Trajectory Optimisation for Photovoltaic Panels with 2 Degrees of Freedom

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Abstract: The paper proposes a new methodology for the output optimization of solar panels, by increasing the amount of available solar irradiation. The connection and relationship between the orbital positions of the Earth around the sun offer the possibility to force a mathematical model for the available solar irradiation at different times and angles. By using this model, the optimal path for the solar panel to take year-round can be calculated in an offline medium. This approach differs from the already existing solutions, by shifting the computational weight into an offline environment where the optimization work is performed. This is combined with a second-order optimization meant to limit the number of activation instances of the positioning system, thus obtaining optimal irradiation with minimal waste. Using the trajectory thus created the use of low-power and low-cost controllers will be enabled and the commercial viability of systems with 2 degrees of freedom will be increased. The performances of the proposed method are validated in simulation, using the MATLAB/SIMULINK environments.

Keywords: Renewable energy, Photovoltaic, PV, Modelling, Trajectory optimization.

1. Introduction

With the expanding need for power generation that the present society faces, it is imperative for the new power sources to be sustainable and carbon neutral. To this end, the most cost-effective and environmentally friendly available solution is the optimization of the existing energy infrastructure with minimal investment and modifications. Renewable energy sources have been considered a viable solution for developing green energy production. Photovoltaic panels are an important source of renewable energy, and significant research work has been carried out in articles such as (Boussaada et al., 2023; Cazzaniga & Rosa-Clot, 2021; Dobrea et al., 2023).

Since the Sun is the most reliable and abundant source of energy available, it becomes clear that optimization efforts in photovoltaics would be extremely fruitful.

This paper presents a solution for an autonomous tracking controller that follows the Sun's visible position on the celestial sphere, with no feedback or active computation.

The goal of this paper is to reduce the needed controller's memory and processing power to as little as possible, while maintaining a simple and efficient positioning solution.

To optimize the photovoltaic (PV) system, a positioning system with 2 degrees of freedom is used. They will be the tilt between the panel and the soil and the azimuth to the panel's central axis.

The current paradigm in solar tracking is a closed-loop system that provides feedback from various sensors. Plachta (2018) used a GPS module, a real-time clock (RTC) module, a magnetometer, temperature, humidity, light sensors, and a gyroscope to provide feedback to a tracking algorithm.

Patra et al. (2023) achieved great results with maximum power point tracking (MPPT) based optimization of fixed-position solar panels and their work could greatly benefit from the increased irradiation provided by a positioning system, while Torous et al. (2016) illustrated a robust RST controlled MPPT algorithm that is sensitive to irradiation conditions and could benefit from the scope of this paper.

Other major advances are being made in the grid integration of solar panels through complex monitoring systems. Bhau et al. (2023) made use of IoT technology, to balance the relationship between consumer and producer. Abdallah et al. (2023) took a different approach and attempted to predict consumption by means of an artificial neural network.

Zhengxi et al. (2015) used a more complex mathematical model to limit the number of the

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needed sensors to a single photovoltaic sensor, while Rougab et al. (2021) stated that the major drawback found is the effectiveness of MPPT techniques during variations in weather conditions, such as irradiance and temperature.

Given the robustness and the lack of perturbation in the relationship between the Earth and the Sun, there is no need for an active control solution for its position. Therefore, it is preferable to create a predefined optimal path based on a complex mathematical model for the system to follow from memory.

While the proposed solution attempts to maximize the output by bringing the PV panel under the conditions it was designed to operate, as Fernández-Ahumada et al. (2020) proved to be the best approach, it does not take into account the limitations of the local grid or its ability to support the inherent fluctuations from solar systems. Choi et al. (2024) proposed that a solution can be achieved by adjusting the tilt and azimuth of fixed panels. Even without any degree of freedom, the authors achieved a 77% improvement in power stability by using complementary panels in optimal positions. Similar results could be expected from a mobile system as well.

By examining existing research in photovoltaic positioning, an optimal movement range can be determined for the system proposed in this paper. Elghamry et al. (2018) helped prove that the panel only needs to achieve angles between -100 and 100 degrees while moving around its azimuth and between 15 and 85 degrees while tilting, in order to perfectly follow the Sun.

In an offline environment, it will be paramount to have the best accuracy in estimations. For this reason, the accuracy of the model will be compared with both real data and the Solar Positioning Algorithm (SPA), in order to validate it. This is done, because SPA is a more accurate algorithmic tool than other commonly available tools (de Melo et. al., 2019).

Marciu et al. (2018) used a simple Arduino board to prototype its control algorithm with a pneumatic positioning system. This is a desirable situation, as it allows for a low-cost all-in-one solution for control. But for the present algorithm to work with such few resources, it will need to be carefully optimized.

This paper aims to achieve the goal described here in Section 1 (Introduction) by first constructing a mathematical model for the available irradiation at different angles. This will be presented in Section 2 (Mathematical Model Estimation). Next, Section 3 (Path Optimization) will present the development of an algorithm that uses the mathematical model to produce an optimal path. This path will then be used in Section 4 (Simulation Results) of the paper in order to ascertain its benefits by testing it against more widely used positioning schemes or tracking algorithms. Section 5 (Expanding the Model) will aim to improve the algorithm by accounting for the cost of positioning and introducing real-world data into its parameters and Section 6 (Conclusion) will analyze the results and shortcomings of the work done.

2. Mathematical Model Estimation

The mathematical model proposed in this paper will be based on the Equatorial coordinate system (His Majesty's Nautical Almanac Office (HMNAO) & the U.S. Nautical Almanac Office, 1974) and on the Horizontal coordinate system (Clarke & Roy, 2003). The present approach will differ from the standard approaches. To create an accurate mathematical model, the 0 values for the azimuth and tilt must be first defined. For the tilt, the 0 value will be parallel to the soil. For the azimuth, the 0 value is defined as pointing to the sun at 12 PM (while the panel is situated in the northern hemisphere). These positions are imposed to simplify the model that will be created for the PV panel-sun relationship.

The variables of the present mathematical model will be:

- latitude;
- date;
- atmospheric distortion;
- azimuth;
- angle of tilt.

A series of simplifications will also be made to the model, in order to reduce the computational effort while preserving precision. This will limit the precision of the work proposed in this paper to the year 2050; after that, the model will require adjustments.

They will be:

1. The sun is a point.

Nothing is gained by accounting for its size and shape.

2. The system exists in a fixed point around which the sun revolves.

By neglecting the size of the Earth, the position of the system can be considered a fixed point with a negligible impact on precision.

3. The system will always try to remain perpendicular to the sun.

By ignoring the issue of tracking through the ground and at nighttime, and accounting for these factors in other ways.

4. Any resulting value of 0 or lower, obtained from the model, will be considered an instance of nighttime.

Postprocessing the results to remove the impossible cases is more effective than accounting for them in the model.

5. The theoretical maximum of solar irradiation on Earth is 1366.1 W/m^2

This is the same value that a square meter of space receives while in the same orbit as the Earth. This value would theoretically be possible under the most optimal of circumstances.

6. It will be assumed that no meteorological conditions or clouds are present.

7. While they impact the output of the PV, they do not affect the sun. Therefore, they can be ignored for geometrical positioning.

8. It will work only during solar time and, as such, 12 AM will be reached when the sun is 180 degrees from the 0 value that was assigned to the azimuth.

9. Solar time will allow for a more intuitive and universal model, while removing the need to account for leap years.

Therefore, the starting formula for solar irradiation will be:

$$Irrad = MID(DD) * C * \cos(AOI(Tilt, Azim, Lat)) \quad (1)$$

In this equation MID is the Maximum Irradiation at the specified Date (DD) and has the formula:

$$MID(DD) = 1266.1 * (1 + (0.033 * \cos(\frac{360 * DD}{365}))) \quad (2)$$

C represents the atmospheric distortion, and for the time being, it will be considered 0.95.

AOI represents the angle of incidence between the system and the Sun. This angle will require multiple stages to be obtained.

Firstly, the relationship between the system and Earth will be established, followed by the relationship between Earth and Sun. The position between the ground and the PV panels must be defined too.

This will have two components: tilt and azimuth. They will be defined as shown in Figure 1.

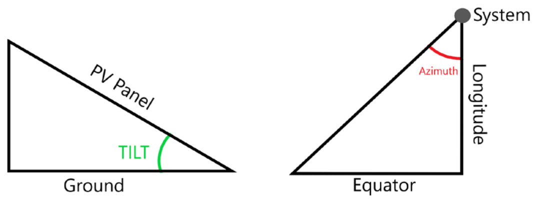

Figure 1. Graphic representation of tilt and azimuth

Next, the position of the system will be identified by means of latitude. Afterward, the orientation of the system will be defined. Finally, the relationship between the Earth and the Sun will be defined, as shown in Figure 2.

The angle of declination will be defined as:

$$decl = 23.45 * \sin(\frac{360}{365} + (dd + 284)) \quad (3)$$

HRA will be defined as a vector with a domain of -180:180 degrees in increments of 0.25.

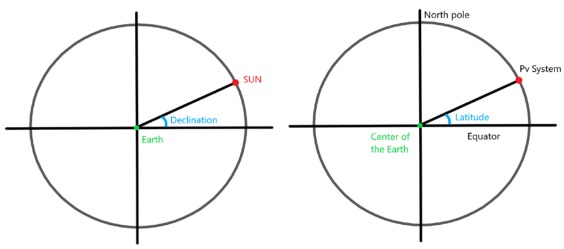

Figure 2. Graphic representation of angle of declination and latitude

Therefore, AOI *(Tilt, Azim, Lati)* will have the following formula:

$$AOI = \cos^{-1}\begin{pmatrix} -\sin(Tilt)*\sin(Azim)*\cos(decl)*\sin(HRA) \\ +\sin(Tilt)*\cos(Azim)*\sin(decl)*\cos(Lat) \\ -\sin(Tilt)*\cos(Azim)*\cos(decl)*\sin(Lat)*\cos(HRA) \\ +\cos(Tilt)*\sin(decl)*\cos(Lat)*\cos(HRA) \\ +\cos(Tilt)*\sin(decl)*\sin(Lat) \end{pmatrix} \quad (4)$$

The AOI formula was built around the arccosine of a sum of 4 basic trigonometric formulas that are used to describe the relationships of the various objects in the system.

The first and second multiplications are used to describe the position of the system relative to both Earth and the Sun, the last two are used to describe the position of the Sun relative to both Earth and the system, while the middle one accounts for the plane of the panel.

MATLAB Simulink will be used to simulate the irradiation and verify the equations. The setup shown in Figure 3 will be used:

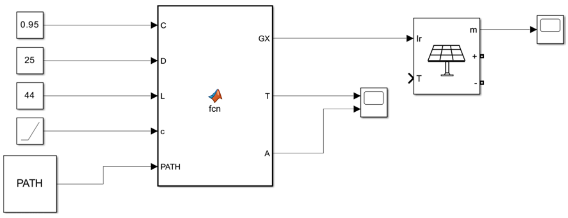

Figure 3. Modular MATLAB setup to simulate a PV panel

The PV array block will imitate a real PV Panel and the MATLAB Function will contain the obtained equations. While not perfect, the PV block models adequately the studied behavior, as it uses the concepts laid out in (Prasanth Ram et al., 2018). The date of January 25 will be simulated, for the latitude of 44 degrees north.

The clearness indices will be considered 0.95. The panel will be assumed to be placed at 0 value, for both tilt and azimuth, thus it will be parallel to the ground.

The MATLAB model will be supplied with the variables of clearness indices (a scalar value), date (supplied as a number between 1-365), latitude (a scalar value), and a clock signal with a rate of 1s. Finally, the position of the panel will be suppplied at a rate of once per second through the vector PATH.

Simulating in the MATLAB gives the following results:

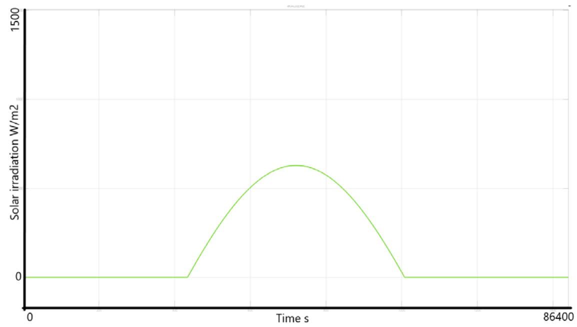

Figure 4. Simulated solar irradiation on January 25, 2024, for tilt 0 and azimuth 0

Because of the chosen date, latitude, and positioning, Figure 4 shows a short day, which is what one would expect to see during winter.

The data shown in Figure 5 are the recorded times of dawn, dusk, sunset, sunrise, and midday for the latitude of 44 degrees north, on the date of January 25, 2024. Thus, it can be concluded that the algorithm is correct, as it matches the real data. This test has been performed for multiple days, latitudes, and seasons and was passed. Different dates and their behavior will also be used in subsequent sections.

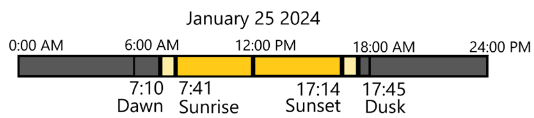

Figure 5. Recorded times of dawn, dusk, sunset, sunrise, and midday for January 25, 2024

3. Path Optimization

It is imperative to adjust the position of the PV system to optimize it. Firstly, the problem of the projection effect (see Figure 6) has to be solved.

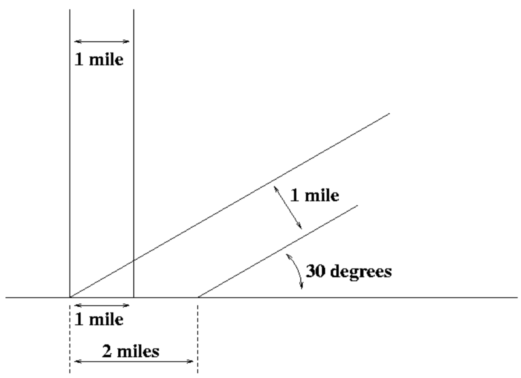

Figure 6. Exemplification of the projection effect

The projection effect can be negated for the panel if the line defined by the center of the Sun and the center of the PV system is at a right angle relative to the plane of the system. Secondly, from a purely geometrical point of view, it would be possible to maintain perfect tracking for 12 hours, with another 2.4 hours of diminishing returns from the twilight period of the solar cycle, as seen in Figure 7, for at least a good portion of the longitudes on Earth. This should be achievable for at least one day a year.

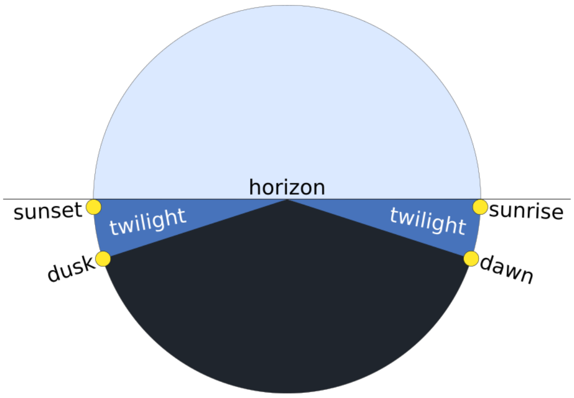

Figure 7. Geometrical representation of astronomical dawn, dusk, sunset, and sunrise (Wikipedia Commons, n. d.)

Therefore, it will be considered that the ways in which the optimization algorithm proposed in the present work should come as close as possible to this, keeping track of the physical realities.

Conventional optimization methods will struggle to provide realistic results, given the simplifications done to the model. Because the algorithm is so abstract, it can track at night and through the surface and will always provide a theoretically perfect output.

To determine a realistic optimal path, a modified version of a brute-force algorithm will be used to prune impossible trajectories.

Because the direction the Sun moves is constant, it is possible to align the direction of the algorithm's search with the solution in the case of the azimuth. However, in the case of the tilt, a problem from the Sun's arch first ascending and then descending will be encountered. Next, the logic of the algorithm will be shown using pseudocode.

Algorithm 1.

```
for SECONDS IN A DAY(s) {
for AZIMUTH RANGE OF MOTION(a) {
for TILT RANGE OF MOTION(t) {
            If (first iteration)
            {        (work normally)
                 }
            Else
            {(skip to the a to have been found as a solutions)}
            IF (before noon)
            {
            skip to the t to have been found as a solution
            Solve AOI of a, t
            Solve MID of AOI
                        If(MID ≥ prev_MID & next_MID <MID)
                        {            (Solution is a, t
                                     Add a, t to the trajectory
vector
                                     Skip next values)
                                           }
                        Else
                            {        (Move to the next set of
values)}
            ELSE
            {
            t=prev_t-t
            Solve AOI of a, t
            Solve MID of AOI
                        If(MID ≥ prev_MID & next_MID <MID)
                            {        (Solution is a, t
                                     Add a, t to the trajectory
vector
                                     Skip next values)
                             }
                        Else
                            {        (Move to the next set of
values)}
                        }
}}}
```

The paths will be pruned first by imposing a limit to the possible movements of the 2 angles of freedom to a maximum of ±90° from the 0 point for the azimuth and from +30° to plus +85° for the tilt. These are the domains that logically provide viable paths for the Northern Hemisphere.

The next step is introducing a date (DD) based equation, in order to determine the length of the night and reset the system to the start position, at the end of each day.

The time constraints of such a method are mitigated by their singular occurrence, as once calculated for a full year the path would be correct again the following year.

With these limits in place, the paths obtained for a 3-day interval are the ones in Figure 8.

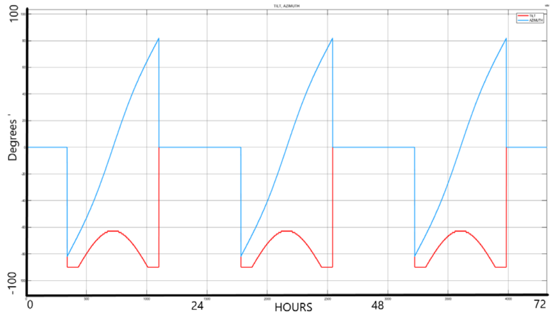

Figure 8. Tilt and azimuth variation for three days during January

The difference is minimal, as these 3 days are consecutive, and the Sun always rises from the east to west. By comparing these results with those from a simulation from July, significant differences can be observed, as in Figure 9.

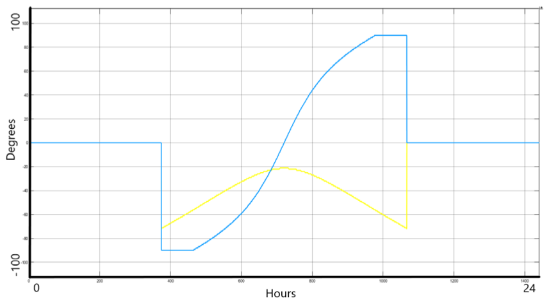

Figure 9. Tilt and azimuth variation for a day in July (tilt is represented by the blue graph and azimuth by the yellow graph)

4. Simulation Results

To determine the theoretical efficiency of a system with 2 degrees of freedom, it will be compared with the initial readings from a panel placed flat on the ground, but also with a fixed system placed at an optimal angle and with a system with 1 degree of freedom that, while at an advantageous tilt, is free to rotate on the azimuth as needed.

This simulation will be done to showcase the behavior of the proposed algorithm in comparison with the most common current approach in practice (a fixed panel at an optimal angle). Therefore, the MATLAB simulation will be expanded to simulate 4 panels in parallel, for one day, resulting in the setup in Figure 10. The date, latitude, and clearness index will remain unchanged and only the paths the panel takes will be adjusted.

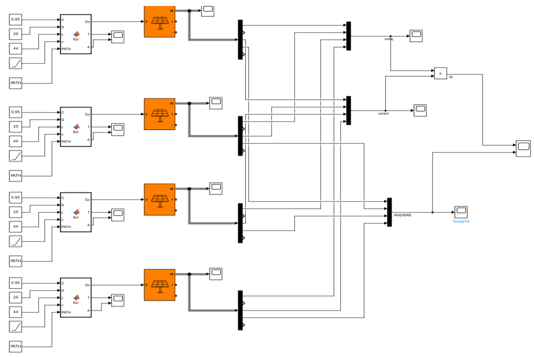

Figure 10. Expanded MATLAB model for testing

For the flat panel, the following results will be obtained:

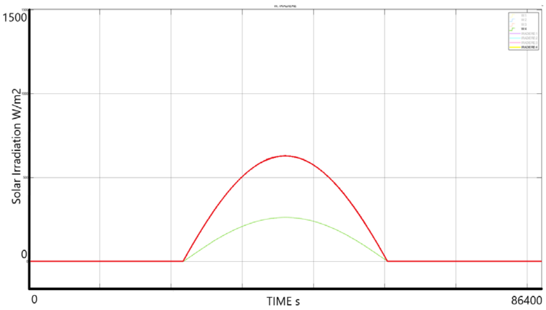

Figure 11. Irradiation (red graph) and wattage (green graph) for a panel at tilt 0 and azimuth 0 values

The results obtained in Figure 11 will serve as a baseline, not only for Figure 12 but also for Figures 13-15.

For the fixed panel at optimal tilt, the following results will be obtained:

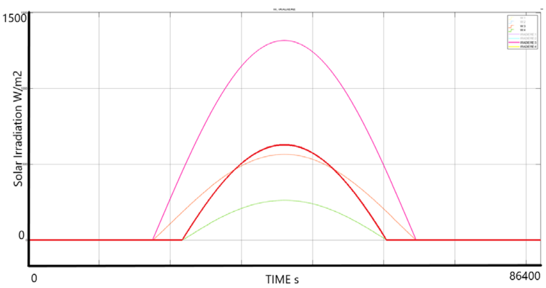

Figure 12. Irradiation and wattage of a fixed panel at optimal tilt (light purple and brown graphs) compared to baseline (red and green graphs)

For the panel with one degree of freedom, the obtained results are presented in Figure 13, and, for the one with 2 degrees of freedom, the obtained results are presented in Figure 14.

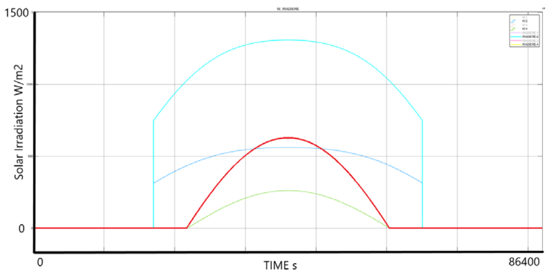

Figure 13. Irradiation and wattage of a panel with one degree of freedom (light blue and blue graphs) compared to baseline (red and green graphs)

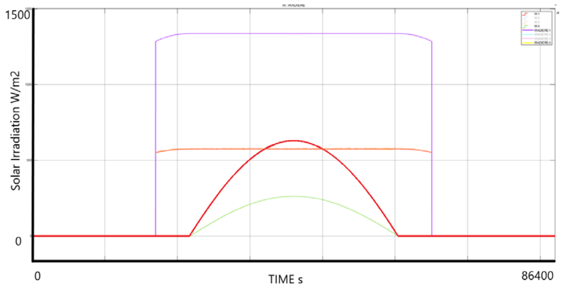

Figure 14. Irradiation and wattage of a panel with two degrees of freedom (purple and orange graphs) compared to baseline (red and green graphs)

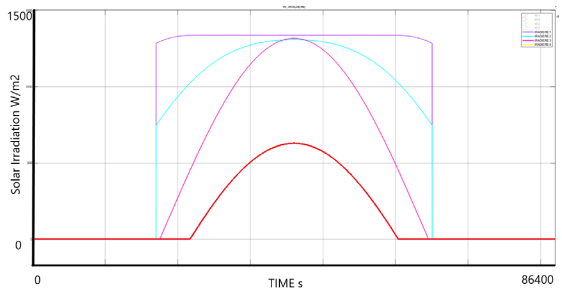

Figure 15. Comparison of all four irradiation cases

By examining them all together in Figure 15, it can be noticed that a fixed panel, at an optimal angle, is subject to 164% more sunlight than the baseline.

A panel with one degree of liberty is subject to 108% more sunlight than the fixed one and to 272% more sunlight than the baseline. The panel with 2 degrees of freedom is 61% more efficient than a system with one degree of freedom and 333% more efficient than the baseline.

These results are exceedingly large, because the examined day is during winter.

Next, the same relationships will be examined for the 180th day of the year (June 29, 2024).

Just like last time we will use the results in Figure 16 as a baseline. Due to the sun taking a sharper arc during the summer days, the available irradiation has a higher value.

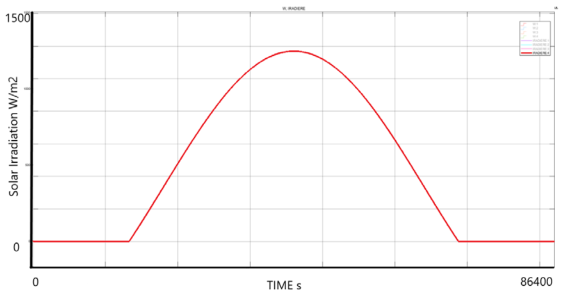

Figure 16. Baseline irradiation for June 29, 2024

It can also be noticed in Figure 17 that the optimal angle for fixed panels has a more noticeable behavior.

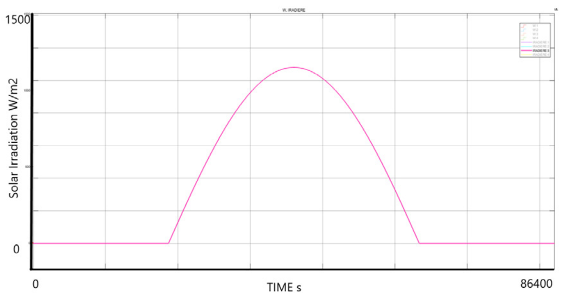

Figure 17. Optimal tilt irradiation for June 29, 2024

It is also remarkable that the baseline panel is more effective at collecting sunlight than the one at a fixed "optimal" tilt for the winter. By examining them together, it can be noticed that a fixed panel, at an optimal angle, is subject to 27% less sunlight than the baseline.

The behavior of panels with at least one degree of freedom (Figure 18) is also remarkably different at twilight. A panel with one degree of freedom is subject to 32% more sunlight than the baseline.

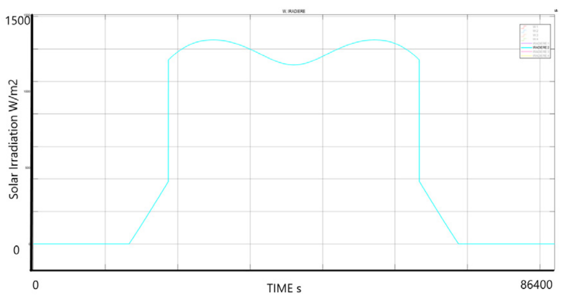

Figure 18. One degree of freedom irradiation for June 29, 2024

The panel with 2 degrees of freedom is 38% more efficient than the baseline, as seen in both Figure 19 and Figure 20.

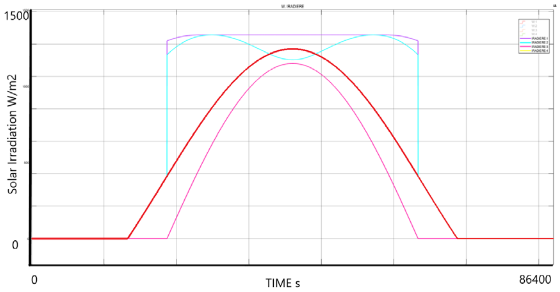

Figure 20. Comparison of all irradiation for June 29, 2024

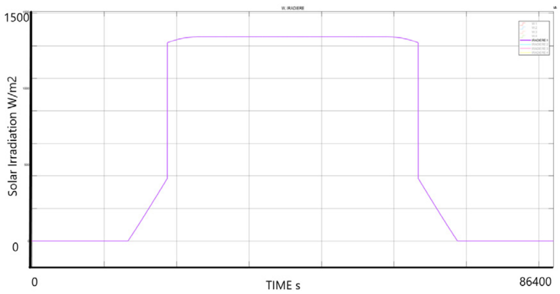

Figure 19. Two degrees of freedom irradiation for June 29, 2024

5. Expanding the Model

The next step in optimization will be to expand the model by replacing the fixed value of 1366.1 W/m^2 with a model based on real-life data gathered on the date of April 11, 2024. The irradiation available on that day can be observed in Figure 21.

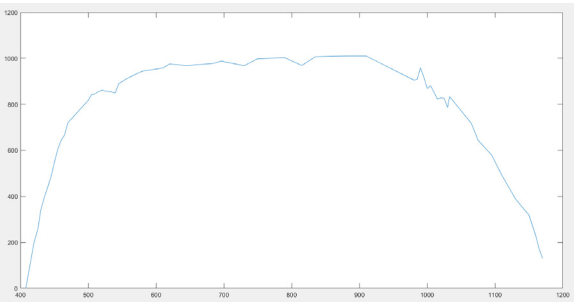

Figure 21. Data gathered on April 11, 2024

The data was gathered with a FLUKE IRR1-SOL pyranometer that was set up at an elevation of 25 meters to avoid environmental shadows on a tripod that had its position adjusted every 15 minutes for optimal incidence angle with Sun. The experiment started at dawn and ended 20 minutes before dusk, as the local architecture prevented the last 2 measurements from being taken.

While the data are not perfect because of weather phenomena, it will provide a more realistic simulation. The extracted mathematical model is a 5th-order polynomial that can be seen in Figure 22 and has the following formula:

$$\begin{aligned} Y(X) = {} & 0.000000000112499777 \cdot X_5 \\ & - 0.000000490680846 \cdot X_4 \\ & + 0.000829677973304839 \cdot X_3 \\ & - 0.682836190580059 \cdot X_2 \\ & + 274.545926267632 \cdot X_1 \\ & - 42309.972813498 \end{aligned} \tag{5}$$

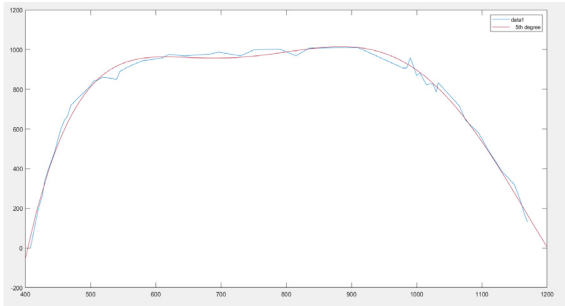

Figure 22. Validation of the irradiation model (red graph) in comparison to the real data (blue graph)

Next, the HRA vector will be expanded from an increment of 0.25 to one of 0.0041666666666666 6666666666666667 to simulate second-to-second instead of minute-to-minute. These 2 changes will result in Figure 23.

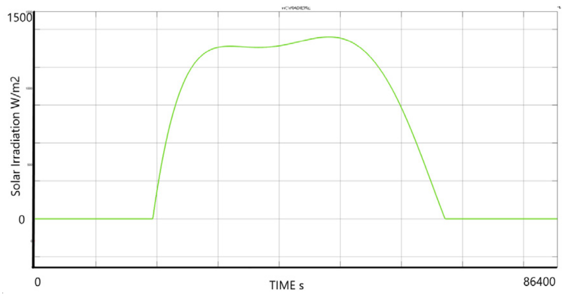

Figure 23. Result for a panel with 2 degrees of freedom for the new model

As far as known, there is a lack of accounting in the specialized literature for the power draw of the positioning system, especially for optimization work done for this parameter. Likewise, there is little work done in reducing the computational power required to run such systems.

Therefore, the model will be expanded to account for the power consumption of the 2 linear motors that allow the 2 degrees of freedom.

It will be assumed that, for each second of movement, the motors consume 60W and move the panel one degree. While this is a large simplification and does not match the current direction in research, in implementation one should consider either piecewise tracking, as in (Song et al., 2023), or the employment of model matching controllers, instead of the present flat value.

With the panel moving the optimal amount as needed, an extremely high number of micro adjustments and a significant power draw can be noticed both at the beginning and at the end of the day, to restart the cycle, as seen in Figure 24. There is a cost to starting the motors as they need to overcome the system's inertia. This will be estimated to be 10W for each instance.

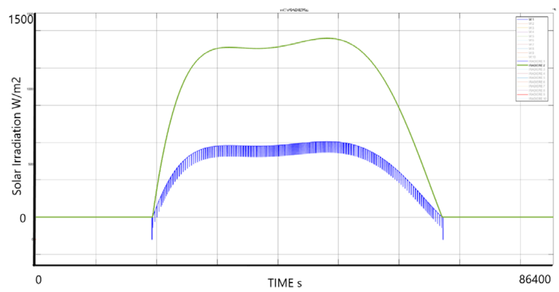

Figure 24. Irradiation (green graph) and wattage for a panel with 2 degrees of freedom that accounts for the power draw (yellow graph) of the positioning linear actuator

There exists a secondary cost of storage space, as each adjustment must be stored not only as data regarding the new angles but also as time of activation.

As such, it can be noticed that the cost of operating the system is 41.52 KW/s (0.01152kWh/day) when moving, with an additional 6.91 kW/s (0.00192kWh/day) in inertia, and with 0.008292 MB of memory needed. If expanded to a year, that will be 3.02658 MB worth of storage.

This is inefficient and will require optimization. Utilizing a divide-and-conquer algorithm, an optimal fixed period to reposition the system will be found. This new sampling period is exemplified in Figure 25 and compared with the first approach in Figure 26.

A period of 18 minutes and 48 seconds results to be optimal.

Now, the cost of operating the system is 40.32 KW/s (0.01116 kWh/day) when moving, with an additional 0.44 kW/s (0.00013 kWh/day) in inertia.

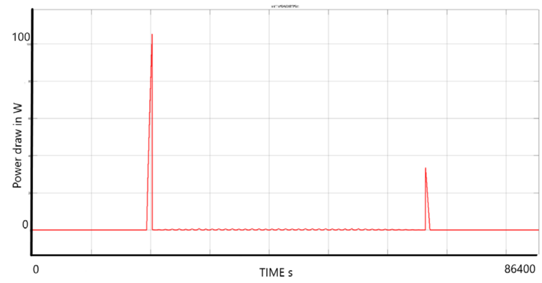

Figure 25. Linear actuator power draw for an optimally sampled system

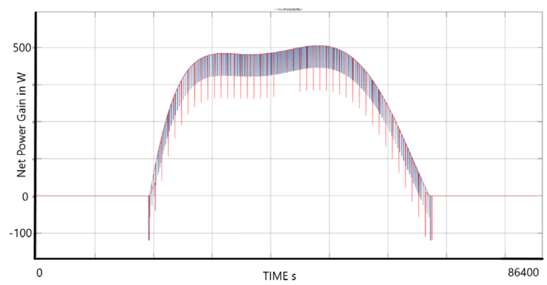

Figure 26. Comparison between the power generation of a move-as-needed (blue graph) system to an optimally sampled system (red graph)

It produces errors of less than one-thousandth of a percent in available irradiation during the optimal production hours, as seen in Figure 27 and as detailed in Figure 28.

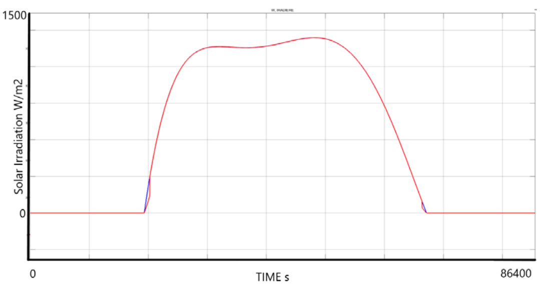

Figure 27. Comparison between the available irradiation of a move-as-needed system (blue graph) to an optimal system (red graph)

If used to make calculations for the entire year, the algorithm will provide a solution that takes up 0.1314 MB of storage.

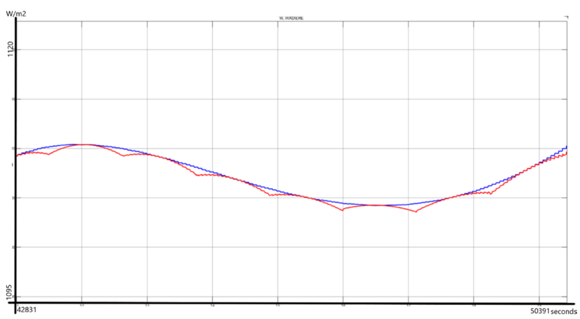

Figure 28. Detailed view of Figure 27

6. Conclusion

The paper proposes a new methodology for the output optimization of solar panels by maximizing the amount of available solar irradiation.

Based on the robust relationship between the orbit of Earth and the Sun, an offline system that does not compromise the accuracy of performances is created.

A mathematical model is estimated and expanded using real-life data. By using this approach, the optimal path for the solar panel to take year-round in an offline environment has been calculated for a static system, but also for a one-degree and a 2-degrees freedom system, in order to prove the need for the second axis.

The first iteration of the optimal path has resulted in a theoretically perfect solution. However, it was problematic, because of the extremely large number of adjustments it required.

This was fixed by further optimizing it to achieve near-peak irradiation while minimizing both the power draw of the positioning system and the memory needed to store a year's worth of trajectories.

The optimization algorithm led to a trajectory that only activates the positioning system every 18 minutes to maintain a 1% error in tracking.

The trajectory could be loaded along with the control scripts on a single microchip such as ATMEGA 2560, with no additional flash memory.

This massive reduction in necessary computational power and memory while accounting for the particularities of the positioning system is a necessary step in making positioning systems standard practice while increasing reliability.

As stated above, the model has a limited window of use, with the trajectories becoming imprecise starting with 2050. This could be mitigated by expanding the model, or by reconstructing the model with the predicted values for the solar system at that time.

The work presented here is also a good foundation for research in heat management for solar panels. The constant irradiation the panel would be exposed to, under the proposed orientation system, changes its thermal behavior from that of a curve with a pick at midday to a more constant high value, due to the constant maximized irradiation. This behavior is reminiscent of how electronic components that are placed under load behave thermally and would, therefore, necessitate a change in approach.

The optimized tracking model could further be improved by incorporating the dynamics of the motors used, a model for atmospheric events like the one proposed by Rougab et al. (2023), and their stochastic impact on the system.

If the routines created here were to be optimized for real-time use, it could be connected to a GPS to allow photovoltaic systems to be installed on moving platforms.

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