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Mobile Testing Device to Determine the Accuracy of Photovoltaic Solar Tracking Systems

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Abstract: Solar photovoltaic (PV) systems play an increasingly significant role in global energy production. Compared to fixed-mount installations, PV power plants equipped with solar tracking technology can utilize solar energy more efficiently by continuously orienting the modules toward the sun. This approach can boost energy output by 20–30% for conventional monofacial PV modules, and by up to 50% for bifacial technologies. However, solar tracking systems vary widely in terms of design, accuracy, and cost, making it challenging for investors to identify the most suitable technology for a given project. Selecting the optimal tracking strategy requires careful consideration of technical goals, financial constraints, and site-specific conditions. In practice, investors often rely on manufacturer documentation and anecdotal operational experience prior to installation. Unfortunately, performance limitations or tracking inaccuracies frequently become apparent only after commissioning—leading to costly post-installation corrections. To address this issue, the present study introduces a mobile testing platform designed to evaluate the real-world performance of various solar tracking systems. The proposed device allows for flexible integration with multiple commercially available tracking controllers, enabling direct, field-based validation of their accuracy and behavior. The innovation lies in the platform's modular architecture, which facilitates broad compatibility and practical pre-investment analysis under realistic conditions.

Keywords: active tracking system; dual-axis solar tracker; efficiency; PV energy optimization; PV technology; solar energy; sun tracking

1. Introduction

This first part introduces the wider context of the research by focusing on three major themes: the increasing importance of PV technology for electricity generation, the potential of solar tracking PV systems, and the available solar tracking technologies.

The world's energy situation has changed significantly in recent decades 1,2). Fossil fuels such as coal, oil, and natural gas provided the basis of the world's electricity supply for decades 3). However, due to the risks of environmental pollution and climate change 4), as well as the energy challenges, their use has been showing a declining trend 5,6). As an alternative to using fossil fuels, the use of renewable energy sources, of which the role of solar PV technology is outstanding, is increasingly coming to the fore 7–11). The growing popularity of PV systems is due to a number of factors 12,13). Firstly, the increasingly low investment costs play a significant role in this process. PV modules and their manufacturing technology are constantly evolving, which is continuously reducing their price 9,14). This has allowed PV power plants to be competitive with other technologies and make them attractive to both industrial and residential investors 8,15). Secondly, PV systems are also a popular solution because of their reliability. PV modules have a long service life and reliably produce green and sustainable electricity for decades 16,17). Thirdly, the environmental friendliness of this technology also increases its popularity 18,19). Electricity generation produces no greenhouse gases and has a negligible environmental impact 20). Due to the growing social awareness of sustainable energy sources and the fight against climate change, PV systems have become attractive to those looking for an environmentally friendly and sustainable alternative 15,21).

When designing PV systems, it is becoming increasingly important to use a given area with the greatest efficiency, and for this purpose, solar tracking plays an important role 22–25). The purpose of solar tracking systems is to track the position of the sun in order to achieve greater energy

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efficiency [26–28]. Compared to fixed-installed PV systems, power plants using traditional, monofacial PV technologies with solar tracking can produce up to 30-40% more energy [29]. This value can be further increased by bifacial PV technologies, which is greatly influenced by the reflectivity of the area [30,31].

Solar tracking technologies can be classified into two major mechanical groups, namely single-axis and dual-axis tracking solutions [32]. In the case of dual-axis tracking solutions, azimuth-elevation and polar or tilt-roll solutions can be distinguished [33]. In the case of single-axis tracking solutions, there are three categories: horizontal-axis, vertical-axis, and tilted-axis versions [34]. Nowadays, these mechanical structures are moved by active solar tracking systems, which use motors to rotate the PV modules in the direction of the sun [35,36]. Active solar tracking solutions can be divided into five main groups:

- Open-loop and closed-loop systems and their hybrid variants.
- Intelligent driver systems, which include neural networks, fuzzy logic, and their combined versions.
- Microprocessor drive systems, including programmable interface controllers (PIC) microcontrollers, digital signal microcontrollers, and Rockwell automation.
- Sensor driver systems, which include electro-optical sensors, light-dependent resistors (LDRs) and light intensity sensors.
- Combined versions of sensor driver systems and microprocessor driver systems [36].

It can be seen that there are many solutions for controlling solar tracking PV systems. However, nowadays it is the sensor versions and the global positioning system (GPS) versions that are easily available to investors. There is a significant price difference between the two technologies, which is why the use of sensor solutions is dominant [37–39]. Within these two versions, there are different sun-tracking strategies.

GPS versions can be applied to both single- and dual-axis PV systems. This type of equipment performs continuous sun tracking on the PV system, which needs to be set specifically for geographical location. After that, the unit will operate automatically. The advantage of the solution is that no internet connection is required. However, the disadvantage of the system is that it does not have wind protection in itself and there is no real feedback on the accuracy of solar tracking. Moreover, continuous "sun tracking" is implemented regardless of the weather, even in overcast weather, and thirdly, in some parts of Europe (e.g. Poland, Romania, Bulgaria, Estonia, Latvia, Lithuania) GPS signals are often jammed [40–42], resulting in false positioning. However, it is worth mentioning that there is a patented innovation (WO2020185271A1) that follows the movement of the sun by a combination of GPS data and sensors in order to detect weather conditions.

Currently, sensor technologies are very popular on the market due to their affordable price. These solutions deploy different sun tracking strategies, which can make it difficult for investors to choose the ideal technology for a given investment. The cheapest version is characterized by the constant search for the brightest point in the sky. Such solar-trackers do not have other functions such as protection against cloudiness, stronger winds or unnecessary wobble of sun-tracking motors, or positioning after sunset [43]. Among the more advanced sensor technologies are solutions that partially or completely solve the above-mentioned challenges, such as the DS-50D6W, DS-100D10, STA2000-HW devices, and the patented solution p2100209. In the case of all these systems, it can be stated that they do not have adequate feedback on the accuracy of solar tracking. Therefore, if the solar tracking structure gets repositioned for any reason, the sun tracking will become inaccurate [43].

Based on the above, it is clear that there is a wide range of solar tracking systems available for PV technology, with different solutions, accuracy and prices. This can make it difficult for investors to select the ideal technology for a particular investment. In addition, to choose the right sun tracking strategy, they need to comprehensively consider the purpose, budget and location of the investment. It is part of the problem that before choosing a solar tracking technology or a specific type, it is primarily the manufacturer's documentation and reports where information about the accuracy of sun tracking and the expected operating conditions can be obtained. However, after the PV power plant is commissioned, the selected technology may not operate as expected, which may result in subsequent costs. Therefore, before making an investment, it is worth getting to know the operating parameters of the selected solar tracking technology in detail under real conditions.

The focus of the present research is the development of a mobile testing device for PV technologies which enables the testing of real-life operation of various solar tracking technologies. The device is currently in the proof of concept (PoC) phase, thanks to which the functions can be demonstrated. The novelty of the research lies in the fact that a number of active solar tracking technologies can be connected to the mobile test equipment with appropriate adaptation (Sections 2.1 and 3.2), allowing for extensive testing and evaluation.

2. Overview of development considerations

2.1. Background

In 2017, a measuring station capable of single- and dual-axis solar tracking was built in Keszthely, Hungary (46.76750° N, 17.26609° E). The original purpose of the

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system was to facilitate the joint comparison of four traditional PV technologies (monocrystalline, m-Si; polycrystalline, p-Si; amorphous silicon, a-Si and concentrated solar cells, CPV) under the same environmental conditions. In the meantime, the system has been expanded with a number of scientific instruments, the types and locations of which are shown in Figure 1. For various research projects, several measurement data collection tools have been deployed to collect data, namely the PicoLog 1012 and 1216, the CR1000 Measurement and Control Datalogger and the HOBO 4-Channel Analog Data Logger devices. The support structure is moved by two motors, which can be controlled manually or automatically. In automatic mode, tracking can be continuous or control unit-specific. In manual mode, the automatic solar tracking can be switched off with a switch. The design of the system made it possible to perform accurate and high-precision measurements using CPV technology [44,45]. The peculiarity of the CPV technology is that in the case of a 0.5° solar tracking inaccuracy, there is already a 10% decrease in power compared to that of the ideal position, while in the case of a 1.5° solar tracking inaccuracy, energy production ceases [46].

In connection with the measurement accuracy of the measuring station, it is necessary to mention the result of one of the measurement series, which was compared with literature data. A study published in 2018 concluded that PV module power only decreased by 1.5% in the case of a solar tracking inaccuracy of 10°, regardless of the cardinal direction. Contrary to that, measurements by the measuring station showed that the power change of the traditional, monofacial m-Si, p-Si and a-Si PV modules is influenced by both the magnitude of the deviation from the so-called focal point (FP) and its direction, i.e. the cardinal direction [45].

The FP setting was important because of the CPV technology, which requires the sun's rays to hit the PV cells perpendicularly, without error. This meant that the issue of the expected extent of module-specific performance degradation due to inaccurate sun tracking was clarified. These discoveries later laid the foundations for patents (e.g. P2100437, P2100209, P2100339). In addition, as a result of continuous improvements to the station, the system has now become suitable for integrating and testing a wide range of solar control units related to PV technology available on the market. The condition of connectibility is that the solar tracking device to be examined needs to be able to provide on/off contact with open collectors or relays to the motor controller of the measuring station, according to the motor directions.

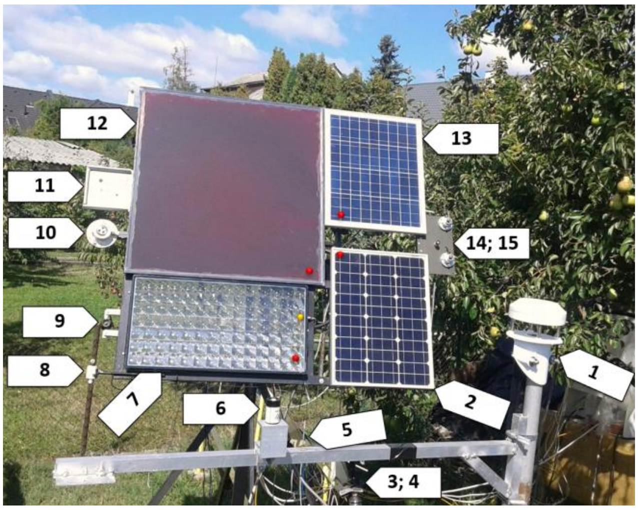

Fig. 1: Appearance and measuring instruments of the permanently installed measuring station capable of single- and dual-axis solar tracking according to [44,45] (1: DS-2 Sonic anemometer; 2: m-Si PV module; 3: HYTE-ANA-1735 humidity content of air meter; 4: JL-FS2 aluminum device with 3 spoons; 5: manual/automatic tracking control unit; 6: EMS 11 Silicon photovoltaic detector; 7: CPV module; 8: SN-500 four-component net radiometer; 9: photosensors; 10: Eppley Black and White pyranometer; 11: bracket mounted to detect angle change; 12: a-Si PV module; 13: p-Si PV module; 14: Hukseflux LP02 pyranometers; 15: EMS 11 Silicon photovoltaic detector; Orange dot: Pt 100 sensor in the CPV module; Blue dot: Pt 100 sensors at the bottom of PV modules)

2.2. The relevance of the innovation presented herein

During research related to solar tracking, it would have been necessary to measure the solar tracking accuracy of PV power plants on site several times due to the detection of inadequate operational characteristics. A permanently installed measuring station, however, is not suitable for on-site measurements. Therefore, in order to better understand the operational characteristics of solar tracking systems, solar tracking devices had to be dismantled from PV power plants. After that, it was possible to examine and measure the equipment in detail at the Keszthely measuring station. It was for this reason that the construction of a mobile testing device that is capable of receiving a number of active solar tracking technologies, also at the PV power plant site, became necessary.

2.3. Validation measurement setup

The validation measurements were conducted at a solar research station in Keszthely, Hungary (46.76750° N, 17.26609° E), which corresponds to the location depicted in Figure 1. The measurements were carried out on July 5, 2025, between 10:30 and 10:40 AM, under clear sky conditions. The primary objective of the measurements was to verify that the mobile rotating mechanism is capable of receiving, interpreting, and reacting to signals from external solar tracking control units.

During the test, specific measurement instruments were installed on the platform of the mobile rotating mechanism, as illustrated in Section 3.3. A Hukseflux LP02 pyranometer was used to measure the global solar irradiance. This sensor was mounted directly on the platform, and its analog output was logged using a HOBO 4-channel analog data logger, allowing the irradiance values to be recorded continuously during the test periods. Additionally, a sensor control unit was placed on the platform. This sensor unit is a proof-of-concept development based on the Hungarian patent P2100209, held by the University of Pannonia, and it was integrated into the mobile platform for the purpose of operational validation. The voltage signals generated by this unit were transmitted via USB connection to a notebook computer. The data were visualized in real time using the Arduino IDE software. This allowed for the immediate verification of the connection and made the signal changes clearly observable during the movement of the platform.

Three measurement cycles were performed, each lasting approximately 20 seconds. Each cycle generated approximately 400 individual data points, which were collected and analyzed. The signals recorded from the sensor control unit were in the millivolt (mV) range. The characteristic change in signal levels — corresponding to the realignment of the platform — was clearly visible and confirmed the correct system response.

The initial position of the platform was intentionally offset from the ideal solar position to ensure that the signal response of the sensor control unit could be clearly observed. The starting orientation of the platform was southwest-facing (azimuth 257°), with a tilt angle of 82°, representing a deliberately misaligned orientation relative to the sun. Upon activation, the sensor control unit automatically adjusted the platform to align with the sun's position. As a result of this autonomous tracking, the platform was oriented at an azimuth of 82° (northeast-facing) and a tilt of 36.5°.

The development characteristics of the mobile rotating mechanism — including its components, 3D design, and physical realization — are described in Sections 3.1 and 3.2. The validation results are presented in Section 3.3.

3. The results of the developments

3.1. The 3D model of the mobile rotating mechanism

During the development of the PoC version of the mobile testing device, it was indispensable to use 3D modeling, which made it possible to design and visualize the equipment. This also helped to understand the expected operation and appearance of the device before creating the physical PoC version. The Fusion 360 software was used for the modeling, because it is a powerful and versatile 3D modeling platform that offers a range of features, including specific 3D editing, simulation, 3D printing design, and virtual reality applications. The software enables the efficient creation of 3D models, a function that was important when designing the mobile testing device.

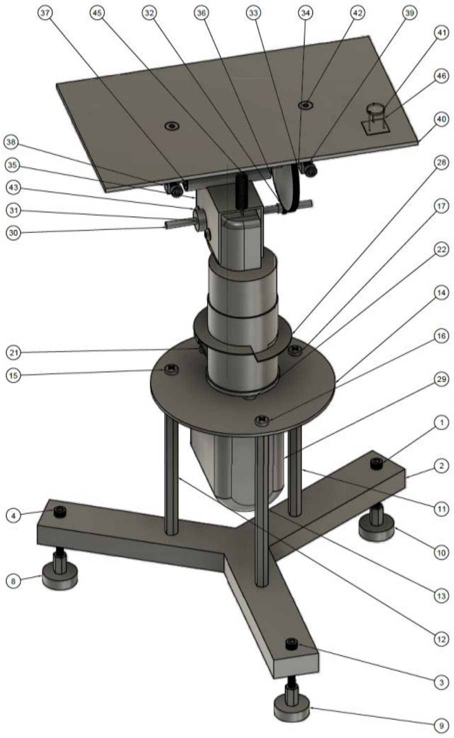

Fig. 2: The 3D model of the mobile rotating mechanism, without electronics and casing, setting "A"

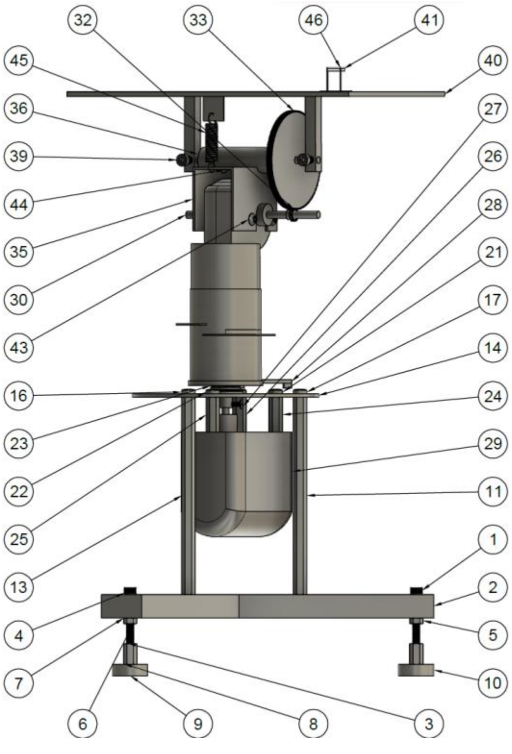

Fig. 3: The 3D model of the mobile rotating mechanism, without electronics and casing, setting "A"

Fusion 360 allowed the 3D model to be virtually assembled and tested, which helped identify and eliminate potential issues before they were physically created. This feature made it possible to understand how each element of the equipment would work together in reality.

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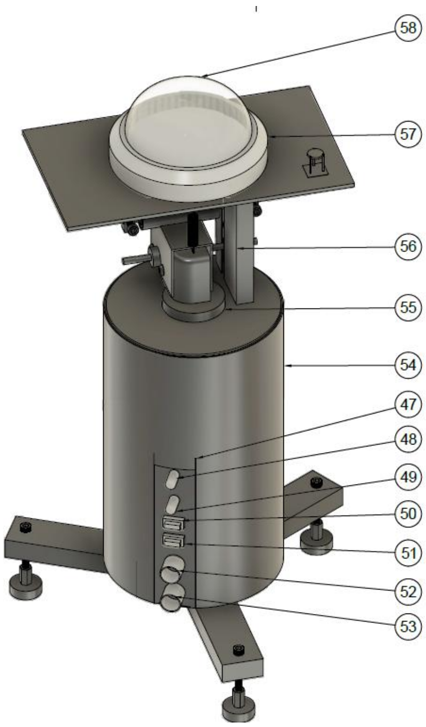

Fig. 4: The 3D model of the mobile rotating mechanism, with electronics and casing

The names of the parts of the device, which are illustrated in Figure 2-4, are listed in Table A in the Appendix. The completed 3D designs are displayed in Figures 2-4.

3.2. The actual physical appearance of the mobile rotating mechanism

During the mechanical and control design and construction of the device, the following aspects were taken into account:

- Ease of use and portability.
- Easy maintenance and repairability.
- Receiving and executing the control signals of active solar tracking control units that are capable of providing on/off contact with open collectors or relays to the solar tracking motor control unit in accordance with the motor directions. It should be noted that device-specific adaptation units are required for solar tracking control units with unique features, and this testing equipment is not suitable for receiving them directly. These should be developed in cooperation with the manufacturer or based on the service manual of the equipment.
- Creating a manual control option for individual measurement settings.
- Focal point design using a lens to visually verify the accuracy of various solar tracking technologies.
- Designing a platform for angle measurements to digitally record the accuracy of various solar tracking technologies.

The actual physical appearance of the finished device is shown in Figures 5-7. Figure 5 shows the device without electronics and casing, Figure 6 with a casing, and Figure 7 with the sensor control unit mounted on the base.

Fig. 5: The mobile rotation mechanism without electronics and casing with the base set in the south position

Fig. 6: The mobile rotation mechanism complete with electronics and casing

Fig. 7: Sensor control unit placed on the base of the designed mobile rotating mechanism for testing purposes, to determine the accuracy of the solar tracking

3.3. Validation results of the mobile rotating mechanism

To support the understanding of the measurement process, Figure 8 presents the assembled setup of the applied devices—prior to powering on—including the mobile rotating mechanism, the sensor control unit, and the pyranometer. The mobile rotating mechanism served as the central element of the system, and the aluminum platform mounted on top provided the base onto which the sensor control unit and the Hukseflux LP02 pyranometer were installed. The sensor connectors and signal lines, along with the power and data communication interfaces, enabled real-time signal acquisition and external control. A notebook was connected via USB to visualize the voltage signals during the measurement cycles, while a manual/automatic remote controller allowed for user-initiated operations. The platform ensured mechanical stability for the measurement sensors throughout the test.

Figure 9 shows the typical voltage signals recorded during the validation measurement, as controlled by the sensor control unit. The graph highlights three key phases: the initial misaligned position, the automatic solar positioning phase, and the final stabilized state after tracking.

At the beginning of the cycle (box on the left), the platform was intentionally placed in a suboptimal orientation: azimuth 257° (southwest), tilt 82°, where the irradiance measured by the pyranometer was only 164 W/m². In this phase, the voltage signals from the directional sensors showed clear asymmetry—indicating the non-aligned state of the sensor relative to the solar position. After the activation of the automatic control mode, this misalignment served as the trigger for the system to begin the solar positioning process.

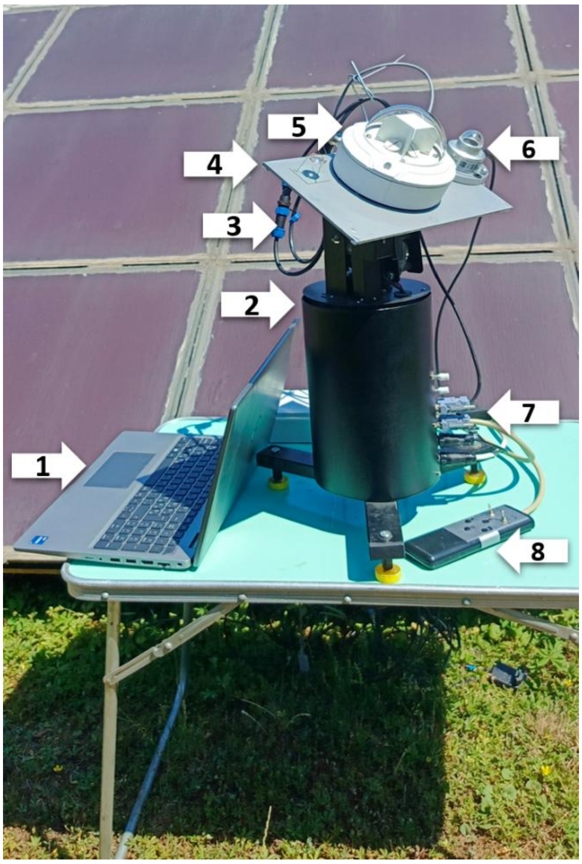

Fig. 8: The assembled validation setup of the mobile rotating mechanism, including the pyranometer, the sensor control unit, and the data acquisition system prior to the start of the measurements (1: notebook; 2: mobile rotating mechanism; 3: sensor and control connectors; 4: platform ; 5:sensor control unit; 6: Hukseflux LP02 pyranometer; 7: signal and power connectors; 8: manual/automatic remote control)

During the transition phase (box in the middle), the sensor control unit actively controlled the motors to rotate the platform. This movement is clearly visible as a dynamic change in all sensor signals. The momentary fluctuations reflect the mechanical movement and the progressive alignment with the sun's position.

Following this automatic adjustment, the platform reached a stable orientation: azimuth 82° (northeast), tilt 36.5°, with a measured irradiance of 996 W/m². In this final state (box on the right), the signals from the four sensors stabilized and became relatively constant, indicating the completion of the alignment process. This result was also visually confirmed by the optical lens mounted on the platform, as the focused sunlight appeared precisely at the

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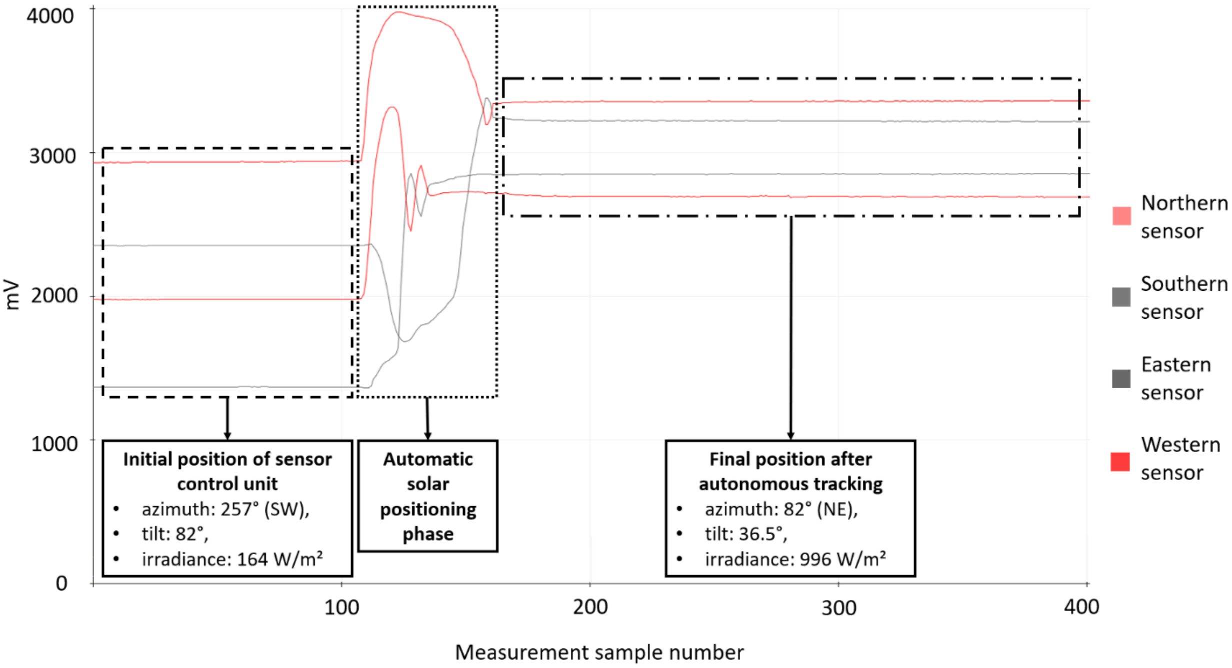

Fig. 9: The measured sensor signals during the solar tracking validation process

center of the lens holder—demonstrating accurate solar alignment.

Although the signals did not converge to identical values (due to minor differences in sensitivity and calibration among the individual sensors), each opposing sensor pair (North–South and East–West) showed less than 5% deviation relative to each other. This level of deviation—remaining below the 5% threshold defined in the control logic—is considered acceptable and indicates that proper alignment was achieved. For instance, the final signals of the East–West sensor pair differed by approximately 3.3%, and those of the North–South pair by about 2.9%. The result confirms that the sensor control unit successfully identified the solar direction and adjusted the platform accordingly. The voltage trends also supported the mechanical response of the system and validated the correct signal interpretation and actuation.

The performed validation measurements confirmed the successful integration and interaction between the external sensor control unit and the developed mobile rotating mechanism. Specifically, the results demonstrate that:

the sensor control unit could be electrically and logically connected to the system;

the system successfully detected and visualized the analog millivolt-level voltage signals via Arduino-based acquisition;

the mechanical structure responded correctly to the input signal patterns by initiating and executing an autonomous alignment procedure;

and all of this occurred under real-world outdoor conditions, not merely as a theoretical simulation.

This constitutes the most critical point of functional validation. The novelty of the presented research is not focused on the analysis or development of the sensor itself, but rather on proving that the mobile measurement platform is capable of accommodating and evaluating various solar tracking control strategies through real-time sensor feedback. The system's ability to interpret and respond to external sensor logic in a field-deployable configuration substantiates its application potential in broader solar energy research contexts.

Moreover, the final position analysis (as shown in Figure 9) confirmed that the system reached a stable alignment state, with the signal differences between paired sensors (north–south and east–west) remaining below 5%. This falls within the threshold defined by the sensor's characteristics and indicates proper tracking response. This outcome validates the essential capability of the platform to reliably receive and respond to external sensor input in real-world conditions.

To support the credibility of the measurements, the irradiance value recorded by the Hukseflux LP02 pyranometer after alignment (996 W/m² at 36.5° tilt) was compared with a theoretical estimation (using the Haurwitz clear-sky model based on the solar zenith angle of 37.03° at the time of measurement). The resulting theoretical irradiance on the tilted surface was approximately 994 W/m². The close agreement confirms that the measurements were performed under favorable conditions and supports the accuracy of the platform's mechanical alignment and sensor response.

Although the current study did not rely on theoretical irradiance models or long-duration daily comparisons, the applied measurement approach provided direct, real-time

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insight into the behavior and effectiveness of the mobile solar tracking validation platform. The observed millivolt-level responses and corresponding irradiance changes under clear sky conditions were sufficient to confirm correct mechanical alignment and signal interpretation.

Moreover, the validated platform presented in this study offers a practical means of assessing the positioning accuracy of various external sensor units. When future measurements identify deviations in tracking performance from alternative control systems, the degree of misalignment can be quantitatively interpreted using established empirical findings. For instance, studies such as Zsiborács et al. (2019) 45) have demonstrated how angular deviation affects the energy yield of monocrystalline, polycrystalline, and thin-film PV technologies. In such cases, the validated mobile platform can serve as a practical tool for estimating performance losses, without relying on complex modeling. By measuring the alignment error of any connected tracking unit, and comparing it with known photovoltaic sensitivity curves from prior studies, the expected impact on energy yield can be assessed.

4. Conclusions

Solar energy continues to play a pivotal role in the transition toward a sustainable global energy supply. The dynamic growth of PV technology—driven by environmental concerns and policy support—is expected to persist throughout the coming decades. In densely populated areas, where the available surface for PV deployment is limited, maximizing energy output per unit area becomes increasingly critical. Beyond optimal panel orientation and tilt, solar tracking systems offer a viable method for increasing energy yield. In European climatic conditions, depending on the applied photovoltaic technology, dual-axis solar tracking systems can increase energy output by approximately 30–50% compared to optimally tilted, fixed south-facing systems. However, these gains strongly depend on the precision and reliability of the applied tracking mechanism. Inaccurate or poorly controlled systems may lead to suboptimal orientation, diminishing both daily and annual energy yields—especially when combined with PV module technologies sensitive to angular misalignment.

This study introduced and validated a mobile testing platform designed to evaluate the tracking accuracy of solar positioning systems under real-world conditions. The system is capable of interfacing with various external solar tracking control units, enabling flexible, sensor-adaptive validation. Field measurements demonstrated that the platform can accurately capture the alignment behavior of connected tracking systems. Sensor signal responses were recorded and interpreted both electrically and visually, while the mechanical platform autonomously executed the required adjustments. The results confirmed that the system fulfills its intended function: it reliably receives, interprets, and responds to sensor inputs, providing tangible insight into the operational quality of solar tracking systems.

The modular design of the platform makes it suitable for testing a wide range of solar tracking systems. If later measurements show alignment errors in other systems, these can be compared with known PV sensitivity data to estimate how much energy loss they might cause. This makes the platform useful not only for validation, but also as a practical tool for helping investors and designers choose the right tracking strategies and PV technologies to optimize performance in real-world conditions.

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Contributions

H. Zsiborács: Conceived, designed, and performed the experiments, conceptualization, data curation, methodology, supervision, validation, writing—original draft, writing—review & editing. N. Hegedűsné Baranyai: conceptualization, data curation, methodology, supervision, validation, writing—original draft, writing—review & editing. A. Vincze: methodology, supervision, validation, writing—original draft, writing—review & editing.

Declaration of competing interests

The authors declare no conflict of interest.

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Appendix

Table A: The list of the components of the mobile rotating mechanism

No.	Description	No.	Description
1	Base bolt	30	Axis
2	Y base	31	Top motor
3	Base bolt	32	Cogwheel, small
4	Base bolt	33	Cogwheel, big
5	Nut	34	Top axis
6	Nut	35	Top axis, base
7	Nut	36	Top axis, tube
8	Levelling base	37	Bearing
9	Levelling base	38	Platform support
10	Levelling base	39	Platform support bolt
11	Spacer	40	Platform
12	Spacer	41	Lens
13	Spacer	42	Bolt
14	Platform	43	Bolt
15	Bolt	44	Bolt
16	Bolt	45	Spring
17	Bolt	46	Lens holder
18	Bolt	47	Connector platform
19	Bolt	48	E-W motor rotation controller
20	Bolt	49	N-S motor rotation controller
21	Bolt	50	D-SUB connector (connection point for solar tracking control units)
22	Bolt	51	D-SUB connector (remote control connection point)
23	Axial bearing	52	4-pin connector (position sensor transmitter connection)
24	Long nut	53	Three-pin power supply connector (energy supply)
25	Long nut	54	Casing
26	Long nut	55	Casing
27	Bolt	56	Casing
28	Top bearing, cup	57	Solar tracking sensor unit
29	Bottom motor	58	Solar tracking sensor unit protective casing

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