabilities of a standard servo. This transformation allows you to accurately orient the panel both vertically (tilt) and horizontally (left-right). The calculated angles are transmitted to the corresponding servo motors. And the servo motors perform smooth positioning, setting the panel in the desired position, in accordance with the current position of the Sun.

If the driving conditions above are met, the system works. Or after normal conditions are restored, the position of the panel is automatically updated and it returns to the corresponding position.

With a combination of mathematical modeling of solar motion, adaptive control and the use of simple electromechanical components, the system achieves maximum efficiency in the automatic tracking of the Sun.

Displaying information

Displaying parameters and easy access to values allows you to monitor the status of all major processes in real time. This scheme uses a SSD1306 display with a resolution of 128 * 64 pixels. The code is implemented in such a way that each cycle begins with a screen cleanup, which prevents new values from being superimposed on the previous ones.

The display is displayed in turn:

1. Time (hours and minutes).
2. Illumination in the digital sense from the photosensor.
3. The angle of rise of the Sun.
4. Azimuthal position of the Sun.
5. Air temperature from the sensor.
6. Air humidity from the sensor.

The display acts as a local user interface, allowing you to directly assess system performance, sensor status, and panel orientation without the need to connect to an external computer or monitor. This makes the system autonomous, informative and easy to use.

Signal indicator operation

The LED in this circuit is a simple but extremely important component that quickly informs about the activity of the control system without the need to view the data on the screen.

The LED is connected via a limiting resistor (220 ohms), which prevents overloading of the output of the microcontroller and the component itself. The anode is connected to pin 13 of the Arduino, and the cathode through the resistor is connected to the "ground".

When the system is in working condition, i.e. all the necessary conditions are met, the microcontroller sends a logical high signal to pin 13, to which the LED is connected.

At this moment, the indicator lights up, signaling that the panel is oriented towards the Sun and the servos perform the appropriate positioning.

But, if at least one of the conditions is not met, then the system goes into a standby state and the indicator turns off. This allows you to quickly understand that the system is temporarily inactive.

We can conclude that the developed system of automated control of the angle of inclination of the solar panel functions as an intelligent complex that combines the collection, processing and analysis of data from the environment with subsequent response in the form of mechanical movement of the panel to achieve maximum efficiency in the use of solar radiation.

3.3. Program code for implementation

For the correct operation of the circuit, an implementation code was developed to ensure the stable operation of the system in real time, carrying out constant monitoring of the environment, analysis of the position of the Sun and appropriate control of servo motors.

Let us take a look at code snippets and how they work.

```
#include <Wire.h>
#include <RTClib.h>
#include <Servo.h>
#include <SunPosition.h>
#include <Adafruit_GFX.h>
#include <Adafruit_SSD1306.h>
#include <DHT.h>
```

At the beginning of the program, we connect the necessary libraries, the explanations of which were discussed earlier.

```
#define SCREEN_WIDTH 128
#define SCREEN_HEIGHT 64
#define OLED_RESET -1
Adafruit_SSD1306 display(SCREEN_WIDTH, SCREEN_HEIGHT, &Wire, OLED_RESET);
#define DHTPIN 2
#define DHTTYPE DHT22
DHT dht(DHTPIN, DHTTYPE);
RTC_DS1307 rtc;
```

```

Servo tiltServo;
Servo azimuthServo;
const float LAT = 50.45;
const float LON = 30.5236;
const int16_t TIMEZONE = 3;
const int ledPin = 13;
const int LDR_PIN = A0;
const int LDR_THRESHOLD = 600;
DateTime simulatedTime(2025, 6, 18, 4, 0, 0);
//DateTime now = rtc.now();

```

Next, hardware variables are announced. The width you are the height of the display screen in pixels, the pin to reset the display (we have a value of -1, which means that the pin reset is not used). Then we create a display object of type `Adafruit_SSD1306`, which is used to control the OLED display. We indicate that the signal pin of the humidity and temperature sensor is connected to digital input 2 on the Arduino Uno board and that we use the DHT22 sensor type. Create a `dht` object that will be used to obtain temperature and humidity values.

The next step, creating a class `RTC_DS1307 rtc` object to interact with the DS1307 real-time module. It is used to obtain or set the date and time.

We declare two Servo-type objects. `TiltServo` for up-down tilt and `azimuthServo` for azimuth left-right rotation.

We set the geographical coordinates of the latitude and longitude of Kyiv and the time zone that is required for the correct calculation of the solar position.

Then, we indicate that the digital output pin 13 is used to control the signal LED and that the analog pin is connected to a photoresistor that determines the light level. Set the lighting threshold.

At the end of this code snippet, create a `simulatedTime` variable of the `DateTime` type with a fixed start date and time. This variable is used to simulate time in the Wokwi virtual environment, in real conditions this value would come from the RTC module.

```

void setup() {
  Serial.begin(9600);
  Wire.begin();
  dht.begin();
  rtc.begin();
  pinMode(LDR_PIN, INPUT);
}

```

```

    pinMode(ledPin, OUTPUT);
    if (!rtc.isrunning()) {
rtc.adjust(DateTime(F(__DATE__), F(__TIME__)));
    }
    tiltServo.attach(10);
    azimuthServo.attach(9);
    if (!display.begin(SSD1306_SWITCHCAPVCC, 0x3C)) {
Serial.println(F("OLED display could not be started "));
    while (1);
    }
display.clearDisplay();
    display.setTextSize(1);
display.setTextColor(SSD1306_WHITE);
}

```

The setup function initializes everything you need before starting the main loop loop.

First, the serial port is configured at a speed of 9600 bps to output information to the port monitor. Next, start I2C to communicate with the clock module and display. Then initialize the temperature and humidity sensor, prepare the library for reading from this sensor, configure the clock module.

Set the pin to which the photoresistor is connected to the input mode to read the analog light level. Set the pin of the signal LED to exit mode as an indicator of system activity.

We check if the RTC is working, tie the servo motor for tilt to foam 10, and the servo motor for azimuth to foam 9.

Establish a connection between the OLED display at address 0x3c (standard for SSD1306). If the display does not respond, display a message in the port and stop the program from running.

Clear the screen, set the size of the text on the display and select the text color white.

```

void loop() {
    simulatedTime = simulatedTime + TimeSpan(0, 0, 10, 0);
    int lightLevel = analogRead(LDR_PIN);
    float temp = dht.readTemperature();
    float hum = dht.readHumidity();
    Serial.print("Time:");
    Serial.print(simulatedTime.hour()); Serial.print(":");
}

```

```

    Serial.print(simulatedTime.minute()); Serial.print(":");
    Serial.println(simulatedTime.second());
    uint32_t unixTime = (simulatedTime - TimeSpan(0, TIMEZONE, 0, 0)).unixtime();
    SunPosition sun(LAT, LON, unixTime, TIMEZONE);
    float elev = sun.altitude();
    float azim = sun.azimuth();
    Serial.print("Elevation: ");
    Serial.print(elev);
    Serial.print("°, Azimuth: ");
    Serial.println(azim);
    display.clearDisplay();
    display.setCursor(0, 0);
    display.print("Time: ");
    if (simulatedTime.hour() < 10) display.print('0');
    display.print(simulatedTime.hour()); display.print(":");
    if (simulatedTime.minute() < 10) display.print('0');
    display.print(simulatedTime.minute());
    display.setCursor(0, 10);
    display.print("Light: "); display.print(lightLevel);
    display.setCursor(0, 20);
    display.print("Elev: "); display.print(elev, 1);
    display.setCursor(0, 30);
    display.print("Azim: "); display.print(azim, 1);
    display.setCursor(0, 40);
    display.print("Temp: "); display.print(temp, 1);
    display.setCursor(0, 50);
    display.print("Hum: "); display.print(hum, 0); display.print("%");
    display.display();
    if (elev > 0 && lightLevel > LDR_THRESHOLD && hum < 80) {
        digitalWrite(ledPin, HIGH);
        int tiltAngle = map(elev, 0, 90, 0, 180);
        int azimAngle = map(azim, 90, 270, 0, 180);
        tiltAngle = constrain(tiltAngle, 0, 180);
        azimAngle = constrain(azimAngle, 0, 180);
        tiltServo.write(tiltAngle);
        azimuthServo.write(azimAngle);
    } else {
        digitalWrite(ledPin, LOW);
        Serial.println("Dark, cloudy or high humidity - the servo does not move.");
    }
    delay(1000);
}

```

Loop is the main loop of the program, which is constantly repeated after each pass is completed.

For more visual testing, add 10 minutes with each repeat of the cycle.

Then we read the illumination level from the photoresistor (values in the range from 8 to 1015). We also read the temperature and humidity values from the DHT22 digital sensor.

We display the simulated time in the format hours:min:sec on the serial monitor.

To calculate the position of the Sun, we calculate a unique time taking into account the time zone shift. We calculate the altitude and azimuth of the Sun based on coordinates and time and output these values to the serial monitor.

Clean the display before displaying new information. We display the current time on the display in the first line, the illumination level in the second, the angle of rise of the Sun in the third line, the value of the Sun's azimuth in the next, then the temperature and in the last we display the humidity level.

We check the three main conditions for the movement of the panel, if they are met, turn on the signal LED and convert the angles of the Sun's position into values for servos. We limit the value from 0 to 180° to avoid going beyond the permissible range. Next, we transmit commands to servo motors to rotate the panel.

If the conditions are not met, the LED goes out, the servos do not move and we display a message on the monitor.

We set a pause of 1 second before the next cycle to avoid loading.

We can see that for the correct operation of the system, the implemented code simulates time, collects data from sensors, calculates the position of the Sun, checks weather conditions, controls the position of the panel and outputs data to the display and serial port, that is, it does everything according to the principle of operation.

3.4. Simulation of system operation under favorable conditions

As stated above, favorable conditions are considered when the Sun is above the horizon, illumination greater than the threshold of 600 and humidity less than 80%. The initial position of the servos is shown in Fig.3.3. When the conditions are met, the servos begin to move, the indicator lights up and the values are displayed on the display, all this can be seen in Fig.3.4.

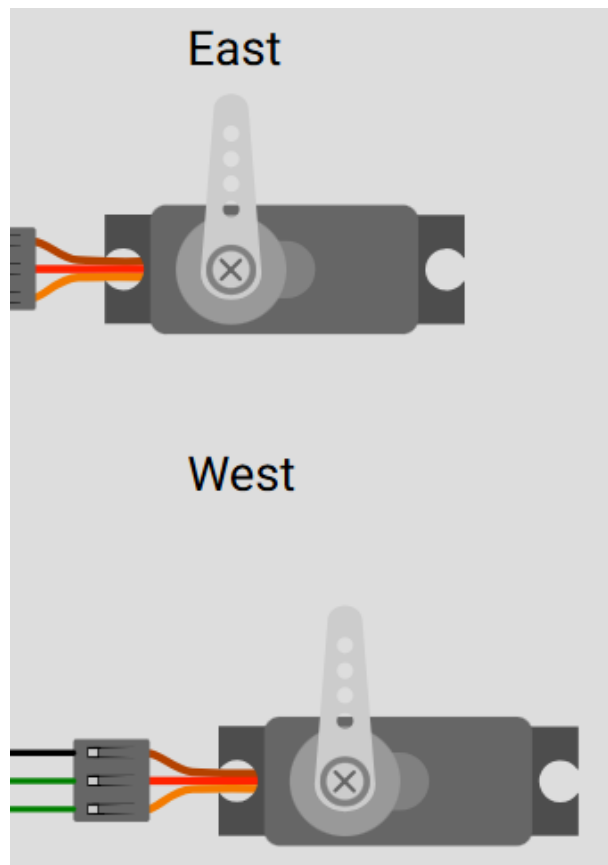


Fig.3.3. Initial position of servos

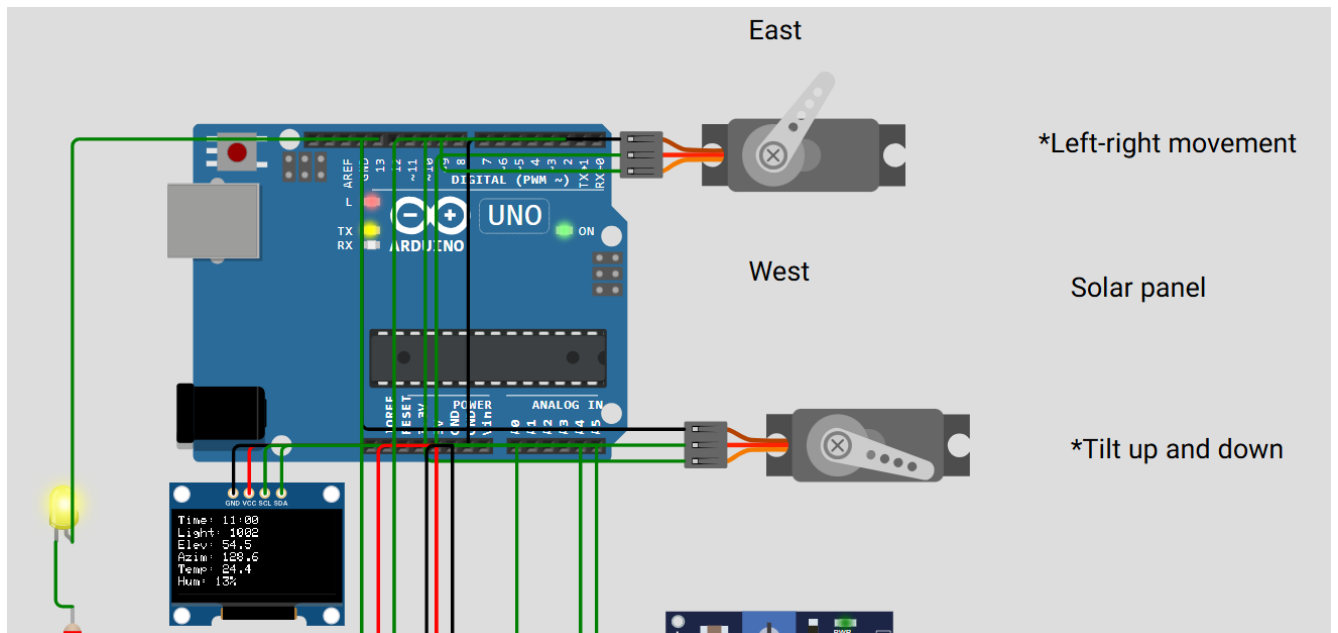


Fig.3.4. Simulation of work under favorable conditions

We see that the condition `if (elev > 0 && lightLevel > LDR_THRESHOLD && hum < 80)` activates the system. The servos have changed their position angle, the system indicator is on, the desired values are displayed on the display. Additionally, the time

and values of inclination and azimuth are displayed in the port, which can be seen in Fig.3.5.

```

Чac: 10:40:0
Elevation: 51.87°, Azimuth: 122.30
Чac: 10:50:0
Elevation: 53.19°, Azimuth: 125.39
Чac: 11:0:0
Elevation: 54.46°, Azimuth: 128.62

```

Fig.3.5. Displaying a value in serial port

Let us take a closer look at the dependence of the angle of the panel on the position of the Sun in Table 3.2 (as of 18.06.2025 every 2 hours under normal weather conditions). We take the value of the position of the Sun from the display and calculate the angles for the servo using a proportional conversion.

Tilt: from the Elevation range (0-90°) for servo (0-180°), i.e.

$$TiltAngle = \frac{Elevation}{90} * 180, \quad (3.1)$$

where TiltAngle is the angle of inclination of the servo;

Elevation is the angle of rise of the Sun.

For example, using the formula (3.1), we calculate the angle of inclination of the servo motor at 10 am:

$$TiltAngle = \frac{46,19}{90} * 180 = 92.38°.$$

Azimuth: from the Azimuth range (90-270°) for servo (0-180°), since the azimuth range is 90-270°, the angle of rotation of the servo can be calculated using the formula:

$$AzimuthAngle = \frac{Azimuth-90}{180} * 180 = Azimuth - 90, \quad (3.2)$$

where AzimuthAngle is the angle of rotation of the servo;

Azimuth is the azimuth of the Sun.

For example, using the formula (3.2), we calculate the angle of rotation of the servo motor at 10 am:

$$AzimuthAngle = Azimuth - 90 = 21.28^\circ.$$

Table 3.2

Angles of the servo motor

Time	Elavation, °	Azimuth, °	Servo Angle (TiltAngle, °)	Servo Rotation Angle (AzimuthAngle, °)
06:00	9.08	64.09	18.16	0
08:00	27.42	85.80	54.84	0
10:00	46.19	111.28	92.38	21.28
12:00	60.61	151.78	121.22	61.78
14:00	60.39	209.47	120.78	119.47
16:00	45.76	249.44	91.52	159.44
18:00	26.97	274.73	53.94	180.00
20:00	8.68	296.42	17.36	180.00
22:00	-6.27	319.50	0	180.00

We can clearly see the position of the servos at the appropriate time in Fig.3.6-3.9.

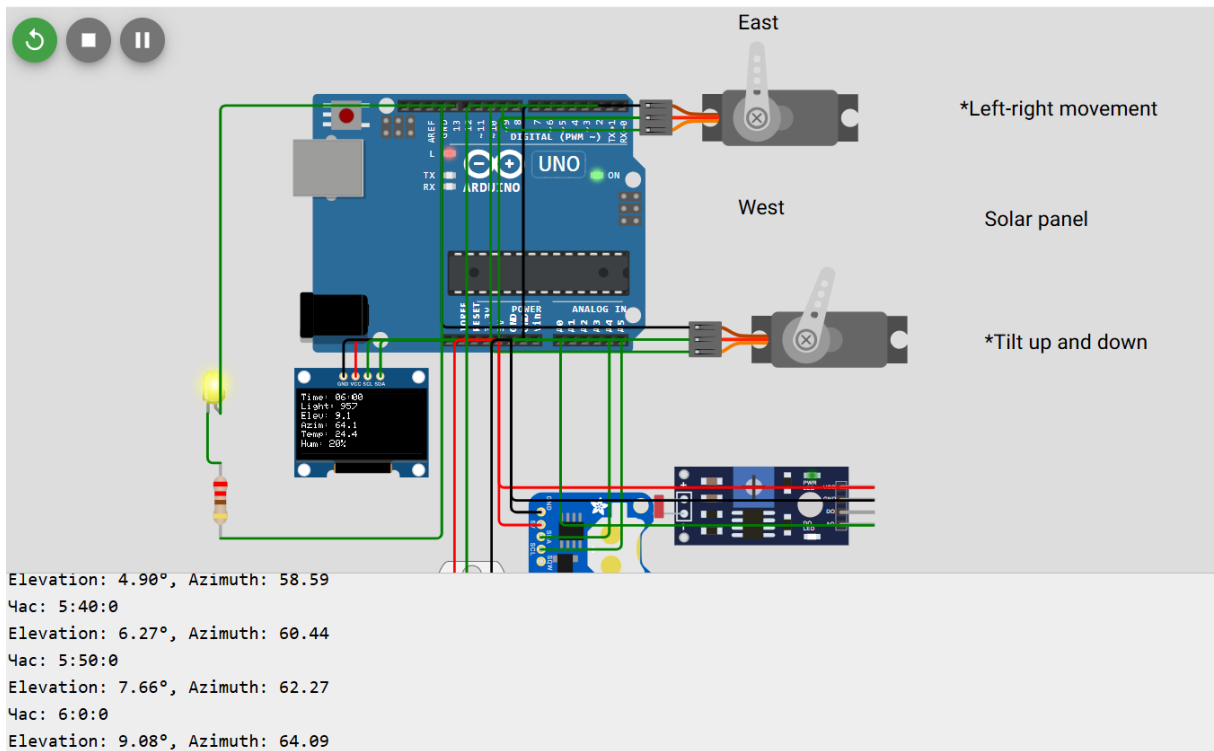


Fig.3.6. Position of servos at 06:00

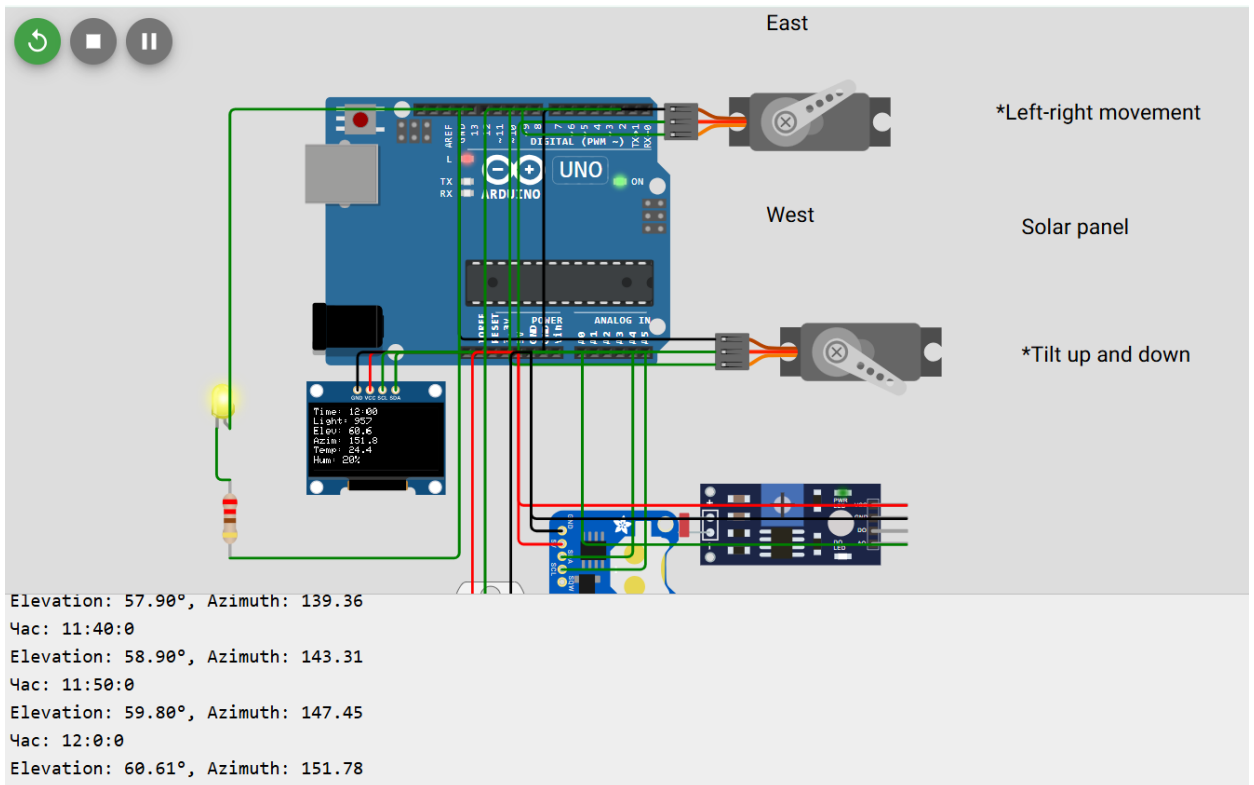


Fig.3.7. Position of servos at 12:00

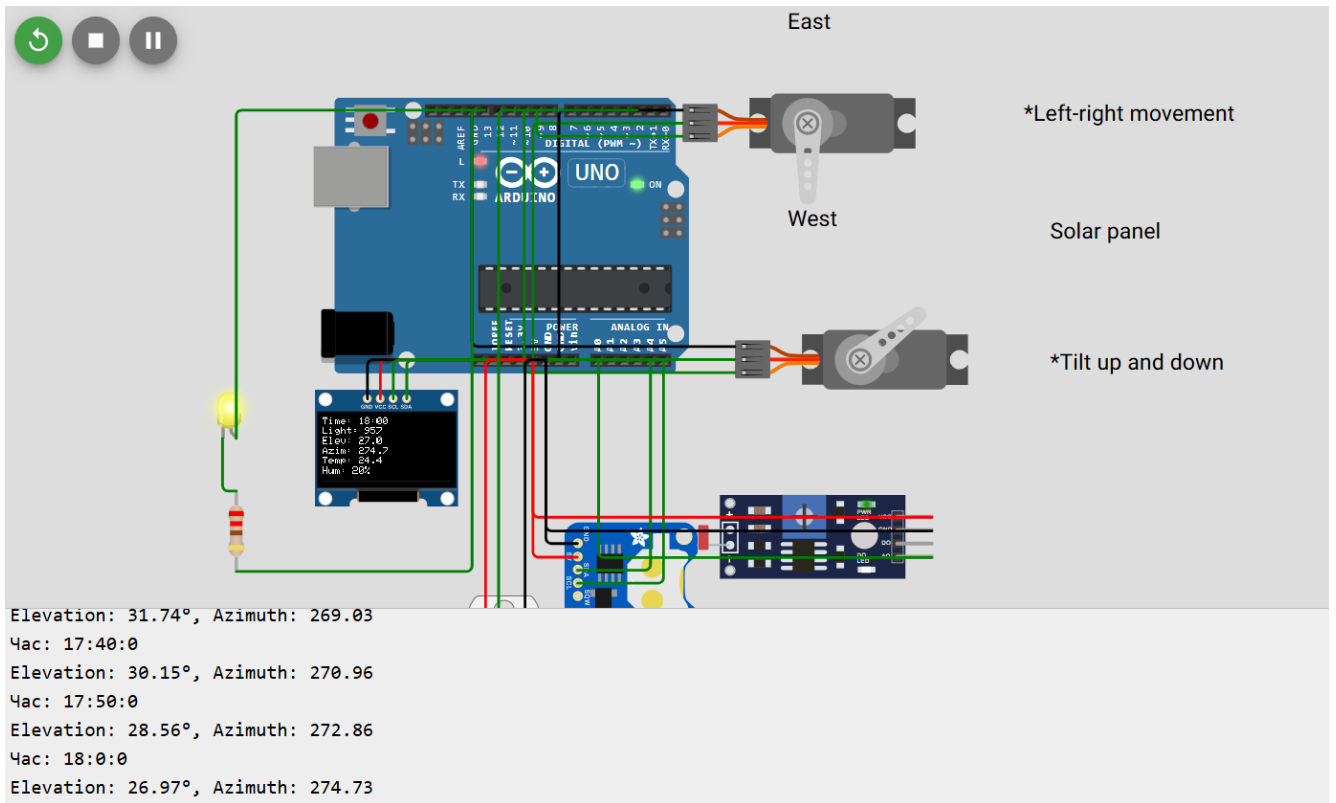


Fig.3.8. Position of servos at 18:00

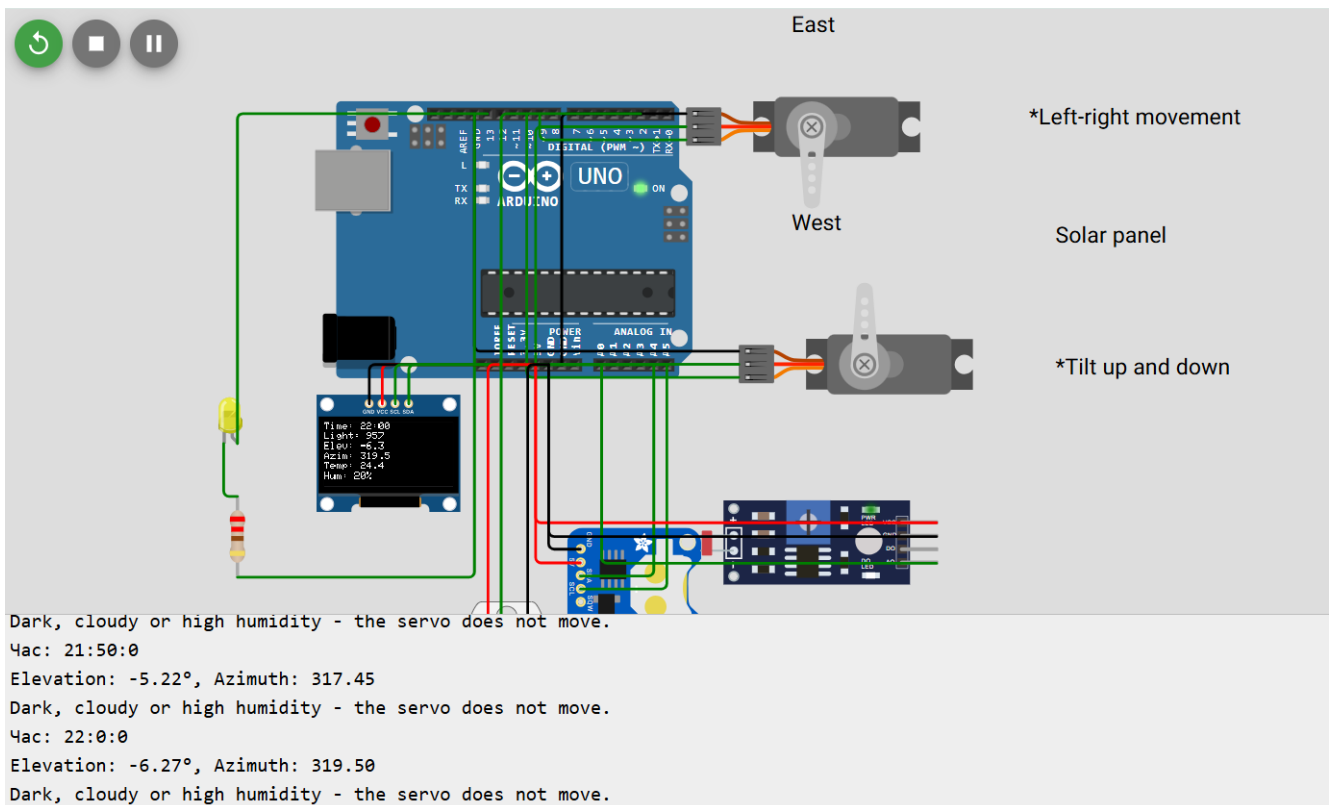


Fig.3.9. Position of servos at 22:00

During the simulation in the Wokwi environment, the system demonstrated stable operation under intense light conditions and moderate humidity. The panel accurately orients itself to the Sun, which is confirmed by the dynamics of changing the angles of the servo motors and the output of data to the OLED display. The system works in sync, which allows for effective tracking of the Sun in real time.

3.5. Testing different weather conditions

Let us check the operation of the system under adverse conditions. We will set the low level of illumination and high humidity on the appropriate sensors. In Fig.3.10, we can see that the servos do not move the panel, the Led does not light up, and the Serial port displays a message that the system is inactive.

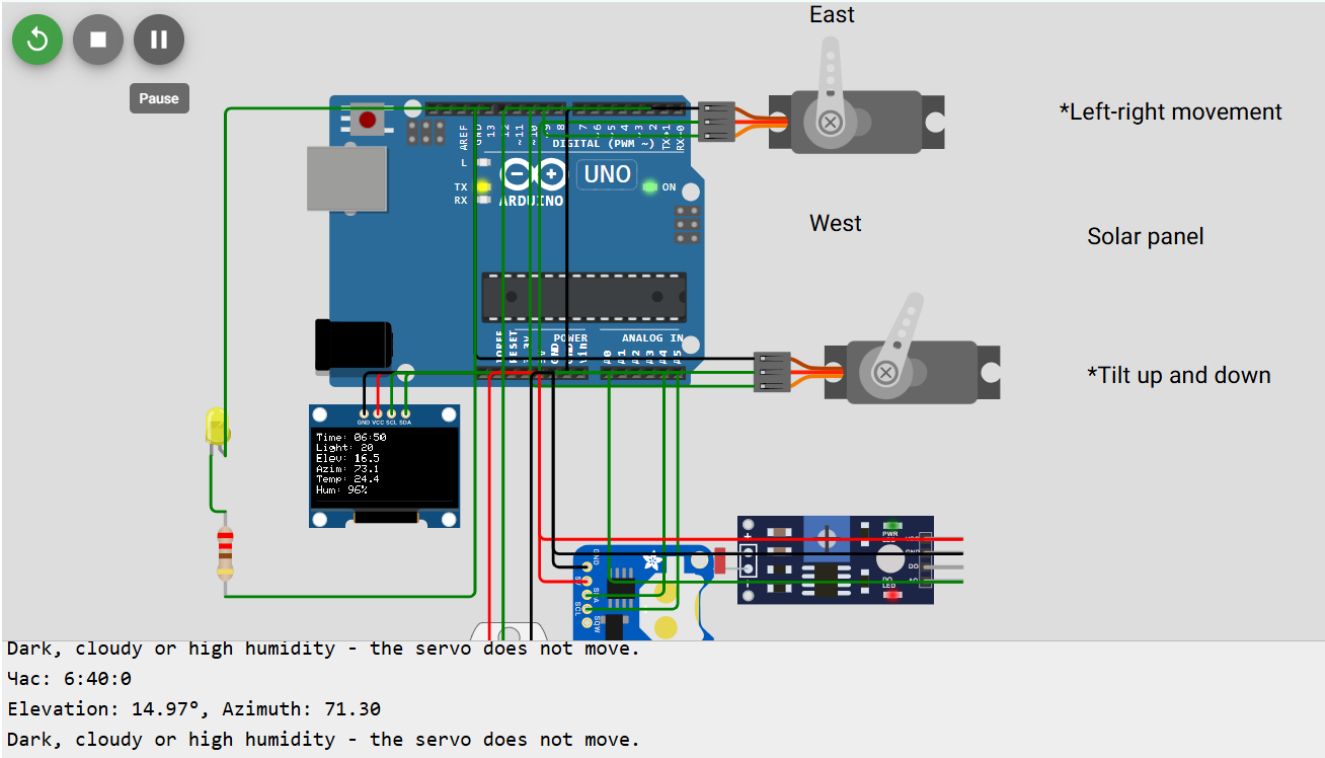


Fig.3.10. System operation at low light level and high humidity

We will test if at least one condition is violated. The operation of the system at low humidity and low light levels can be seen in Fig.3.11. We see that the system reacts as in the previous case.

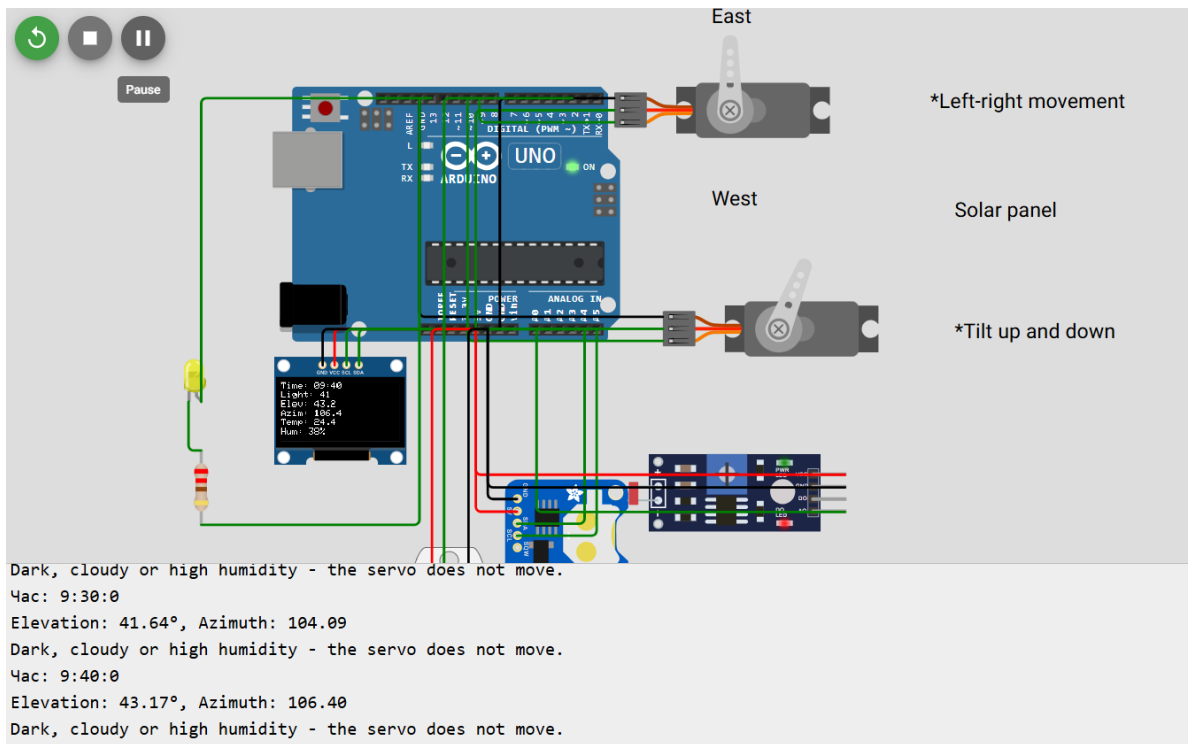


Fig.3.11. System operation at low light and humidity levels

Let us set the high humidity and illumination on the sensors, the reaction of the system is shown in Fig.3.12.

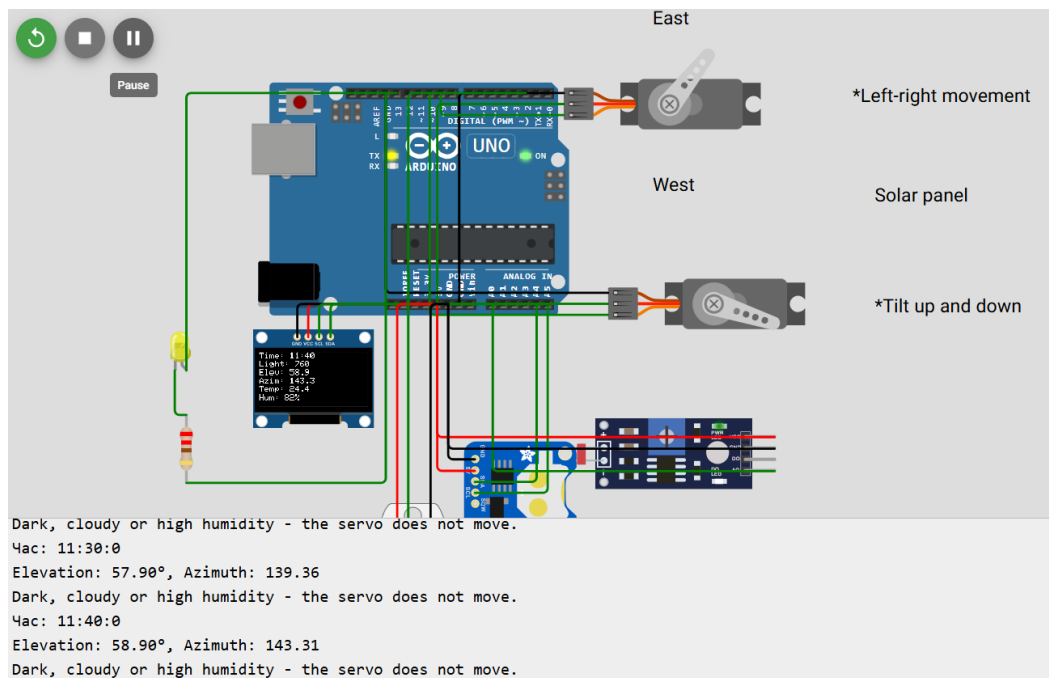


Fig.3.12. System operation in high humidity and illumination

We will test the weather scenario if there was high humidity and enough light in the morning, and the humidity decreased in the afternoon. In Fig.3.13, you can see that the servos change the angle of the panel according to the position of the Sun.

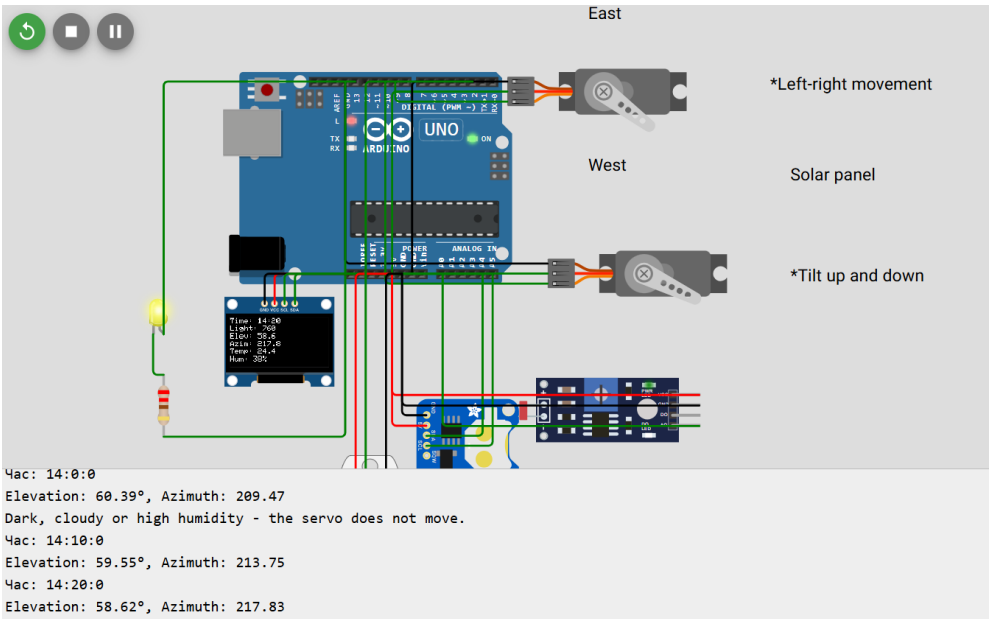


Fig.3.13. Position of servos when weather conditions improve

We will also check the operation of the circuit after sunset, we can see the reaction in Fig.3.14.

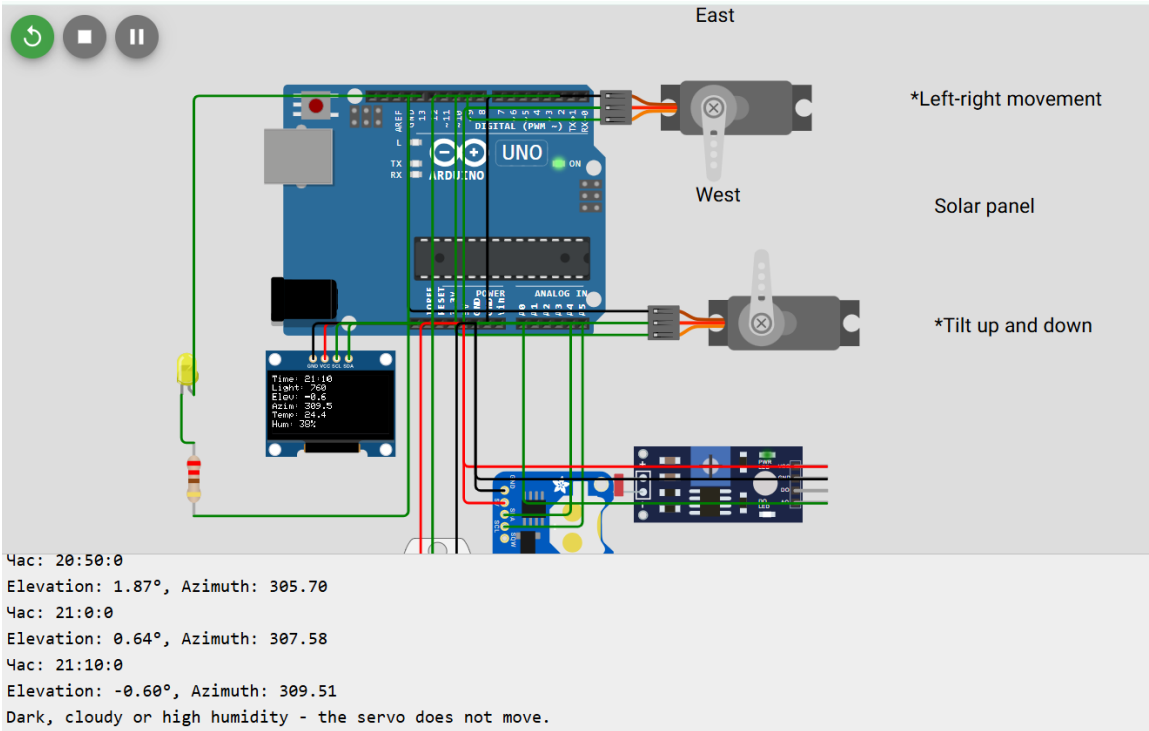


Fig.3.14. System provided that the Sun is below the horizon

Tests have shown that the system responds correctly to changing weather conditions. In case of adverse conditions, the servos are stopped, which increases the reliability and durability of the device. If the Sun is below the horizon, the system also goes into an inactive state, which excludes the rotation of the panel at night.

3.6. Conclusion

In this chapter, the basic principle of operation of the automated solar panel angle control system using the Arduino Uno microcontroller and the necessary components for correct operation in the Wokwi virtual environment was considered. Both the hardware part is described - the scheme for connecting sensors and actuators, and the software that provides data collection, decision-making and control of the panel position.

We considered the logic by which the system analyzes the level of illumination, temperature and humidity of the environment. Under favorable conditions (sufficient illumination and low humidity), the panel automatically orients itself according to the position of the Sun calculated using the SunPosition library. If the conditions are unfavorable (low light and high humidity), the system goes into an inactive state, the servos do not move the panel. When weather conditions improve, the system automatically resumes movement behind the Sun.

Particular attention was paid to visualization using an OLED display, which displays information about the current time, weather conditions and the position of the Sun. This not only facilitates monitoring, but also demonstrates the readiness of the system for practical use.

The system was also tested under various weather conditions. The angles for servos were calculated according to the position of the Sun. All checks confirmed the correct and stable operation of servo control algorithms. It has been proved that the built system is workable, adaptive to external conditions and can be used as the basis for a real solar tracking system to increase the efficiency of the solar panel.

CHAPTER 4

COMPARISON OF THE OPERATING EFFICIENCY OF A MOVABLE AND FIXED SOLAR PANEL

4.1. Criteria for the efficiency of solar panels

To determine the real performance of solar panels, in particular when comparing fixed and sun-tracking systems, it is necessary to establish objective and measurable indicators that will allow evaluating their energy efficiency. The main of these criteria are:

1. Amount of electricity generated

This is one of the key indicators that demonstrates the overall efficiency of the panel during the day, month or year. The energy volume depends on the size of the photomodule, as well as the duration of its stay at the optimal angle to sunlight. It is this parameter that allows you to directly compare panels with a constant inclination and those that automatically adapt to the position of the Sun.

2. Average daily insolation

Insolation is an indicator of the solar energy that falls on a unit area of a solar panel during a specific time period. This indicator directly affects how efficiently the panel produces electricity. Moving panels make better use of sunlight in the morning and evening hours, while fixed panels show the best performance during the lunch period.

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Standards insp	Dyvnych M.P.				Ba-151-21-2CY		
Head of department	Tachynina O.M.						

3. Angular efficiency

This indicator takes into account changes in the performance of the panel depending on the angle at which the sun's rays fall. The greatest energy generation occurs when light falls perpendicularly. A system capable of automatically adjusting the angle of inclination brings the panel closer to this position throughout the day.

4. Time period of active energy production during the day

A solar panel with the ability to track the Sun shows performance for a large part of the daylight hours, starting at sunrise and ending at sunset. The fixed design, on the other hand, is most active for only a limited number of hours. This aspect directly correlates with the total amount of energy produced during the day.

5. Profitability and payback

Automated systems, although they require higher installation costs due to their complexity, show a faster payback. This is due to an increase in electricity production. This factor is key when evaluating their long-term effectiveness.

The application of the above criteria allows you to comprehensively assess the operation of solar panels in different modes. At the same time, it is the ability of the system to adapt to real lighting conditions that turns out to be a key factor that ensures the superiority of a movable structure over a fixed one.

4.2. Fixed panel electricity generation indicator

To assess the efficiency of a fixed solar panel, we will calculate the amount of electricity it is capable of generating per year in specific climatic conditions using the PVWatts calculator.

The PVWatts calculator is an online tool developed by the US National Renewable Energy Laboratory (NREL) that aims to predict the efficiency of solar panel systems. This tool is actively used by both solar energy specialists and ordinary consumers seeking to install solar panels in their own homes or businesses.

The main goal of PVWatts is to estimate the monthly and annual electricity production capacity of a solar installation in a specific location. Numerous factors are

taken into account for the calculation, in particular, geographical coordinates, the angle of inclination of the roof (in the case of a roof installation), the orientation of the panels, the type of solar panels and other parameters. The user enters data about the location and characteristics of the installation. The calculator then outputs the projected energy performance in kilowatt-hour (kWh) based on local climatic conditions and other factors [12].

Let us set the following data for the calculation:

- City: Kyiv;
- DC system size (kW): 4;
- Panel type: standard;
- Array type: fixed system (open rack);
- System losses (%): 14.08;
- Inclination (degrees): 30;
- Azimuth (degrees): 180.

The 30° tilt angle ensures balanced power generation throughout the year without the need for seasonal adjustments. This value allows the panels to work efficiently in summer high sun and winter low sun conditions, minimizing energy losses in the intermediate seasons.

The result of the calculation can be seen in Fig.4.1.

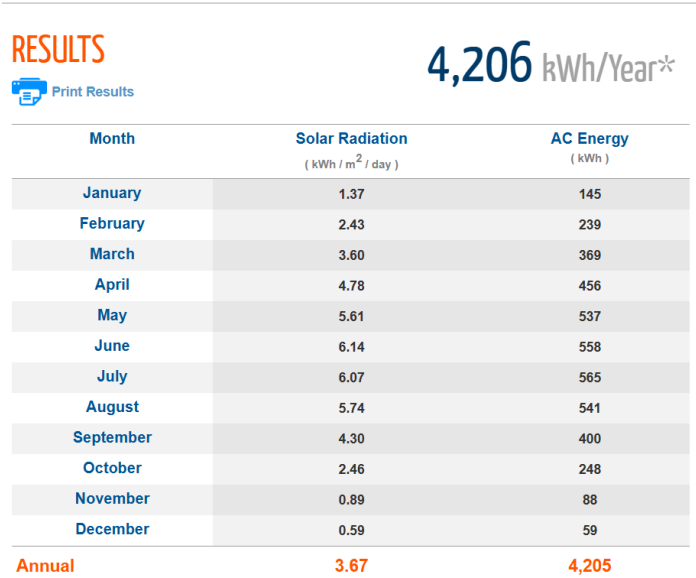


Fig.4.1. Results for a fixed panel

According to the results, we can see that 4206 kWh of electricity was generated during the year of operation of the fixed panel. Most electricity was generated during the summer months, which is obvious. The highest value during the year is energy generation in July - 565 kWh. The smallest generation was observed in winter; in December it was produced – 59 kWh. This is due to a decrease in daylight hours and a lower angle of incidence of sunlight.

4.3. Indicator of the electricity generated of the moving panel

Similarly, we will calculate the operation of the moving system.

Let us set the following data for the calculation:

- City: Kyiv;
- DC system size (kW): 4;
- Panel type: standard;
- Array type: 2-axis tracking;
- System losses (%): 14.08;
- Inclination (degrees): 0;
- Azimuth (degrees): 180.

The results are shown in Fig.4.2.

The screenshot shows a 'RESULTS' window with a 'Print Results' button and a total annual energy output of 5,753 kWh/Year*. Below this is a table with three columns: Month, Solar Radiation (kWh / m² / day), and AC Energy (kWh). The data is as follows:

Month	Solar Radiation (kWh / m ² / day)	AC Energy (kWh)
January	1.96	206
February	3.19	300
March	4.67	473
April	6.29	598
May	7.69	742
June	9.02	825
July	8.77	819
August	7.95	750
September	5.68	525
October	3.23	325
November	1.21	119
December	0.70	70
Annual	5.03	5,752

Fig.4.2. Results for a movable panel with 2 axes

During the year of operation of the moving panel, 5753 kWh of electricity was generated. The highest value during the year is energy generation in June - 825 kWh. The smallest generation was observed in winter, in December – 70 kWh was produced.

4.4. Comparative analysis of results

Based on the results of the simulation conducted using the PVWatts online calculator, we will conduct a comparative analysis of the efficiency (Table 4.1) of two types of solar installations: fixed and mobile. Both systems had the same installed power – 4 kW, the same loss rates (14.08%) and were located in the same climatic conditions – the city of Kyiv.

Table 4.1

Analysis of Moving and Fixed Panel Results

	Fixed	Moving
Electricity generated per year	4206 kWh	5753 kWh
Average level of solar radiation per year	3.67 kWh/m ² /day	5.03 kWh/m ² /day
The most energy produced in a month	565 kWh	825 kWh
Least energy produced per month	59 kWh	70 kWh

The increase in electricity generation is calculated according to the following formula:

$$Increase = \left(\frac{E_{mov} - E_{fix}}{E_{fix}} \right) * 100\%, \tag{4.1}$$

where Increase is the increase in electricity for the year;
 E_{mov} generated energy of the moving panel for the year;
 E_{fix} generated energy of the fixed panel per year.

Using formula 4.1, we calculate the increase:

$$\text{Increase} = \left(\frac{5753 - 4206}{4206} \right) * 100\% = 36.78\%.$$

So, as mentioned earlier, the movable panel can increase the volume of electricity generation by 35-45%, which we obtained as a result of the analysis.

4.5. Conclusion

In this chapter, a comparison of the performance of a mobile and fixed solar panel was carried out, taking into account the key indicators that were also considered.

Based on simulation data using the PVWatts online calculator, it was found that a fixed system is capable of providing approximately 4206 kWh of electricity per year. This indicates stable, but not maximum energy generation, which is highly dependent on the season and the position of the Sun.

Instead, the movable system, which automatically changes its angle of inclination according to the position of the Sun in the sky, provided a higher performance of about 5753 kWh per year, which is about 37% more compared to a fixed panel. This increase demonstrates the significant advantages of using an automatic sun tracking system, namely:

- in summer, the increase is of the greatest importance, which is explained by the long daylight hours and the high position of the Sun.
- Between seasons, the automated system also shows consistently higher performance.
- In winter, the difference also remains, although less pronounced.

Although the increase in electricity generation is accompanied by more complex technical execution and cost of implementation, mobile systems are able to significantly increase energy efficiency without the need to increase the area of photovoltaic modules or install additional panels.

We can see that the comparative analysis confirms the feasibility of introducing automated solar tracking systems in solar generation projects, especially in regions with a sufficient level of solar radiation.

CONCLUSION

In the process of completing the thesis, the main goal was achieved – a study was carried out, an automated system was designed and modeled, which has the ability to dynamically direct the solar panel depending on the position of the Sun in the sky. The task of the project was to increase the efficiency of solar energy generation by automatically adjusting the angle of inclination and azimuth of the panel during the day.

First, an analysis of the current state of solar energy use was presented, the principles of operation of solar power plants were considered, and the influence of the angle of inclination on their performance was determined. The available methods of orientation of solar panels are also analyzed, the advantages and disadvantages of automated solar tracking systems are evaluated.

The second chapter formulates the problem of automatic control. The choice of the Arduino Uno microcontroller and the necessary sensors is justified: a photoresistor for measuring illumination, a DHT22 module for measuring temperature and humidity, as well as a real-time clock (RTC) for time tracking. An analytical calculation of the position of the Sun: altitude above the horizon and azimuth, using astronomical formulas, has been performed.

During the work, the hardware of the system was implemented in the Wokwi environment, where a functional circuit with an OLED display for displaying data was assembled. A software implementation of the control algorithm taking into account weather conditions has been developed. The use of the SunPosition library made it possible to provide accurate coordinates of the Sun in real time, which significantly increased the accuracy of the orientation of the panel. The logic of activating the system with a sufficient level of illumination and favorable humidity is proposed. Simulations have shown the system's successful response to changes in the position of the Sun, ensuring that the panel moves according to its motion. The optimal angles of movement of servo motors for positioning panels have also been analytically calculated. Testing was carried out in various weather scenarios, which confirmed the stability and adaptability of the system to changes in conditions. The applied principle of preliminary analysis of

conditions (humidity, light level, altitude of the Sun) made it possible to avoid unnecessary movement of servo motors, which helps to reduce energy consumption and extend the service life of system elements.

A comparative analysis of the efficiency of the system with a moving and fixed solar panel using the PVWatts online calculator was performed. The test results demonstrated that the proposed system can increase power generation performance by 35-40% compared to fixed-installed panels. This is achieved through dynamic tracking of the position of the Sun, optimization of the operation of panels depending on weather conditions.

Our system especially allows for increased power generation in the morning and evening hours when the Sun is low above the horizon. During these periods, traditional fixed panels work less efficiently due to the unfavorable angle of incidence of the rays. Thanks to the automatic adjustment of the angle of inclination and orientation, the developed system ensures the optimal position of the panel even at low solar rise, which allows you to use the potential of daylight to the fullest.

This is especially true in winter, when daylight hours are shorter, and the Sun is at a low altitude throughout the day. The system compensates for this deficiency by precise orientation, which has a positive effect on the overall balance of energy produced. Adaptive panel position control makes the installation more efficient throughout the year, regardless of the season or time of day.

The developed system is energy efficient, adaptive to environmental changes and has the potential for further implementation, which makes it relevant for the modern renewable energy market.

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