Maximum energy efficiency on photovoltaic solar panels by using an innovative solar tracker

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Abstract The solutions currently used for the acquisition of solar energy are based on fixed mechanical structures, in which the photovoltaic panels are either ground-mounted or building-integrated, positioned on suitable rooftops. Both solutions involve the partial take-over of solar energy, thus a reduced energy efficiency of the photovoltaic installation. The solution proposed by the authors of the paper has an innovative mechanical construction and a mixed mode of operation, which combines the secular way with that of the tracking. The operation of the solar tracker presented in the paper is based on the programming in LabVIEW, with the use of a general module for the acquisition/generation of analogue and digital signals. The design developed by the authors has a simple mechanical construction, and the positioning considers the clock of the PC, so that the initial positioning (at start-up) is done in a simplified manner, regardless of the geographical placement of the tracker. The authors performed experiments in the laboratory and in the field, the results being consistent with the theoretical assumptions.

1. Introduction

Solar energy is facing a rapid advance in the world's top economies, due to its reliability, the possibility of distributed installation and the lack of greenhouse gas emissions [1].

Photovoltaic panels have a number of benefits, the most significant being: (i) sustainable technology, (ii) availability of solar radiation, (iii) small impact on the environment for the installation, (iv) lifetime of more than 15 years, (v) low maintenance requirements, (vi) modularity, (vii) possibility of installation near car charging centers and (viii) noise-free and emission-free operation. Unfortunately, the efficiency provided is not as high as in other renewable sources, such as hydropower plants [2].

In order to improve the energy generation by the photovoltaic panels and therefore the viability of the costs, the generation output can be increased throughout the day by tracking the position of the sun, thus keeping the panel perpendicular to the solar radiation.

The scientific literature in the field proposes two main approaches to design and build a solar tracker:
- in the open circuit, by using the secular position of the sun, deduced either by calculations or by observation tables from international institutes recognized in astronomical studies; these solutions are known as secular solar trackers [7];
- in closed circuit, using automatic tracking systems on one or both axes, using appropriate positioning systems relative to the position of the sun (known as solar trackers with tracking, an example is presented in [6]).
According to studies from the United Kingdom [7, 9, 10], the two-axis tracking system can lead to an annual energy increase of about 48% compared to a fixed model and about 36% compared to a tracking system with a single axis. The use of tracking systems on both axes can thus be very attractive, because the advantage of tracking enhances the economic efficiency of the system.

A careful analysis on the result of [10] shows that tracking the sun's position with an error below ±1° - both at the horizontal (azimuth) and vertical (elevation) axis - does not reduce the energy efficiency of the photovoltaic cell sensor. This aspect will be found in the accuracy of the solar tracker shown below.

2. Developing a simple and efficient solar tracker
The solar tracker described below is based on several features that differentiate it from other similar categories, as follows:

- Is developed in **LabVIEW**, so that it benefits from all the facilities offered by this application development environment.
- Effectively combines the tracking of the secular position of the sun with that of the closed circuit on both axis of rotation.
- It has a robust mechanical configuration, in which the movement of the rotation axis designated to azimuth tracking is performed with a stepper motor, and the one designated for the elevation is handled by the closed circuit system (with tracking).
- Uses an innovative technique - not found in other mechanical structures - to generate the tracking position on the vertical axis (elevation), which ensures a fixed position of the drive motor and a combined transmission (rotation on a vertically positioned screw, to which is added a double articulation for the vertical axis).
- Uses screw-wheel technology for horizontal displacement (relative azimuth), so that the drive motor is fixed relative to the rotation reference; this property guarantees long lasting mechanical stability for the mechanical system.
- Uses photodiodes - operating in the visible spectrum - as elements to capture the tracking position. These are placed in a mechanical structure which ensures a positioning accuracy below ±1°.
- The time positioning of the azimuth is guaranteed to be correct, as it uses the system clock (PC).
- Uses a simplified algorithm for initial positioning (secular position for azimuth), the quality of positioning being managed by the tracking system (closed loop).

Figure 1 shows the block diagram for the developed solar tracker, in accordance with the characteristics enumerated above.

The sunlight is captured by the photodiode system, helping to position the tracker on the closed loop principle (with reaction), the photovoltaic panel being fixed on the same board. The respective plane is driven horizontally by the reversible motor DC1 and in vertical plane of the reversible motor DC2.

The 4 photodiodes - used to receive sunlight - are inserted into a suitable electronic circuit, so that the resulting voltages at their active terminals are differentially picked up on 4 analog channels of the **NI USB-6001** module.

The application developed using the **LabVIEW** environment, is designed to be controlled by logic levels - set out in paragraph 4.1 - the reversible DC1 and DC2 motors track the position of the sun, its rays always falling perpendicular to the photovoltaic panel.

The entire mechanical system controlled in the closed loop is operated - every minute - by a stepper motor, which ensures a low precision positioning (the accuracy is given by the azimuth calculation method taking into account the geographical coordinates of the place where it is placed tracker).

The program running on the **PC** under **LabVIEW** is using the system clock - the initial position corresponding to the sunrise is determined, respectively the time of setting. On this principle it is realized - from minute to minute - the horizontal movement with the help of the **SM** stepper motor, from sunrise to sunset, respectively the return to the initial position (when the sun will rise the next
day). For the elevation, the solution is followed by the closed-circuit scheme. It should be noted that when returning the tracker for the next day, a vertical tilt of $45^\circ$ is ensured by a simple DC motor drive structure.

The external circuits from the photovoltaic panel are used for the storage of electricity, the corresponding conversion for the electric drive of the tracker, or the conversion into alternative electricity and sending it to the national energy system.

**Figure 1.** Block diagram of the solar tracker.

### 3. Hardware structure of the developed solar tracker

As we want to exemplify the viability of the solution developed according to the block diagram in figure 1, the proposal paper team has developed a mini solar tracker – depicted in figure 2, which respects the characteristics enumerated in the previous chapter; this experimental model can be used on the realization of a real size configuration that can be used in suitable places in a smart city (for example on the roof of some administrative buildings/ large corporations). Further, all constructive references will be based on the physical model made.

**Mechanical structure** is dedicated to the closed loop tracking of the sun’s position and the stepper motor for traveling on azimuth; it is observed that the photodiode panel, which permanently follows the position of the sun on the closed loop principle, is rigidly fixed on the same plane as the photovoltaic panels, so that they will move identically under the action of reversible d.c. micromotors (horizontal and vertical displacement respectively).

**The photodiode panel** uses four PD204-6C type photodiodes of 3 mm diameter, high sensitivity, with spectral band between 400 nm and 1100 nm (covers the visible and infrared spectrum), delimited by a right angle support made of pertinax with a thickness of 1.6 mm and a length of 27 cm (thus ensuring an angular positioning accuracy below 1°).

**The electronic circuits** provide:
- for photodiodes, the supply in reverse conduction by means of resistors of 4.22 kΩ, at +5V, the value of the resistance being chosen in accordance with the maximum sensitivity of the photodiode, and the voltage of + 5V is that obtained from the PC via NI USB-6001 module;
- control of reversible d.c. engines DC₁ and DC₂ using a L298N monolithic high voltage and current integrated circuit, which is a double H-bridge designed to accept standard TTL logic levels for control;
- stepper micromotor control by using the A3967 integrated circuit.
Figure 2. Final appearance of the developed mini solar tracker.

The NI USB-6001 Analog and Digital Signal Acquisition/Generation Module is a high-speed USB device that contains eight analog input channels (ai), which can be adapted as four differential channels. The device also comprises two analog output channels (ao), 13 digital input/output channels (DIO) organized in 3 ports, as well as a 32-bit counter [12]. Connecting the module via USB cable allows obtaining the stabilized voltage of +5V which is used to power the photodiodes.

4. Development of innovative solar tracker software application

LabVIEW development environment is used because it provides graphical programming abilities, which facilitate the visualization of the application. With the help of the program, data can be easily measured and observed, additionally - if necessary - intuitive debugging is possible [15].

Due to the visual facilities, the circuit connections can be easily realized and all the interruptions in the scheme can be visibly detected (with the naked eye). Another advantage is its ability to represent complex logic algorithms, which is the case for this project.

The development of the program was performed using the facilities and tools offered by LabVIEW 2011.

4.1. Closed-circuit motor control software

The front panel contains the modules specific to the visualization of the signals acquired from the four photodiodes, the offset signals and their values, the logical states obtained after the comparison of the 0 V offset signals, respectively the logic commands to the two reversible motors. An overview of the front panel for this component of the application is shown in figure 6.

The correspondence between the color represented for each acquired/offset signal and the photodiode from which it comes is in accordance with figure 3.
For the control of DC motors the concept of combinatorial logic design of logic circuits was used, based on the Karnaugh diagrams, according to the component elements of the unit - the outputs from 1 logic were used and not the ones from 0 logic. For example, in figure 4 are presented Karnaugh diagrams for outputs $C_1$ and $C_2$.

$$C_1 = \overline{A}C\overline{D} \cup \overline{A}BD = \overline{A}D(C \cup D) \quad (1)$$

$$C_2 = A\overline{B}C \cup \overline{B}CD = \overline{B}C(A \cup D) \quad (2)$$

where $\cup$ represents the symbol OR and $\overline{}$ represents the negation of the state.

4.2. Software calculation of initial position and displacement azimuth secular position

The initial position of the mini solar tracker is important, for the device to be used anywhere in the world. It is known that any location on the globe is defined by geographical coordinates, latitude and longitude, depending on the northern/ southern hemisphere and the position relative to the reference meridian (Greenwich). These coordinates can be easily found by using Google Maps and following the instructions specified by that application.

The initial position is set when the mini tracker is switched on, that is, the power supply and the activation of the LabVIEW application, after which it works according to the steps:
- moves - with the help of the stepper motor - the whole assembly to the initial state, until the initialization switch is reached;
- the start command is given from the button placed on the electronic module, which has the effect of moving the whole assembly clockwise by activating the motor step by step, so that the position according to the system time is reached (only hours and minutes are taken into account);
- the closed loop tracking system is activated, which will work as long as the mechanical structure and the LabVIEW application are activated;
- after each minute incremented by the system clock, the stepper motor performs a clockwise movement of 0.25°;
- after dark, the stepper motor is ordered, which brings the whole assembly to the starting position for the next day (the engine stops when the system clock reaches the next day's sunrise).

The front panel for this subsection is shown in figure 5.

![Front panel for initial position.](image)

**Figure 5.** Front panel for initial position.

### 5. Experimental results

Mainly the operation of the solar tracker was followed in accordance with the characteristics presented in chapter 2.

About the efficiency of such a system the specialized literature has concrete data that prove the necessity of the tracking system [2], [3], [6], [7].

#### 5.1. Front panel of the application

After the Mini Solar Tracker and **NI USB 6001** have both been connected to the laptop, the simulation can be started.

As can be seen in figure 6, this is the case when two photodiodes are in illumination and the other two are in shadow effect. This situation can also be described on the numerical indicators on the right side of the second waveform graph, because two of the values are negative and two of them are positive. At the same time, you can see the concordance between the round green LEDs and the rectangular LEDs (controls) according to figure 3.

**NOTE:** After all the tests were performed and the results were found according to the assumptions, data were saved on the external environment, obtaining an executable that can be ported and run on any computer, provided that the **runtime.exe** module exists (it is free to download) from the National Instruments website.

#### 5.2. Results obtained for one day

The tests performed so far were conducted in the laboratory, using a coherent source from a photometric lamp, and in natural environment. In mid-May 2020, outdoor experiments were carried out over the course of a day, measuring the voltage provided from the photovoltaic panels by comparison with two identical fixed panels. The results highlight the expected energy performance [2, 3, 6], as well as the flawless behavior of the mechanical structure.

#### 5.3. Comparison with other dedicated achievements

We make the following remarks:
- a solar tracker solution that combines closed-loop tracking with open-loop tracking (with one-minute positioning resolution) has not been found in the specialized literature (to the authors’ knowledge);
- the solution developed in [6] uses for the detection of the position in the closed-circuit photoresist, and the correction in the open circuit is made every half hour. We mention that the authors also tested this solution in the development phase of the mini solar tracker, but they gave up on it due to the low precision of the model;
- other solar tracker solutions analyzed [2], [3], [7] are developed only for a single way of tracking the position of the sun, which makes us affirm that our solution is innovative.

6. Conclusions
The paper presented an innovative mini solar tracker that uses both a closed-loop and open-loop tracking system based on the secular position of the sun. The proposed design uses the **LabVIEW** development environment and the external communication module **NI USB-6001**, that made possible to realize complex solutions for the simultaneous tracking of the sun in both systems.

We must emphasize the innovative aspect of mechanical construction, which allows the use of DC and low power stepper motors.

The proposed methodology is an innovation considering that all the characteristics (performances) proposed in chapter 2 of the paper have been achieved. The positioning accuracy of the tracker should be noted by the combined use of the two tracking systems, as well as the connection with the PC system clock, which guarantees a permanent open loop correction.

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