The control system for terrestrial two-axis devices for orientation to the Sun has been improved with a high-speed microcontroller operation algorithm. A geomagnetic sensor was introduced into the system to increase the reliability of monitoring the positioning of solar cells. The basis of the algorithm is a simplified astronomical and geographical model of the movement of the Sun in the celestial sphere. The control system automatically tracks the trajectory of the Sun and calculates its angular coordinates for the current moment of time on any day of the year and for any point on the globe. The derived equations of the simplified mathematical model are suitable for calculations of orientation angles to the Sun in real time on 8-bit microcontrollers with low computing power. The control system by AVR-328 microcontrollers was studied. It was established that the use of the algorithm when programming microcontrollers for two-axis orientation systems ensures high stability and reliability of the tracker`s functioning process. The technical parameters of the AVR-328 microcontrollers in the case of using the developed algorithm ensure that the control system performs one reorientation step in a time interval of less than 2 seconds, which ensures the minimum technical period of the reorientation process by the tracker drive mechanisms which is about 5 seconds. Deviations of the calculated orientation angle from the exact value do not exceed 3°, which corresponds to the relative accuracy of recording the solar radiation intensity, which is less than 0.3 %. The microcontroller program written according to the developed simplified algorithm occupies about 35 % of its memory. Therefore, the use of the developed algorithm frees up the resources of AVR-328 microcontrollers for performing additional data processing operations and automatic control over various additional devices related to the process of orientation to the Sun. In the case of solar energy, the algorithm ensures the use of about 98 % of the power of solar radiation

Keywords: astronomical-geographic model of solar orientation, automatic ground trackers, microcontroller program algorithm

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IMPROVING THE SYSTEMS FOR CONTROLLING GROUND-BASED SUN ORIENTATION DEVICES

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1. Introduction

The issue of determination and optimal application of geographical and astronomical quantities remains relevant in solving many different practical problems of geodesy, meteorology, solar energy, surveying, etc. [1, 2]. Their use is the basis of new generations of electronic theodolites, robotic geodetic systems, automated orientation systems, automatic astrometric instruments, and devices. They make it possible to increase both accuracy and performance of measurements and processing of their results. This requires the construction of new effective control systems and methods and algorithms for automatic calculations of geographic and astronomical quantities for them. At the same time, it is necessary to calculate a large number of trigonometric functions for the existing accurate astronomical and geographical models. Therefore, such control systems are quite difficult to design using microcontrollers (MCUs) and even industrial logic controllers because they do not have enough computing power to quickly perform such mathematical operations in real time. To this end, it is necessary to introduce computational microprocessor modules into the control system, which significantly complicate orientation devices. Therefore, scientific research into the possibility of using much simpler astronomical models for microcontroller devices is important for the development of modern terrestrial orientation systems.

In [3], a simple mathematical model of the visible movement of the Sun in the celestial sphere was built. This movement is completely described by only two variable coordinates: the astronomical local solar time t (in minutes) and the latitude φ (in degrees) for the point on the globe where the electronic device is operating. Based on these two coordinates for a specific geographical point on the globe, two angular coordinates of the location of the Sun in the celestial sphere – azimuth and altitude – can be unambiguously calculated. In addition, standard models introduce different starting points of astronomical time (midnight) and time angle (noon). As a result, the calculated coordinates of the Sun's azimuth are negative before noon and positive after noon. This way of determining the azimuths of the Sun is quite inconvenient for programming terrestrial orientation systems based on MCU.

Currently, researching the properties of real algorithm of the MCU program, developed on the basis of a simplified astronomical model, and the information and technical parameters of ground-based systems for orientation to the Sun, which work according to such an algorithm, is becoming relevant.

2. Literature review and problem statement

The widest application of tracker systems is expected in solar energy. Work [4] shows that the development of power stations based on photovoltaic panels and solar concentrators is an important task for many countries of the world. However, an important unsolved problem is the intermittent output of power from such stations, which creates various serious challenges for the planning, operation, and management of power system networks. As a result, it is noted that the use of conventional stationary local photovoltaic systems in the larger territory of Europe is economically unattractive if the "green tariff" policy is not applied. In particular, depending on the season and weather conditions, the average monthly profitability index of stationary solar power plants for the climatic conditions in the territory of Ukraine ranges from 0.1 to 0.5. To solve this problem, various systems for monitoring the movement of the Sun in the celestial sphere are considered promising, the technical implementation of which in the form of a separate device is termed a tracker.

The results of using this approach are given in works [5, 6] for single-axis solar trackers and in [7] for two-axis trackers. Their authors showed that two-axis tracking systems provide 30–40 % more electrical energy output on average per year, compared to stationary power stations. A similar effect is given by single-axis tracking systems if they are reoriented to the optimal position 4 times a year. At the same time, the authors of paper [8] concluded that two-axis solar tracking systems should be used for low-power solar power plants and systems for automatic monitoring of the power of solar radiation. But the wide implementation of such systems is restrained by their economic parameters. For example, the cost of a modern two-axis orientation system with an industrial SN1500 controller is approximately the same as the cost of installing a small power stationary rooftop solar power plant [9]. This means that the financial costs of installing such a power plant with a tracker are twice the costs of a stationary power plant mounted on the roof of a building. An option to overcome this situation is a significant reduction in the cost of trackers, a significant part of which falls on the corresponding control systems. For example, the cost of the powerful ST1500 controller is about 30 % of the cost of the entire orientation system of a solar power plant with a capacity of up to 5 kW [9].

Most researchers of modern automatic solar tracking systems use either a method based on multiple photosensors, or a method based on astronomical calculations of the position of the Sun during the day. Works [10, 11] show that tracking systems based on optical sensors allow tracking the Sun only when the sky is clear and under good weather conditions. In this case, the problems of stability and reliability of the operation of control systems when external conditions change remain unsolved. The astronomical method of controlling solar tracking systems is based on various algorithms and mathematical calculations of the equations of motion of the Earth around the Sun and is devoid of the disadvantages of the previous method. But the analysis performed by the authors of works [12, 13] reveals that exact astronomical equations contain several dozen trigonometric expressions, for the calculation of which modern standard MCUs are not adapted. An option to overcome such difficulties can be a significant simplification of the mathematical model and the corresponding algorithm for the possibility of their implementation on 8-bit MCUs. Therefore, in work [3] it is proposed to use a simpler method, which is based on the application of the moments of sunrise and sunset for a specific geographical area.

The authors of work [12] also emphasize the importance of providing reliable automatic control of continuous current positioning of solar cells by technical means for the astronomical-geographic control method. This is due to the fact that the final and intermediate position sensor systems used on typical trackers give significant errors in large ranges of angular movements.

The results of the design and development of various automatic solar trackers for solar energy, reported in [14], also show that the created tracker systems and their work algorithms should be easily integrated into modern energy systems. To this end, it is necessary to enable simultaneous fulfillment of several important conditions:

a) their cost will be less than 30 % of the total cost of the solar power plant;

b) the use of such systems will allow automating the entire process of energy generation and transportation to consumers with minimal human involvement;

c) easy installation (ideally – automatic) in any point of the globe;

d) the period of reorientation of solar cells should be about 5 minutes for maximum use of solar energy;

e) minimum own consumption of electricity by the tracker system itself;

f) the tracker control system will simultaneously provide a number of additional service functions during the operation of the solar power plant both in autonomous mode and in connection with various electrical energy accumulating systems (generation of "green" hydrogen, gravity systems, etc.);

g) the possibility of simplified production using ready-made standard mechanical, electrical, and electronic modules.

An important direction of the development of solar energy is the constant monitoring of the intensity of solar radiation at the points of the planned installation of power generating stations. Simple trackers are also a mandatory module for monitoring stations to solve this problem. However, for them, the sensor reorientation period should not exceed two minutes to ensure the accuracy of solar radiation intensity measurements required for such meteorological devices [15].

Another important area of application of trackers is mobile systems of orientation to the Sun for geodesy, navigation, and for meteorological stations, the reorientation period of which should be less than one minute. For such systems, the reorientation period of the control algorithm becomes a critical parameter even for industrial controllers.

The above review allows us to state that it is expedient to carry out research on control systems for various solar orientation devices aimed at solving the following important unsolved problems:

a) simplification of the astronomical algorithm of ground tracker control systems for the possibility of its software implementation on simple MCUs;

b) improving the process of controlling the positioning of solar cells;

c) experimental and theoretical research of the parameters of the mathematical and information components of the two-axis tracker control systems, which meet the basic technical and economic requirements for solar orientation devices.

3. The aim and objectives of the study

The aim of our research is to improve the control systems of ground trackers for orientation to the Sun, which use an astronomical-geographical algorithm of operation. This will make it possible to implement such systems based on 8-bit MCUs and improve the informational, technical, and economic parameters of modern orientation devices.

To achieve the goal, the following tasks were set:

– to analyze the possibility of applying an approximate mathematical astronomical model of the movement of the Sun in the celestial sphere;

– to increase the reliability of the control process of the positioning of the solar cells placed on the tracker;

– to simplify the algorithm of ground tracker control systems for simple MCUs;

– to investigate the timing diagram and various limit parameters that can be achieved in solar orientation control systems based on 8-bit AVR-328 type MCUs when implementing a simplified algorithm.

4. The study materials and methods

The object of our study is the control system of terrestrial devices for orientation to the Sun using the astronomical-geographical method of their positioning. To improve such systems, the algorithm of their operation was simplified using theoretical methods of standard transformations of the coordinates of the position of the Sun on the celestial sphere in various angular coordinate systems. To this end, such a simplification of mathematical ratios was allowed, which introduce errors into the determined angular coordinates, which are comparable in magnitude to metrological values for modern meteorological instruments of a high accuracy class. The adequacy check of the created simplified algorithm was carried out by comparing the angular coordinates generated by it with the corresponding values according to exact astronomical data.

In order to increase the reliability of monitoring the real current spatial positioning of the solar cells placed on the tracker, an electronic geomagnetic compass CJMCU-9911 AK09911C from Philips was introduced into the control system.

The information and technical parameters of the simplified algorithm were studied by simulating the execution of individual operations and steps of the MCU AVR-328R (Germany) algorithm based on the ArduinoNano (Italy) module. The emulation was carried out in the Arduino IDE software shell (Italy) [16]. Data from [17] were also used to assess the sufficiency of MCU information resources for the implementation of a simplified algorithm and the time intervals for performing basic control operations. At the same time, the MCU AVR-328R clock frequency of 16 MHz was used as a basis.

During the emulation process, separate small programs in the CI++ language were created in the Arduino IDE shell, each of which corresponded to one separate step of the implementation of the simplified control algorithm. Special operators for recording the start and end of the corresponding MCU operations in a computer file were entered into the programs. The created programs were installed in the MCU memory, and their execution was initiated. According to the received data from the time modes of MCU operation, the corresponding intervals of execution of various control operations in real time of MCU operation were calculated.

5. Results of improving the control system of ground devices for orientation to the Sun

5. 1. Approximation of the mathematical astronomical model

The basic values of the astronomical model of the movement of the Sun in the celestial sphere are the serial number of the corresponding calendar day N and the current moment of the local solar time for this day t in the geographical location of the control system installation. The time angle of the Sun's position is determined by these two initial coordinates:

$$\psi=(t\pm 720)/4, \qquad (1)$$

and the angle of declination of the Sun:

$$\delta=\varphi+23.45^{\circ}-\sin\left[0.986-(N+284)\right]. \qquad (2)$$

In the above ratios, the "minus" sign corresponds to time intervals before noon, and the "plus" sign corresponds to afternoon.

For terrestrial orientation systems, the time change interval t is determined by the moments of sunrise and sunset, which on the celestial sphere are set by two corresponding time angles ψ_{EW}. The latter are easily calculated using a simplified ratio:

$$\cos\psi_{EW}=-\mathrm{tg}\varphi\cdot\mathrm{tg}\delta, \qquad (3)$$

where φ is the geographical latitude of the operating point of the control system.

The given equation gives two approximate solutions for the time angle of the moment of sunrise ψ_E (in the range from –180° to 0°) and the moment of its sunset ψ_W (in the range from 0° to +180°). This method is typical for astronomical research, where the reference points of time are the moments of "midnight" and "noon". However, the method of setting these angles, which is more convenient for technical systems, was used in the simulation. During the "light" part of each day, the current time angle ψ was assumed to vary from an initial value of zero at sunrise to a final value of $2\psi_W$ at sunset. It is this range of angles ψ that determines the time interval of active operation of the ground orientation system. Therefore, the simplified mathematical model of the tracker control is based on the determination by the MCU at each moment of the administrative time t of the current value of the solar angle ψ in the range from 0 to $2\psi_W$. At the same time, the value of the angle ψ_W is calculated by MCU only once for each current day.

The time angle ψ uniquely determines the astronomical coordinates of the position of the Sun on the celestial sphere relative to the location of the tracker on the Earth's surface. One of these coordinates is the Sun's elevation angle h, which is easily calculated by the ratio [2, 3]:

$$\sin h = \cos\psi \cdot \cos\varphi \cdot \cos\delta + \sin\varphi \cdot \sin\delta. \quad (4)$$

The second coordinate is the azimuthal angle of the Sun's position α. There is an approximate mathematical relationship between the azimuth and the time angle of the Sun [3]:

$$\cos\alpha = (\sin\varphi \cdot \sin h - \sin\delta) / (\cos\varphi \cdot \cos h). \quad (5)$$

The above equations from (1) to (5) represent the constructed approximate mathematical model for the operation of terrestrial systems of orientation to the Sun, which was the basis for the development of a simplified control algorithm for MCU.

The theoretical accuracy of recording the intensity of the incident radiation in the tracker systems will be determined by the accuracy of the reproduction of the real angular coordinates of the position of the Sun by a mathematical model. To determine this accuracy, changes in the angular coordinates of the Sun's position during the daylight hours were calculated according to the exact astronomical model [2] and the proposed simplified model. The results of such calculations for the azimuthal angle are shown in Fig. 1.

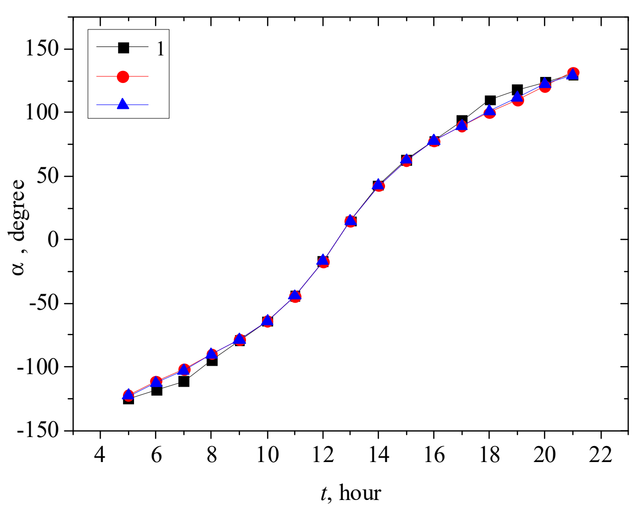

Fig. 1. Change in the azimuthal angle of the position of the Sun on the celestial sphere during the daylight hours of June 21 for the Uzhgorod region, calculated: according to the mathematical model [7] (curve 1), according to the exact astronomical model [2] (curve 2), and according to the accepted approximate mathematical model (curve 3)

To identify the impact on the theoretical accuracy of an even greater simplification of the trigonometric equations of the mathematical model, a plot (curve 1 in Fig. 1) of the daily change in the azimuth coordinate was also built according to the equation:

$$\sin\alpha = \cos\delta \cdot \sin\psi / \cos h. \quad (6)$$

Such a simple mathematical expression is often used in tracker management systems [7].

5. 2. Improving control over the positioning process

The algorithm for the implementation of the control system with an approximate mathematical model was developed for two-axis trackers since only they provide high accuracy of the orientation of the solar cells. The structural diagram of such a control system is shown in Fig. 2. It contains basic MCU electronic modules and a real-time electronic clock (RTC – realtimeclock) typical for the astronomical-geographical method.

Technically, for the astronomic-geographic control method, it is necessary to position the solar elements throughout the daylight in a large range of angles, which exceeds 180°. Under such operating conditions, it is quite important to constantly monitor the process of positioning the solar cells. Experimental studies have shown that the use of final and intermediate contact sensors for this purpose complicates the positioning algorithm and does not provide the necessary control accuracy with errors of up to several degrees. The use of modern geomagnetic sensors turned out to be much more effective in solving this problem. Therefore, along with the generally accepted solar tracker modules, a modern Philips CJMCU-9911 AK09911C device (Compass module in Fig. 2) was introduced into the control system. It is a non-contact three-axis magnetometer with a digital output signal adapted for direct communication with MCU; it provides an absolute error of less than 1° in the determination of angles.

To allow the operator to work with the control system (mainly at the stage of setting up and servicing), a service module of an LED display (LED) and a module of manual control keys (KEY) are introduced into it. Control over all components, which carry out the mechanical process of re-orientation of solar cells in space, is carried out through two separate information channels of drivers for the elevation angle (Drvaxis h) and the azimuth angle (Drvaxis α). The first driver controls the rotation of the solar cells relative to the horizontal axis of the tracker, and the second – relative to the vertical axis.

5. 3. Simplified control algorithm for MCU

The entire operating algorithm developed for the above control system contains several logical modules, each of which corresponds to a certain stage of the tracker's setup or operation. The first stage involves the initial installation of all mechanisms and modules of the tracker in the initial working state. When it is performed, it is bound to the geographical coordinates of the installation point on the globe. This binding is a simple record in the MCU memory of the latitude (φ) and longitude (D) constants of the location of the panels. In addition, the technical topographic coordinates of the base plane on which the mechanical system is mounted are set for the controller. Such topographic coordinates are the angle of inclination of the plane of the tracker base relative to the horizon plane (β) and the angle of orientation of this base relative to the direction to the astronomical south (α_0). These two angles can also be entered as two constants in the MCU memory. This stage can be carried out in two versions of the algorithm:

a) manual input of constants by the operator during installation and adjustment of the orientation system;

b) automatic determination of the given parameters by the Compass electronic module. Below is a variation of the algorithm for the first option. For the second option, the algorithm is easily modified by replacing several data entry operations.

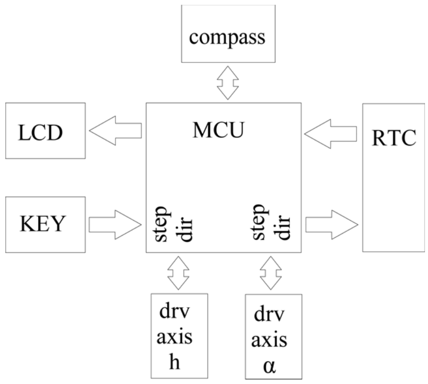

Fig. 2. Block diagram of the automatic control system for two-axis trackers

During initial setup, the MCU's internal timer is also connected to the RTC module, which generates the current date and current administrative time for the area. This allows the MCU to calculate the exact values of the time angle ψ at any instant of time on every day of the calendar year. It is also worth noting that if for some reason the time readings of the non-volatile RTC clock are lost, the settings of the control system must be reconfigured.

At the second stage, the processes of periodic reorientation of solar elements to the Sun take place so that their plane is perpendicular to the direction of direct sunlight. To do this, the control system periodically forms a series of pulses (stepdir) on its two output information channels, which control the tracker orientation drivers by elevation angle (h axis) and azimuth rotation angle (α axis).

At the first stage of setting up the control system, the following actions are performed:

1. Verification of the spatial location of the solar cells in the initial standard initial position according to the signals that the MCU receives from the corresponding end sensors of the mechanical components of the tracker and the geomagnetic sensor of the Compass module, which is installed on the solar cells.

2. Positioning the mechanical components of the tracker in the initial standard position.

3. The operator sets the real-time clock to local administrative solar time (LAST) and enters the current calendar start date.

4. The operator enters the geographic coordinates of the location of the tracker into the MCU memory. These constants are entered in degrees, taking into account the sign of latitude D: negative – for the western hemisphere, positive – for the eastern.

5. Organization of real-time transfer of LAST time and date from the RTC clock to MCU.

6. The operator enters into the MCU memory the value of the parameter p and the calendar dates of the transition to summer time in the form of corresponding constants.

7. The operator enters the number constant N_T of the time zone of the area where the tracker is installed into the MCU memory. The sign of this number should be taken into account: it is negative for the Western hemisphere, and positive for the Eastern hemisphere.

8. The operator enters the technical angle constants β and α_0 (in degrees) into the MCU memory.

9. If necessary, the operator sets in the MCU memory the average correction of the influence of the terrain on the time of sunrise Δt_E and sunset Δt_W in minutes.

10. MCU calculation of the time correction constant for the longitude of the location of the panels as $\Delta\psi=4(15°\cdot N_T D)$ in minutes. This parameter is also stored in the MCU memory.

11. Setting the time interval T (in minutes) by operator in the MCU memory, which sets the frequency of reorientation sessions of solar cells. The optimal value of T depends on the purpose of the tracker as it determines the errors of setting the orientation angle of the elements on the Sun. Usually, this value can vary in the range from one minute to several tens of minutes.

Based on the results of the initial installation of the tracker together with the control system, MCU calculates a number of its own internal parameters that determine the periodic operation of the tracker under the standard operating mode during the daylight part of each day of the year. Details of such calculations are given in [3].

The second stage of the operation of the control system consists in the constant adjustment of the solar cells to the position of optimal orientation to the Sun. This stage consists of two different sub-stages: a short start-up of the system at the beginning of the light part of each day and periodic operation with period T throughout the "light" part of that day.

A short starting step consists in the MCU calculating a number of values for a given day based on receiving a new date from the RTC real-time clock and other constant parameters from the MCU memory. Under this mode, the control system performs the following basic actions:

1. Calculates and remembers the serial number N of days of operation of the orientation system in the current year, considering January 1 as the first day of the year. At the same time, the diurnal angle $B=0.986\cdot(N-81)$ and the solar local time correction $\Delta t_E=9.87\cdot\sin(2B)-7.53\cdot\cos(B)-1.5\cdot\sin(B)$ are calculated.

2. Calculates and remembers the astronomical inclination angle of the Sun $\delta=23.45°\cdot\sin\,[0.986-(N+284)]$ and the time angle of the Sun's rise in the current day: $\psi_{EW}=\arccos(\mathrm{tg}\varphi\cdot\mathrm{tg}\delta)$.

3. Calculates and remembers the number of minutes that pass from the beginning of the current day to the moment of sunrise $t_E=4\cdot(180-\psi_{EW})$ and determines the moment of the start of the next daytime session of the orientation system $t_B=t_E+\Delta t_E$. This parameter is entered in the MCU's special R_B register.

4. MCU enters standby mode. Under this mode, the MCU starts counting the total number of minutes t that have passed since the beginning of the current day. As soon as the value of t exceeds the value of the parameter t_B, the MCU program generates an internal interrupt. After this interrupt, the MCU proceeds to the next stage of controlling the periodic operation of the tracker.

The actions of the control system described above are mainly mathematical in nature and are concentrated in the electronic module. Therefore, for such actions, the graphic algorithm is not very informative. Subsequently, the operation of the control system begins with its active interaction with the technical components of the tracker. This is the stage of the periodic operation of the control system, which ensures the reorientation of the solar cells in the optimal position relative to the Sun during the entire "light" part of the day. The logic of these actions is clearly illustrated by the graphic form of the developed algorithm, which is shown in Fig. 3. It describes the process of controlling rotation relative to one axis. However, the control system executes this algorithm twice in a row to orient the solar cells relative to two axes.

During the periodic operation of the tracker during daylight hours, the MCU monitors the execution of the following points of the algorithm:

1. Checks sensor signals that determine the limits of movement of the solar cell. If all of them generate a "true" signal, the control system proceeds to the next operation. If a "false" signal appears at the output of at least one of the sensors, the MCU generates a procedure for starting the reorientation of the panel along two axes and searching for another extreme position of the panels until the "true" signal appears. This action is possible in emergencies or during the initial installation of tracker elements. Further orientation of the panels and control of their positioning is carried out according to the data of the geomagnetic sensor of the Compass module. If the "true" signal does not appear within the set time (time of reorientation of the elements from one extreme position to another), the system goes into emergency mode with the following message to the operator.

To perform the described operations, the two-axis tracking system must be equipped with at least four end position sensors with analog or digital output. Execution of the operation code "survey" of all installed sensors is not limited in time as it can be done in advance before the tracker starts working.

2. MCU calculates the time angle $\psi=0.25\cdot[t-4\cdot(15\cdot N_T--D)+\Delta t_E+p\cdot 60]$ according to the known values of various parameters in the memory.

3. Calculation of the angle of elevation of the Sun for a given local time according to relation (4) and calculation of the angle of elevation of the solar element relative to the reference base of the tracker $\omega=h-\beta$.

4. MCU generates control pulses for the servo drive to set the height angle of the solar cell ω.

5. The azimuth of the Sun's position at the current moment of time is calculated according to relation (5) and the azimuthal angle of orientation of the solar elements is defined.

6. MCU generates control pulses for the azimuth orientation servo of the solar cells, which enable the reorientation process.

7. MCU writes to its R_B register the new value of the start time of the next reorientation step and goes into standby mode. While waiting, the MCU performs coordinate calculations for the next step of reorienting the solar cells. Therefore, the duration of this stage is equal to the period of reorientation T, which is set by the operator during the installation of the control system. For different tracker systems and for different operating conditions, this period can be equal to one minute (for example, the field of meteorology) to several tens of minutes (the field of solar energy).

8. After the end of the waiting interval T, the MCU program generates an internal interrupt and the control system proceeds to the next step of reorienting the solar cells to the optimal position, controlling the current position according to the data of the geomagnetic sensor. According to the simulation results, this interval lasts several milliseconds and therefore it can be neglected in the total balance of the tracker's operation time.

9. Reorientation steps are performed by the control system until the moment of sunset is reached. After that, MCU puts the solar cells in the "park" state and the control system in the standby mode. This standby mode is maintained until the RTC real-time clock in the control system reaches midnight. According to this data, the MCU resets the current program variables for the completed day and starts the next stage of work for a new day.

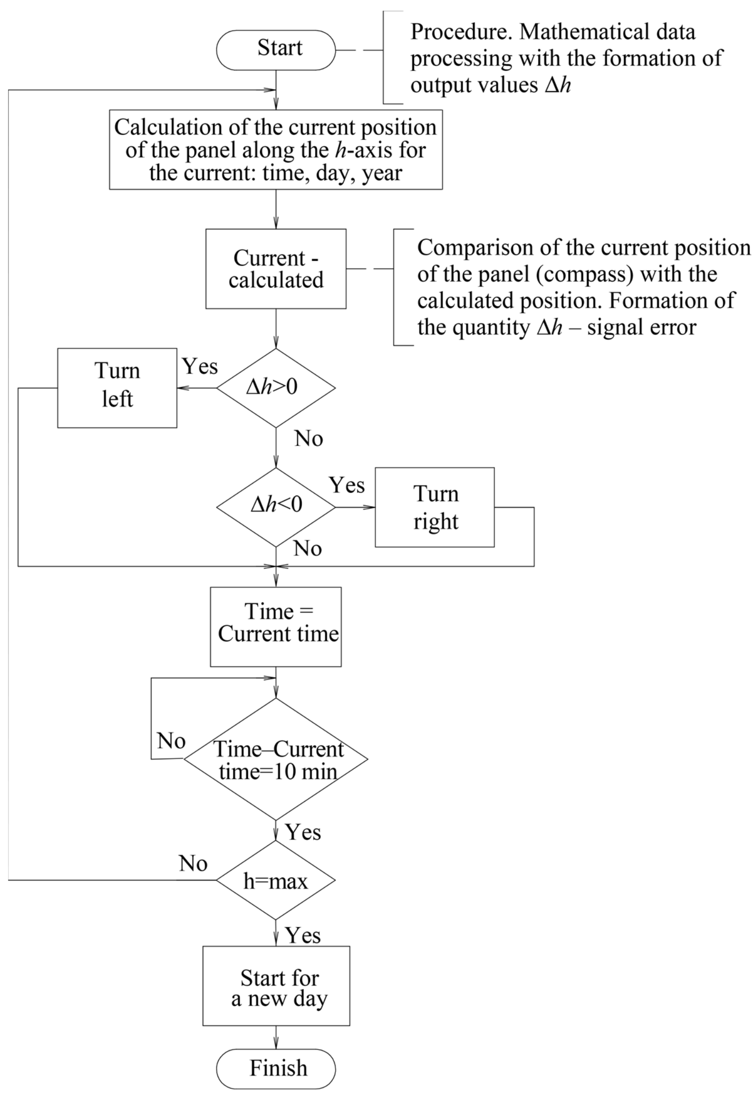

Fig. 3. Algorithm of periodic positioning of the panel relative to one of the axes during the "light" part of the day

5. 4. Time, information, and technical parameters for implementing the control system simplified algorithm based on MCU AVR-328

The results of studies of the process of implementing the developed algorithm over time are shown in Fig. 4. At the same time, it is taken into account that the short start stage of the algorithm at the beginning of each day is not limited by the time interval necessary for its execution since it can be performed at night. In particular, we programmatically "tied" the execution of this MCU step to the moment of transition of the RTC clock to a new day.

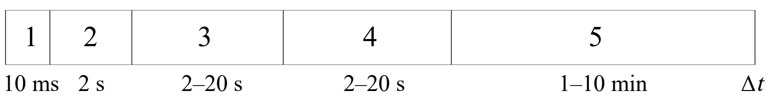

Fig. 4. Timing chart of algorithm stages for one step of reorientation of solar cells (1 – arithmetic calculations, 2 – calculation of trigonometric functions, 3 – reorientation by elevation angle, 4 – reorientation by azimuth angle, 5 – performance of maintenance operations for systems compatible with the tracker)

The stage of periodic reorientation of the solar cells during the "light" part of the day turned out to be the most critical to the time intervals of MCU execution of individual operations. The simulation on the AVR-328R MCU showed that the main time spent during the execution of this stage of the algorithm by the control system is typical for several operations.

During the calculation of the starting values, the MCU performs about 10 different arithmetic operations. At the same time, the execution of almost every action is accompanied by a call to memory to read one or another constant. Under such conditions, several tens of microprocessor clocks are allocated on average to perform each arithmetic operation, which generally determines the duration of this stage in several milliseconds (stage 1 in Fig. 4).

During each step of reorientation according to the simplified algorithm, it is necessary to calculate about 10 values of different trigonometric functions. Modeling and simulation showed that the duration of these MCU calculations significantly depends on the required accuracy of the calculation result. For the studied control system, the maximum absolute error of the calculation of the coordinate angles of the position of the Sun on the celestial sphere was taken to be about ±0.5°. Under such conditions, the duration of calculating the elevation angle and azimuthal angle for any set of input data did not exceed 2 seconds (stage 2 in Fig. 4).

An accurate astronomical model uses mathematical expressions that contain about 40 different trigonometric functions [2]. The simulation results show that in this case the MCUAVR-328R spends up to 7 seconds of time to calculate the angular coordinates of the Sun. This insignificantly increases the duration of one informational step of reorientation of the tracker with the accepted theoretical accuracy of setting the positioning angle.

The execution time of the technical step of periodic reorientation cannot be adequately simulated without the presence of a tracker system with real electromechanical components under actual working conditions. This is due to the fact that the functioning of mechanical devices includes the implementation of many active and passive functions of movement. For them, certain time intervals of "rise" and "decline" of mechanical, electrical, and signal disturbances, which occur during the pulsed reorientation of solar cells from one position to another, should be allocated. Therefore, the duration of this stage significantly depends on the specific technical properties of all electromechanical devices involved in the tracker. To take into account these properties, a driver model with a 17HS4401 type stepper motor was introduced into the simulation scheme. The research results showed that for the reliable execution of the set of actions of this technical stage of reorientation, an average time of up to 10 seconds should be expected. At the same time, the processes of obtaining stable data from the Compass geomagnetic module, which controls the fixation of the new angular position of the solar cells during the reorientation, turned out to be the longest. This period can be twice as long when reorienting massive solar cells such as standard photovoltaic panels with a large weight (stages 3 and 4 in Fig. 4). At the same time, for small-sized solar sensors in the case of meteorological tracking stations and for mobile orientation systems, this interval can be reduced to 2 s.

During the software implementation of the developed algorithm, six main modules that use information resources of MCU are selected. The results of studies of the information capacity of each of these modules are shown in Fig. 5.

Block of input data 2.5 kB
Block of daily parameters 2 kB
Block of orientation angles 4.5 kB
Block of geomagnetic sensor 9 kB
Block of driver control 2 kB
Block of display from 2 kB до 5 kB
Block of accompanying programs from 7 kB to 10 kB

Fig. 5. Memory allocation diagram of MCU AVR-328R with 32 kB of memory in the software implementation of the developed algorithm

During the initial stage of the algorithm, all main input astronomical and geographical values are set by the operator during the initial installation of the control system at the place of operation and are stored in non-volatile memory. Simulation studies on the AVR-328R MCU module have shown that 2.5 kB of memory is enough for the input and storage program module of all these data.

The second program module for calculating algorithm parameters for each new day contains about 30 operators of simple arithmetic operations. In addition, it contains a number of operators for processing information that comes from sensors of the extreme position of the tracker base. In total, this module occupies about 2 kB of information space in memory.

The module of the program for calculating the angular coordinates of the Sun on the celestial sphere during each reorientation step contains about 30 operators with various trigonometric functions and arithmetic operations. At compile time, this module occupies 4.5 kB of MCU memory. For the software implementation of an accurate astronomical model, the complexity of the algorithm for calculating the angular coordinates of the Sun increases significantly. As a result, the program module of such calculations requires about 11 kB of memory space.

A fairly significant information resource is required to host the MCU operating program with the three-dimensional geomagnetic sensor module. The standard version of this program took up almost 9 kB of memory. The program for controlling two stepper motor drivers of the tracker electric drive fits in only 2 kB of MCU memory.

In the simplest version, the module of the program for working with the information display requires about 2 kB of memory. However, to provide a more convenient interface for the control system to interact with the operator, a wider program should be used, which will take up to 5 kB of memory.

Thus, the results of simulation and compilation of various program modules of the developed algorithm show that at least 22 kB of MCU AVR-328R memory is required for its implementation. Accordingly, there remains about 10 kB of free space in it for placing additional modules of the MCU interaction program with accompanying device orientation system.

6. Discussion of research results regarding the informational and technical parameters of the simplified algorithm

The most important technical parameter of trackers is the accuracy of their positioning, which determines the efficiency and errors of solar radiation perception by photocells. The very process of orientation to the Sun consists in adjusting the position of the recording solar elements in such a way that their plane is perpendicular to the direction of direct sunlight at each moment of time. Therefore, the accuracy of measuring the intensity of incident solar radiation in tracker systems will be determined by two main components:

a) the theoretical accuracy of reproduction of the real angular coordinates of the position of the Sun by a mathematical model;

b) the experimental accuracy of the positioning of the plane of the solar cells by the technical components of the tracker drive;

c) accuracy of continuous control over the positioning process by the geomagnetic sensor.

The theoretical accuracy of the simplified algorithm can be estimated from the results shown in Fig. 1. Their analysis showed that the daily dependences of the Sun's elevation angle for the exact astronomical and approximate mathematical models differ from each other at any moment in time by a value of about 1°. For the azimuthal angle of the Sun's position α, the noted dependences differ more significantly, especially in the range of angles near the moments of sunrise and sunset. The maximum differences in this case reached 3° (Fig. 1). Adoption of even more "rough" approximations of the mathematical model, which are used in [7], significantly increases these differences. In particular, for rather long periods of time after sunrise and before sunset, the deviation between the exact and approximate values of the azimuth angles reaches 15° (Fig. 1, curve 1).

In the practical implementation of the model, the theoretical deviations from the optimal orientation of the solar elements are determined by the angle γ, which is the sum of the elevation angle and the azimuthal angle of the position of the Sun. The corresponding deviations lead to a relative error in recording the intensity I of solar radiation by a value equal to $(I-I\cdot\cos\gamma)/I$. Calculations show that for the approximate mathematical model used, the maximum deviation of the angle γ does not exceed 3°. This gives the maximum relative error of solar radiation intensity registration $(1-\cos3°)\cdot100\,\%\approx0.3\,\%$. This value meets the requirements for modern meteorological instruments of a high accuracy class [15]. At the same time, the maximum theoretical error for a "rougher" mathematical model [7] exceeds 5 %, which does not meet the requirements of modern meteorological standards. Even in the case of using such a "rough" model to control solar power plant trackers, there will be significant annual total losses of generated power.

The experimental accuracy of the positioning of the solar cells is determined by the technical electromechanical components from which the tracker is built. When analyzing this accuracy, we shall consider a control system option for meteorological trackers. This type of solar orientation system is chosen because the most "tough" requirements for the accuracy and speed of positioning of the solar cells are established for them by the relevant standards.

The analysis of time intervals of the main operations reveals that the use of a simplified algorithm allows us to reduce the time of one step of reorientation of the tracker system to 5 seconds with the help of a simple MCU of the AVR-328R type. From Fig. 1 it also follows that the maximum angular velocity of the Sun's movement across the celestial sphere is about 30° per hour. In this case, in 5 s, the maximum total change in the angular coordinates of the Sun does not exceed 0.1°, which corresponds to the relative error of measuring the intensity of solar radiation, which is less than 0.1 %. However, as shown above, there are deviations of up to 3° of angular parameters calculated by the approximate mathematical model from exact astronomical data, the errors of which significantly exceed 0.1 %. Therefore, the experimental positioning accuracy of orientation systems according to the developed algorithm will be determined by maximum relative errors greater than 0.3 %. Close to this value are the errors of the positioning process control by the Compass geomagnetic sensor. Obtaining more accurate values of experimental positioning errors requires detailed studies of a real tracker system with specific drive mechanisms.

Maximum errors of more than 0.3 % are characteristic only for small time intervals of the tracker system after sunrise and before sunset (Fig. 1). In the main time of operation of the tracker with good backlash-free movement mechanisms during a "light" day, experimental errors are estimated to be less than 0.3 %. As already noted, such a metrological parameter is characteristic of high-class meteorological instruments.

Thus, the application of an improved management system:

a) provides twice the speed of the control system due to the reduction of the time of mathematical calculations of the angular coordinates of the position of the Sun at each step of reorientation;

b) enables the operator to continuously control the process of positioning solar cells in real time;

c) allows one to free up a large part of the MCU's memory for it to perform other information processing operations and to control various peripheral devices. In particular, for solar orientation systems, these can be solar power plants, meteorological stations, geodetic instruments, and others. At the same time, MCUs of the AVR-328R type have a sufficient number of analog and digital data input/output ports, which are necessary to organize the operation of various accompanying devices.

Another important area of using ground-based solar orientation systems is solar energy. In this case, it is not economically justified to reorient the solar panels more often than once every 5 minutes. Accordingly, the AVR-328R MCU-based control systems with the proposed simplified timing diagram algorithm and memory size are quite suitable for solar power plants. The deviation of orientation angles from the optimal position in 5 minutes does not exceed 3°. If we also take into account the errors introduced by the approximate mathematical model, then the maximum errors of the orientation angle can exceed 6°. This corresponds to an average loss of generated electrical power of less than 2 %. In this case, solar power plants with the proposed control system ensure the production of electrical energy under the peak mode during almost the entire "light" part of the day.

Freed MCU working time and memory resources allow one to enter additional programs to provide important service functions of the solar power plant into the control system:

a) constant monitoring of the power generated by solar batteries;

b) periodic measurement of their temperature;

c) recording the generation results in the database;

d) establishment of sharp deviations from the optimal mode of operation of the power plant and notification of the operator;

e) coordination of trackers and a solar power plant with MPPT controllers, inverters, storage batteries, "green" hydrogen generators, etc.

These functions significantly increase the marketing parameters of tracker systems without significant additional economic costs for their production, installation, and operation.

The use of tracker systems with a simplified control algorithm is especially effective for fully autonomous solar power plants of small power (up to 10 kW), which provide energy to individual households or small business facilities. This is especially relevant if these objects are located far away when the cost of laying a standard electrical network to them may exceed the cost of building an autonomous power plant.

The application of the proposed simplified algorithm is limited to those device control systems that involve the measurement of parameters of direct solar radiation or the use of its energy, in particular, meteorology and solar energy. The use of this algorithm in accurate geolocation devices (for example, geodesy, surveying, etc.) will give errors in determining the angular coordinates of the Sun, which exceed the permissible values for these industries. For mobile objects (for example, in navigation), the application of the algorithm for continuous orientation to the Sun is limited by the small speed of movement of these objects (according to approximate estimates up to 10 km/h) without their sharp turns.

The disadvantage of the proposed algorithm is its "binding" to the geographical coordinates of the installation point of the control system. When changing the location of the control system, it is necessary to enter new coordinates in the MCU memory under "manual" mode. In the case of applying the algorithm to mobile objects, such reinstallation should be carried out when the object is moved from the previous geographical point at a distance of more than 50 km. Without reinstallation, the error in determining the angular coordinates of the Sun will increase significantly. A possible solution to the above-mentioned shortcoming is the introduction of an additional GPRS navigator module or a space navigation module into the control system. Of course, this will complicate the control system itself and the algorithm of its operation.

In the process of analyzing our results, an urgent question arose about the complexity of the practical implementation of the proposed algorithm in a real control system. It is in this direction that the advancement of the current research is planned. Currently, the most significant difficulties on this path have become clear. First, it is the choice of the optimal method for converting the angular coordinates of the position of the Sun into signals for the drive drivers, which will ensure the exact orientation of the solar cells. Second, the complexity of software implementation of some steps of the algorithm for the MCU. Third, the creation of simple feedback links between the elements of the electric drive and MCU to control the execution of each operation of the algorithm and the accuracy of setting the orientation angles.

7. Conclusions

1. The possibility of applying an approximate mathematical astronomical model of the movement of the Sun in the celestial sphere for the improvement of control systems for ground-based solar orientation devices with high positioning accuracy has been shown. The approximate model differs from the exact astronomical setting of the Sun's angular coordinates by reducing the number of trigonometric functions by more than half. The use of such a model provides positioning errors typical of modern meteorological instruments.

2. A geomagnetic sensor was introduced into the control system, which allows for continuous monitoring of the positioning process in real time during operation throughout the day in a range of angles greater than 180°.

3. A simplified algorithm for ground tracker control systems, suitable for implementation on the basis of 8-bit MCUs, has been developed. In the simplified algorithm, a simpler astronomical mathematical model is used, more precise moments of the start and end of the tracker are introduced, methods of determining the exact solar time and angular coordinates of the Sun are optimized. The developed algorithm can be used to design various modern devices that function automatically when installed in any which geographical point of the Earth. It is shown that in the case of tracker solar power plants, the algorithm can ensure almost full use of direct solar insolation during the daylight hours due to sufficiently accurate positioning of photocells. The possibility of implementing the algorithm on simple MCUs reduces the cost and increases the economic attractiveness of using ground tracker systems for orientation to the Sun of various functional purposes.

4. Using the methods of theoretical analysis and computer simulation based on the MCU AVR-328R, time, information, and technical parameters of control systems for automatic devices for orientation to the Sun, created using a simplified algorithm, were investigated:

a) the process of periodic reorientation of solar cells to a new position by the control system in real time takes from 2 s to 5 s, depending on the parameters of the electromechanical drive components of the tracker;

b) the maximum theoretical angular error of orientation of solar elements during the "light" part of the day, which is ensured by the developed algorithm, does not exceed 4;

c) the relative theoretical error of recording the intensity of direct solar radiation by a weather system with a tracker does not exceed 0.3 %;

d) accuracy of continuous control over the process of positioning the solar element by the operator at the level of 1°;

e) in an AVR-328R MCU, the program according to the developed algorithm will occupy about 35 % of the standard memory resources;

f) a significant part of the MCU memory volume remains available for input into the control system of additional control programs for various technical and informational devices associated with the tracker.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study and the results reported in this paper.

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Data availability

All data are available in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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