Performance study of an IoT-integrated solar tracker

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***Abstract*—The End-of-Degree Project (EDP) aims to study the improvement in photovoltaic production achieved with a two-axis solar tracker with respect to a fixed panel. To this end, a prototype will be designed and built consisting of two small solar panels, one of them fixed and the other on a two-axis tracker controlled by bus-type servos. To study the energy production, each panel will be connected to an active load, designed for this work, and controlled by a microcontroller. The data obtained will be uploaded to an Internet of Things (IoT) platform.**

***Index Terms*—Solar tracker, IoT, active load, photovoltaic panel, photovoltaic performance.**

I. Objective of the EDP and work plan

The End-of-Degree Project (EDP) is currently part of all Bachelor's Degree studies. In general, it is one more subject in which the student must demonstrate the acquisition of the degree competences through the development of an autonomous but supervised work. In scientific studies, the EDP is something new and sometimes it is given an excessively research-oriented character, being confused with dissertations after the old Undergraduate Degrees.

The End-of-Degree Project, of which we present its objectives, planning and partial development, is part of the Bachelor's Degree in Physics at the University of Extremadura. In the Degree in Physics syllabus [1], the EDP is assigned 6 ECTS credits and the Teaching Plan [2] states that *"the EDP aims for the student of the Degree in Physics to develop with autonomy the knowledge and skills acquired to carry out work related to this degree, thus demonstrating that they have achieved the competences foreseen in their syllabus"*. The competences of the Bachelor's Degree in Physics focus on the student acquiring a basic training in addressing and solving problems, with a critical spirit and creativity, related to the field of Physics and Science, although not only. Emphasis is also placed on the knowledge of experimental techniques and methodologies. Students on the Bachelor's Degree in Physics take two compulsory subjects in Analogue and Digital Electronics and can take an optional subject in Semiconductor Devices.

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Therefore, in relation to the proposed EDP, the student has knowledge of Analogue and Digital Electronics (including microcontrollers and FPGAs), as well as knowledge of Astrophysics (they have taken one subject) and several experimental methods.

A. *Objectives of the EDP*

The proposed EDP has objectives in two areas. On the one hand, the objectives related to the competences of the degree and, on the other hand, the specific objectives of the work to be carried out.

Competence-related objectives:

The proposed EDP not only addresses the design of an electronic system for a specific application, but mainly aims to enable the student to put into practice the skills to be acquired with the degree [1]. Specifically, the student is expected to work on the following areas:

- The aim is to enhance the knowledge of Analogue and Digital Electronics, in particular in microcontrollers and rapid prototyping systems.
- To introduce students to wireless communication systems and the *Internet of Things* (IoT), based on previously acquired knowledge.
- Apply the skills acquired in Astrophysics to track the position of the sun.
- To develop the general competences linked to the preparation and presentation of the dissertation.

Objectives of the work:

The main objective of the EDP is to study the performance of a two-axis solar tracker, with respect to a solar panel in a fixed position, in a rigorous and systematic way.

To this end, the following specific objectives must be addressed:

- Design and build the mechanical system of the tracker, consisting of a structure (made with 3D printing) and bus-type servomotors. A microcontroller-based system will be used to carry out the tracking, using the physical equations of solar tracking to find the best incidence of solar radiation at all times.
- To measure precisely the energy production capacity of each of the two solar panels (the one mounted on the tracker and the fixed one). To do this, we propose using an active load, controlled by a microcontroller, which seeks the maximum power point of each panel at any given moment.
- Upload periodically the maximum power of each panel to an Internet of Things (IoT) platform, facilitating data capture.

B. Work Plan

The work plan initially proposed divides the development of the EDP into four parts, the first two sequentially and the last two in parallel. These parts are as follows:

1) Development and testing of the active load. This is undoubtedly the part of the EDP with the most electronic content, both analogue and digital. The design, assembly as a prototype and final assembly will be carried out, as well as the corresponding testing. The software for its integration in IoT will also be developed.
2) Design and build of the structure of the tracker. The structure to house the tracker and the fixed solar panel will be designed and manufactured using 3D printing. Software will be developed to guide the solar tracker according to the solar position.
3) Data collection. Once the complete system has been set up, data will be collected for several days in order to obtain statistically significant results.
4) Final dissertation report. Considering that the previous phase will be relatively unattended, the writing of the final dissertation report will be started in parallel with it.

II. Current development

In this section we will describe in general the current development of the EDP, explaining the most relevant parts of it.

A. Global description

The overall aim of the system to be designed and built is to study the performance improvement of a solar panel when it is mounted on a solar tracker, compared to one that remains fixed, with the most favourable orientation. To do this, we will move the tracker according to the equations of solar movement (depending on the GPS position of our system) and at each step of the movement we will look for the maximum electrical power that we can extract from each of the two panels.

To obtain this maximum power we will use an active load controlled by a microcontroller, which we will switch between the two panels. This active load will be designed and assembled as part of the EDP, based on one of the existing designs [3], and will upload the measurements obtained to an IoT platform. In order to find the maximum power, the microcontroller will vary the current demanded by the active load (*setpoint*), performing a sweep and will measure the voltage of the panel under study, obtaining at the end of the sweep the maximum power that can be extracted from the panel in question.

The solar panels chosen for the work have a size of 13x15 cm, with 3 W power and V_{OC} of 6.1 V and an I_{SC} of 600 mA, therefore these values are the work limits of our active load.

B. ESP32 microcontroller

The microcontroller is one of the fundamental elements used in the EDP, as it will be in charge of controlling the active load and the movement of the servomotors that will carry out the tracking.

The chosen microcontroller is the ESP32 microcontroller from Espressif. It is a 32 bits microcontroller, with WiFi and enough power. The detailed specifications can be found at [4], the most important ones being the following:

- Has 520 KBytes of SRAM memory and 448 KBytes of ROM.
- Up to 16 MBytes of external Flash memory through SPI, mappable in the read-only area.
- The operating voltage is between 3.0 and 3.6 V.
- The operating frequency is up to 240 MHz.
- It includes several peripherals integrated in the chip: counters, PWM generators, I2C and SPI buses, etc.
- It has several ADCs of up to 12 bits and two 8-bit DAC outputs.
- WiFi and Bluetooth communications.

The microcontroller itself has no flash memory, so it is normally distributed as a module that includes this memory, as well as the clock and the antenna. In our case we have used the module mounted on a development board.

For the choice of this microcontroller we have taken into account its connectivity (it has WiFi) and its ADC and DAC converters. However, we have encountered some problems when working with the converters.

On the one hand, the ADC converters (SAR type) have a reference voltage of around 1.1 V (the specific value is stored internally and can be read), so they incorporate a programmable attenuator at the input. In our case, we have selected an attenuation of 6 dB, which gives us an effective working range for the ADC inputs of between 150 mV and 1.75 V [5], which requires a signal shift in the signal adaptation stage to enter into the ADC working range. In addition, to improve linearity we have lowered the resolution to 11 bits.

On the other hand, in the DAC we have a similar problem. Its range is approximately from 150 mV to 3.2 V, so we also have to shift the signal, but now downwards, in order to properly control the active load and to obtain sufficiently low currents. In this case, linearity is not so important.

The software development has been done using the Arduino development environment [6], which perfectly supports the ESP32 microcontroller. Arduino, with its C-based syntax, is a simple and convenient environment for the development of this type of rapid prototyping applications, despite its possible limitations.

C. Active load

The design and assembly of the active load is one of the fundamental parts of the work. Its development allows the student to improve his skills in Analogue and Digital Electronics.

The active load has a MOSFET controlled by a current-sampling feedback amplifier, forming a current source whose value will be determined by a control voltage. A DAC and an ADC of the microcontroller will be used to control the current absorbed by the active load. The voltage of the solar panel will also be measured (with another ADC) in order to calculate the power available at any given moment.

The design of each of the blocks has been carried out using the LTSpice [7] simulator, performing the complete simulation to verify its correct operation, including the model of the solar panel.

The complete scheme of the active load can be seen in Fig. 1, in which we have highlighted the different functional blocks, which we will describe in more detail below.

Controlled current source:

The controlled current source is one of the central parts of our design. As we can see in Fig. 1 its fundamental elements are the MOSFET transistor Q_1, the resistor R_5 and the operational amplifier U_{1A}. The scheme corresponds to that commonly used for a voltage-controlled current source, using a feedback scheme of *series current* [8]. Resistor R_5 samples the current and through the feedback loop the operational amplifier U_{1A} controls the MOSFET Q_1 to bring the current to the reference value (*setpoint*), set by the voltage present at the non-inverting input of U_{1A}, according to the expression 1.

$$I_{setpoint} = \frac{V_{setpoint}}{R_5} \tag{1}$$

If we consider that the active load must work in the range of 0 to 700 mA, we have that the control voltage at the non-inverting input of U_{1A} must be between 0 and 350 mV.

With regards to the characteristics of the components, we should point out that Q_1 must have a threshold voltage of around 2 V (we work with a 3.3 V supply), U_{1A} must be of the *rail-to-rail* type and R_5 must have a tolerance of 1 %.

Shifters and level adapters:

As previously mentioned, the problems with the lower range of the ESP32's ADCs and DAC force us to shift our signals to get into the proper operating ranges.

We have used for the displacement and the necessary attenuation the circuit that can be seen in Fig. 2. If we analyse the circuit, the relationship between the output and the input is given by the expression 2.

$$V_{out} = \frac{R_2 R_1}{R_1 R_3 + R_2 R_3 + R_2 R_1} V_{in} + \frac{R_2 R_3 V_{ref}}{R_1 R_3 + R_2 R_3 + R_2 R_1} \tag{2}$$

If the condition $R_1 \gg R_2$ and $R_1 \gg R_3$ are met, then the expression 2 can be approximated by the expression 3, in which we can see that the circuit acts approximately as a voltage divider plus a shift. The sign of this displacement depends on the sign of V_{ref}.

$$V_{out} \approx \frac{R_2}{R_3 + R_2} V_{in} + \frac{R_2 R_3 V_{ref}}{R_1 (R_3 + R_2)} \tag{3}$$

As it can be seen in the global scheme (Fig. 1), we have used three of these circuits to adapt the signals, two of them with a positive displacement (for the ADC inputs of the microcontroller) and the other with a negative displacement (for the DAC output), specifically:

- *Panel current adapter (ADC2):* $V_{in} \rightarrow 0 \ldots 3,3\ V$ y $V_{out} \rightarrow 0,3 \ldots 1,7\ V$
- *Panel voltage adapter (ADC1):* $V_{in} \rightarrow 0 \ldots 7\ V$ y $V_{out} \rightarrow 0,3 \ldots 1,8\ V$
- *Control adapter (DAC):* $V_{in} \rightarrow 0,15 \ldots 3,3\ V$ y $V_{out} \rightarrow 0 \ldots 0,35\ V$

Negative voltage source:

As mentioned above, we need negative voltage in order to adjust the voltage offset of the DAC. The exact value of this voltage is not very important and the current we need is in the order of microamperes. We have therefore decided to generate it using an oscillator, a restorer [9] and a half-wave rectifier.

For the oscillator we have used a PWM output of the microncontroller itself, obtaining a negative reference voltage of about -2.3 V.

Solar panel selector:

Since we want to compare the measurements of two solar panels (fixed and mounted on the tracker), we must either use two active loads or switch an active load between the two panels. We have chosen the second option, as this limits the number of components used and the time required for the measurement allows us to do this without any problems.

For this we have used a simple relay, activated by means of a transistor, as shown in Fig. 1.

Control software:

The active load control software is responsible for regulating the DAC output to maintain the selected *setpoint* for the current. This software includes a PI control loop and a median filter for the ADC inputs, the actuation is performed directly on the DAC.

To find the point of maximum power, the control software makes a sampling, by successive approximations, varying the *setpoint* of the current.

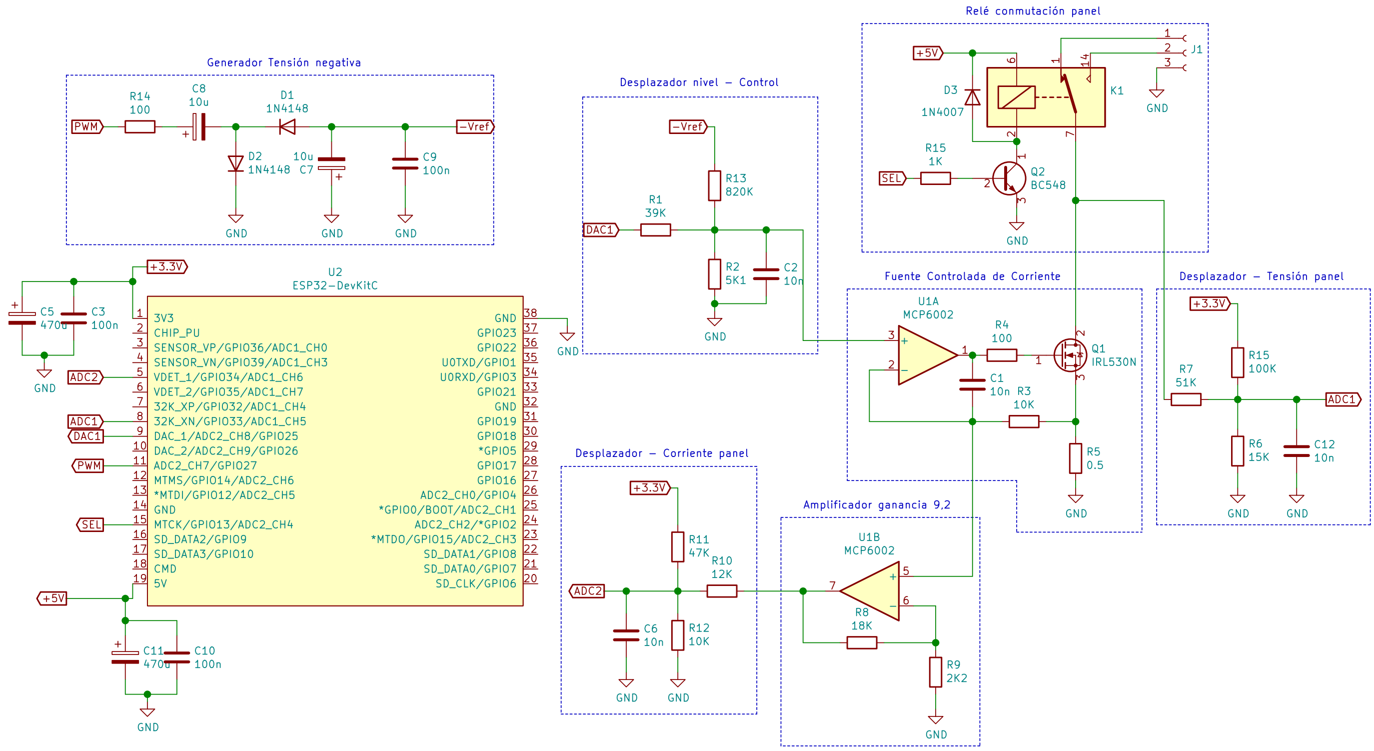

Fig. 1. Overall scheme of the active load and its control.

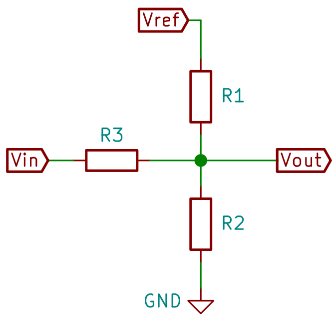

Fig. 2. Schematic diagram of the circuit used to shift and adapt the signals.

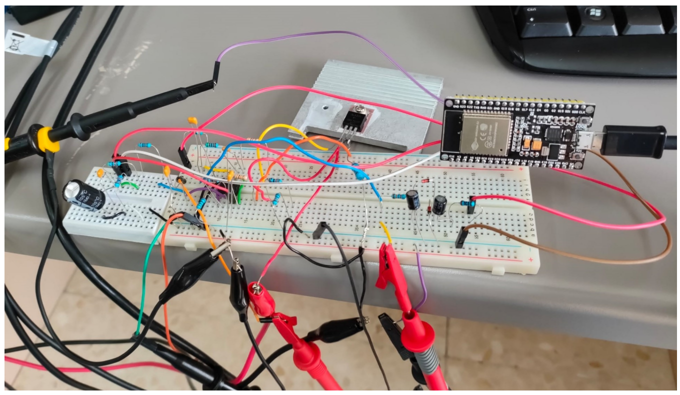

Fig. 3. Assembly of the active load on the protoboard.

Once the maximum point is found, the process is repeated for the other solar panel and the results are uploaded to the IoT platform ThingSpeak [10], which is the one we have finally chosen. The decision to use this platform is due to the simplicity with which it can be used from the Arduino environment.

In Fig. 3 we can see the initial assembly on the protoboard for the test and adjustment of the components and in Fig. 4 the final assembly using a standard dot PCB.

D. Solar tracker platform and solar panels

The current development of the EDP now focuses on the design of the parts to mount the fixed panel with the appropriate inclination and on the design of the tracker itself. For the movement of the tracker we will use bus type servomotors, controlled from the ESP32 microcontroller.

Once the design has been finalised, we will make the designed parts using 3D printing. In order to evaluate possible manufacturing differences between the two solar panels, we will make two fixed supports to compare their performance.

III. Present and Expected Results

Regarding the results, on the one hand, we have calibrated the two ADC inputs of the ESP32 with respect to the voltage and current in the active load. In both cases we have performed linear and quadratic regressions, obtaining better results with

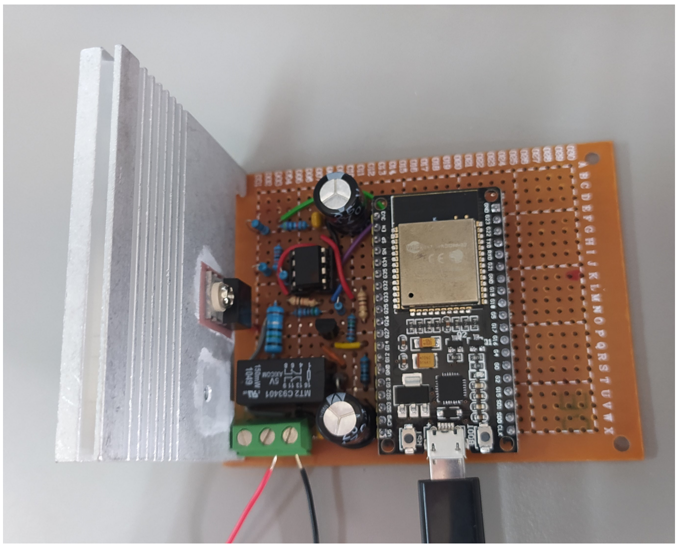

Fig. 4. Assembly of the active load on the PCB.

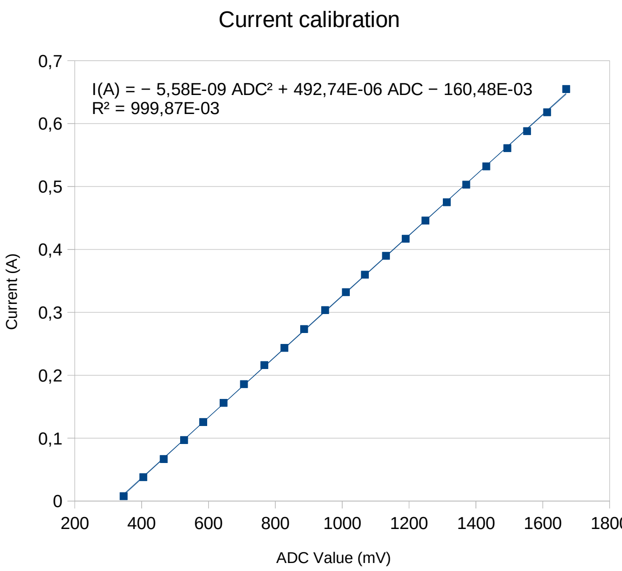

Fig. 5. ESP32 ADC calibration results used to measure the current flowing through the load.

the latter. We can see in Fig. 5 the fit for the intensity and in Fig. 6 for the input voltage. In both cases the correlation coefficient is excellent and the data show an error of less than 1% over practically the whole range, except at the extremes, especially for very low currents.

On the other hand, we have evaluated in the laboratory the performance of the active load by varying the current demanded at the *setpoint*, using a laboratory source instead of the solar panel. These initial results are very satisfactory, obtaining a coherent and fast response of the active load to changes in the current *setpoint*.

Regarding the overall results of the EDP, we expect the solar tracker to obtain a higher energy production than the

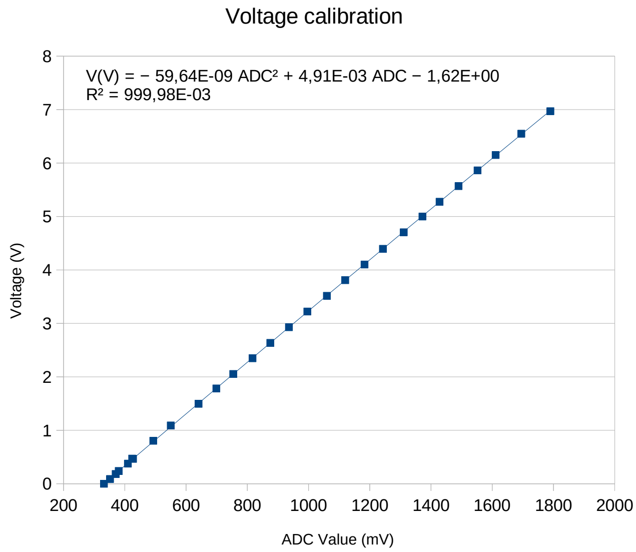

Fig. 6. Results of the ESP32 ADC calibration used to measure the input voltage to the load.

fixed panel [11]. Although some authors obtain contrary results when considering the consumption of the actuators, especially in equatorial areas [12]. In this way, we will be able to establish the margin of energy available to power the actuators and their control electronics.

ACKNOWLEDGEMENTS

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