Design and construction of a solar tracking system for parabolic-trough collector prototype

Diseño y construcción de un sistema de seguimiento solar para un prototipo de colector cilindro-parabólico

B. E. Tarazona-Romero ; J.G. Ascanio-Villabona ; A. D. Rincón-Quintero ; C. L. Sandoval-Rodríguez

DOI: https://doi.org/10.22517/23447214.24792
Scientific and technological research paper

***Abstract*— The search for technological alternatives to satisfy diverse global needs has triggered an arduous process of research and technological developments worldwide for the use of renewable resources. For their part, linear parabolic trough collectors have proven to be an alternative for the water heating process and for the production of electric energy. For its part, the research group in energy systems, automation and control (GISEAC) of the Technological Units of Santander, developed a prototype parabolic trough collector with low-cost materials available in the region (Bucaramanga, Colombia). Consequently, in order to improve the performance of the device, this paper presents the sizing, implementation and testing of a single-axis solar trajectory tracking system in a small-scale parabolic trough collector, applying a closed-loop control system. The control system is governed by a system integrated by an ESP32 module and a Raspberry PI3 microcontroller. The axis of the device is coupled to a mechanism composed of a gear and chain transmission system, directly coupled to an electric motor. The positioning of the collector angle is determined by a sensor that directly measures the amount of LUX and identifies by means of the developed algorithm, the location with the highest levels of direct incident solar radiation. In this way, the system can track the solar position throughout the course of the solar day. Finally, it should be noted that the maximum percentage of deviation of the solar tracking system is less than 1%. At the same time, the performance of the implemented solar trajectory tracking system "Automatic solar tracking system" increased by more than 40% with respect to the initial tracking system "Manual solar tracking system".**

***Index Terms*—Control Algorithm; Control Systems; Parabolic-Trough Collector; Solar Collector; Solar Concentration.**

***Resumen*—La búsqueda de alternativas tecnológicas para satisfacer diversas necesidades globales, ha desencadenado un arduo proceso de investigación y desarrollos tecnológicos a nivel mundial para el aprovechamiento de los recursos renovables. Por su parte, los colectores lineales cilindro-parabólicos, han demostrado ser una alternativa para realizar el proceso de calentamiento de agua y para la producción de energia eléctrica. Por su parte, el grupo de investigación en sistemas de energia, automatización y control (GISEAC) de las unidades Tecnológicas de Santander, desarrollo un prototipo de colector Cilindro-Parabólico con materiales de bajo coste y disponibles en la región (Bucaramanga, Colombia). En consecuente, para mejorar el rendimiento del dispositivo, en este documento se presenta el dimensionamiento, implementacion y testeado de un sistema de seguimiento de trayectoria solar en un solo eje, en un colector Cilindro-Parabólico a pequeña escala, aplicando un sistema de control de lazo cerrado. El sistema de control está gobernado por un sistema integrado por un módulo ESP32 y un microcontrolador Raspberry PI3. El eje del dispositivo esta acoplado a un mecanismo compuesto por un sistema de transmisión de engranajes y cadenas, acoplado directamente a un motor eléctrico. El posicionamiento del Angulo del colector está determinado por un sensor que mide directamente la cantidad de LUX e identifica por medio del algoritmo desarrollado, la ubicación con mayores niveles de radiación solar directa incidente. De esta manera, el sistema puede seguir la posición solar durante todo el transcurso del día solar. Finalmente, se puede resaltar que el porcentaje máximo de desviación del sistema de seguimiento solar, es inferior al 1%. A su vez, el rendimiento del sistema de seguimiento de trayectoria solar implementado "Sistema de seguimiento solar Automático", aumento en un porcentaje superior al 40 % respecto al sistema de seguimiento inicial "Sistema de seguimiento solar manual".**

This manuscript was submitted on June 12, 2021, accepted on March 09, 2023 and published on March 31, 2023.

This work was supported by the Unidades Tecnológicas de Santander, Bucaramanga headquarters, the GISEAC (Sistemas de Energia, automatization y control) and DIMAT (Diseño y Materiales) Research groups, of the Unidades Tecnológicas de Santander (UTS).

B. E. Tarazona-Romero. is a researcher of the GISEAC group, of the UTS, in street Students #9-82 Ciudadela Real de Minas, Bucaramanga (email: btarazona@correo.uts.edu.co).

A. D. Rincon-Quintero. is a researcher and leader of the DIMAT group, of the UTS, in street Students #9-82 Ciudadela Real de Minas, Bucaramanga (email: arincon@correo.uts.edu.co).

J.G. Ascanio-Villabona. is a researcher and leader of the GISEAC group, of the UTS, in street Students #9-82 Ciudadela Real de Minas, Bucaramanga (email: jascanio@correo.uts.edu.co).

C.L. Sandoval R. is a researcher and leader of the GISEAC group, of the UTS, in street Students #9-82 Ciudadela Real de Minas, Bucaramanga (email: csandoval@correo.uts.edu.co).

***Palabras claves*— Algoritmo de Control; Colector Cilindro-Parabólico; Colector Solar; Concentración Solar, Sistema de Control.**

I. INTRODUCTION

SOLAR energy is a renewable resource, abundant, non-polluting and present for long periods of time in most of the planet and has an important role in the face of the growing need for the implementation of alternative systems, capable of meeting the growing energy needs of the world, without contributing to global warming [1] [2]. Solar energy is available in the form of solar radiation that can be actively harnessed with the use of various technologies for the production of electrical energy or heat [3] [4]. Within these, photovoltaic systems take advantage of direct solar radiation (DNI) and diffuse radiation, while concentrating solar technology (CSP) operate using only the DNI [5].

Photovoltaic systems require sophisticated manufacturing facilities and use rare earth elements for the construction of solar cells that limit their production and application to technologically advanced regions [6][7]. For their part, CSP systems classified in [8] [9]: parabolic-trough collector (PTC), linear Fresnel reflectors (LFC) [10], solar dish and tower; offer solutions and opportunities to various regions worldwide, with centralized and decentralized systems, as an alternative for the production of renewable energy [11] [12]. It is important to note that CSP technology currently presents some financing, technological development, operation and maintenance problems that reduce its implementation capacity globally [13].

The technology of parabolic-trough collectors (PTC) [14][15] is currently the one with the greatest maturity in technological developments and research, as well as profitability within CSP technologies [16][17]. PTC systems receive solar rays and direct them towards a linear focal point through which a heat transfer fluid circulates, through the reflection process, through a reflector surface in the shape of a parabolic cross channel [18]. DNI that is concentrated in the focal point, transfers the heat produced by concentrated solar rays, transferring the heat to the heat transfer fluid [19]. This heat can be used for heating water or steam production, applied to electric power generation processes or thermal processes [20].

PTC technology is applied centrally [21] in electricity generation plants [22] and industrial processes with high demands for thermal energy [23], while small-scale parabolic-trough collectors (SSPTC) or decentralized are used in the residential sector in urban and rural areas [24].

By its nature, the efficiency of an SSPTC depends on the accuracy of its geometric design, optical precision, the material characteristics of the reflecting surface, and the solar tracking path. Therefore, making a suitable design, as well as selecting the correct materials and implementing a suitable sun tracking system, allow to increase the performance of the device [25]. Other factors that can influence the efficiency of the system can be: manufacturing and assembly errors, installation and operating conditions, as well as the meteorological conditions of the place of implementation [26].

PTC and SSPTC generally have a unidirectional solar path tracking mechanism system, where the axis can be oriented in an east-west direction [27], granting a degree of freedom [28] or north-south, mounted on structural supports [29]. As usual, only follow the solar azimuth angle rather than the solar elevation angle, key factors in determining the solar incidence angle [30]. On the other hand, PTC with two-axis tracking systems present better efficiencies [31], but they have higher investment, operation and maintenance costs, not applicable to SSPTC [32].

There are several configurations for possible movements of the PTC and SSPTC systems to follow the solar path. The movement of the device can be partial or continuous during the day [33]. For the first configuration, the system follows the solar path for specific time intervals during a set time slot, for the second configuration, the system ensures that the solar rays are reflected at any time of the day to the focal point [34]. Additionally, the control system can be open-loop, where a mathematical algorithm predicts the trajectory, or closed-loop, where a solar radiation sensor identifies the position of the sun during the day and sends a signal to a controller, to define the device tilt angle [35].

This study aimed to improve the efficiency of an SSPTC artisan prototype through the development of a solar tracking system on one axis, through the design of a closed loop control system. The details are organized as follows.

In section two, the materials used, the control system and the methodology developed are presented. In section three, the results and the discussion of the experimentation process carried out are presented, by means of field tests, in order to determine the percentage of tracking error of the designed and implemented system. Finally, in section four, the relevant conclusions of the work are presented.

II. MATERIALS AND METHODS

A. *SSPTC Prototype without Solar Tracking "Manual"*

The solar tracking system was implemented in a craft prototype SSPTC developed by the Research Group on energy, automation and control systems (GISEAC), of the Unidades Tecnológicas de Santander (UTS), Bucaramanga, Colombia [36]. The SSPTC device was manufactured by the GISEAC research group in order to experiment with decentralized thermal systems for the production of hot water, applying the Appropriate Technology (AT) concept, based on the use of easily accessible resources in the construction area. , low cost, easy maintenance and operation.

The SSPTC craft Prototype is based on 4 components:

- Reflector Area
- Receiver tube
- Pumping system
- Structure

Solar tracking is done manually for the entire reflecting surface. Fig. 1 shows the full-scale model of the initial SSPTC device without solar tracking and Table I present the relevant characteristics of the system components.

Additionally, the SSPTC prototype presented an average experimental efficiency value of $\eta = 34.32$ % in hydro-dynamic conditions, under the meteorological conditions of Bucaramanga, Colombia [36].

Fig 1. SSPTC craft prototype with manual tracking

TABLE I
CHARACTERISTICS OF THE ARTISANAL PROTOTYPE SSPTC

PARAMETERS	CHARACTERISTICS
Reflector Area Material	Stainless steel
Grade	Ferritic AISI 430
Dimensions	609 mm * 1700 mm
Thickness	0.8 mm (Calibre 22)
Finish	Mirror polished
Reflector Tube Matter	Copper
Emissivity	0.025
Thermal conductivity	401 W/m K
Area	0.04985 m^2
Concentration ratio	11,85
Water Pump	800 L/h

B. *Solar Tracking Mechanisms*

Fig. 2 shows the mechanical components used in the design and implementation of the solar path tracking system for the SSPTC prototype. Fig. 3 shows the mechanical configuration that allows it to be coupled to the collector shaft composed of: a hoist made up of mechanical pinions, bearings, clamping mechanisms, chain transmission and an electric motor. The time it will take for the SSPTC prototype to travel 180 ° C will be 44 seconds.

TABLE II
CHARACTERISTICS OF THE MECHANICAL COMPONENTS OF THE SOLAR TRACKING SYSTEM

PARAMETERS	CHARACTERISTICS
Pinions	Quantity 8, teeth 14, 16, 48 y 72
Torque transmission	1732 N*m.
RPM transmission	0.7 RPM
Electric Motor	1/6 HP – 110 V

Fig 2. Solar tracking mechanism

C. *Hardware control and power system*

Table III shows the components used in the articulation of the control system for solar tracking of the SSPTC prototype and Table IV the components of the power maneuvering system. It is important to highlight that the elements were selected under the Appropriate Technology model, through a matrix where technical characteristics, cost, local availability, maintenance and operation were evaluated.

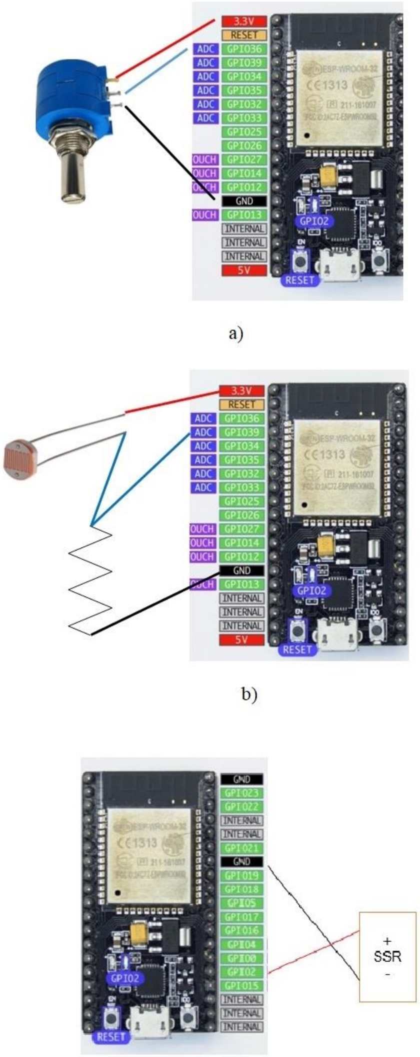
TABLE III
CHARACTERISTICS OF THE CONTROL COMPONENTS OF THE SOLAR TRACKING SYSTEM

PARAMETERS	CHARACTERISTICS
Position Sensor	ESP32
LUX Sensor	BH1750
Micro	Raspberry PI3
Resistance	1kohm
Potentiometer	N/A

TABLE IV
SOLAR TRACKING SYSTEM POWER COMPONENT CHARACTERISTICS

PARAMETERS	CHARACTERISTICS
Contactor Breaker SSR	20 Amperes

Fig. 3 shows the connections of the control and power elements to the ESP32 position sensor. Fig. 3(a) shows the potentiometer connection and Fig. 3(b) shows the connection of the LUX sensor that measures the intensity of solar radiation with the input pins of the ESP32 controller. Finally, Fig. 3(c), shows the connection of the output signal emitted by the ESP32 controller to the solid-state relay (SSR) to energize the electric motor.



a)

b)

c)

Fig 3. Connection of power control and maneuver sensorics with the ESP32 position controller

D. *Control Algorithm*

To determine the trajectory of the SSPTC prototype for the solar tracking process, a control algorithm was developed using the ESP32 position sensor and the Raspberry PI3 microprocessor. For the case of the angular position, the maximum value of LUX is determined with the solar radiation measurement sensor applying a closed control loop as shown in Fig. 4. It is important to note that two modes of operation were designed for the solar tracking:

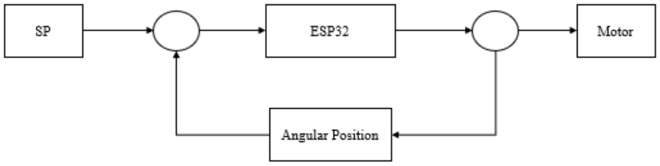


Fig 4. Closed loop control system for angular position

In the case of manual operation, the personnel in charge of the SSPTC decide whether the device turns left or right, while the automatic system performs a monitoring sequence autonomously. Fig. 5 shows the flow chart of the code developed for the manual solar tracking system. For its part, the development of the automatic tracking control algorithm system, made up of different codes developed to fulfill specific tasks, which are finally interconnected in order to maintain a solar tracking trajectory.

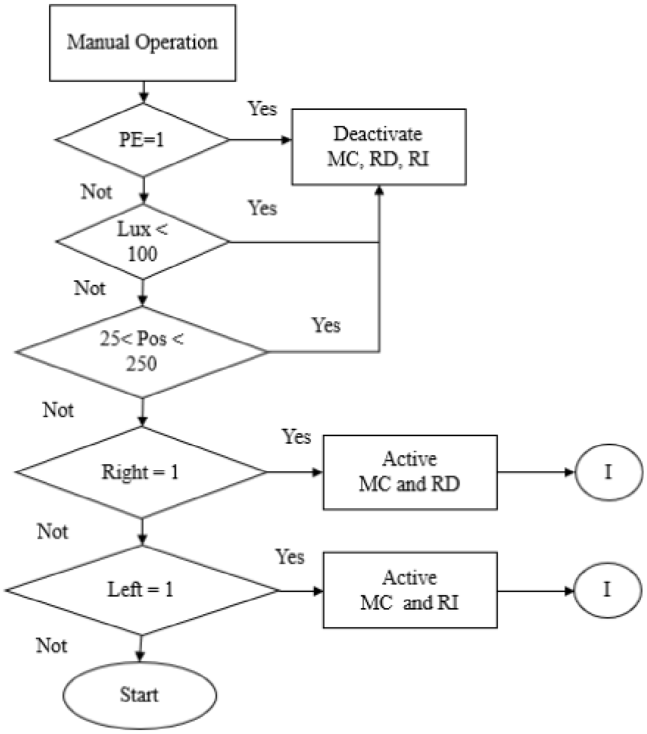


Fig 5. Operation algorithm manual

Fig. 6 shows the first algorithm developed for the automatic solar tracking process, where the code recognizes if the system was turned on and starts a solar radiation recognition process.

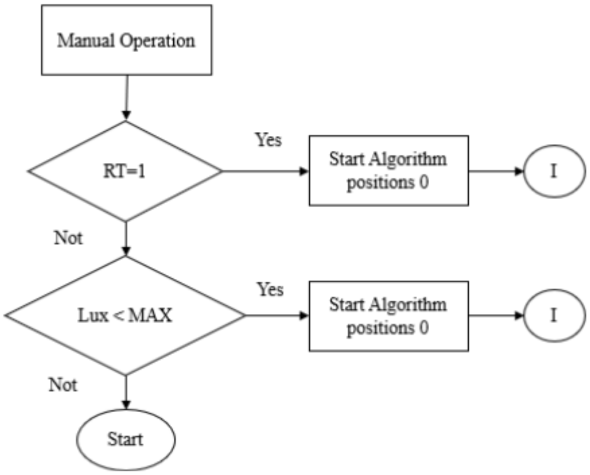


Fig 6. Solar tracking process start algorithm

The sequence of execution automatically starts by the action of the zero-position algorithm as presented in Fig. 7, where the collector looks for the angular position at 25 ° to start the solar trace process.

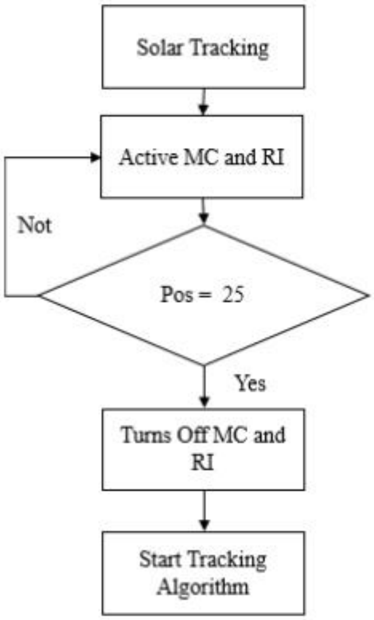


Fig 7. Zero position algorithm

Fig. 8 shows the solar trace algorithm, active by the zero-position system, which seeks to move the solar collector by means of the signal delivered by the LUX meter, in charge of identifying the position with the highest solar radiation.

Once the solar position is identified by means of the tracking algorithm, the final position algorithm is executed (See Fig. 9) that activates the electric motor until the SSPTC prototype is located in the position with the highest solar radiation.

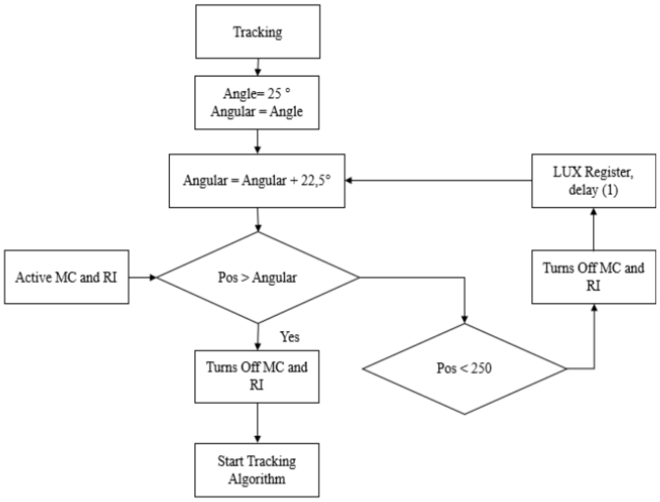


Fig 8. Tracking Algorithm

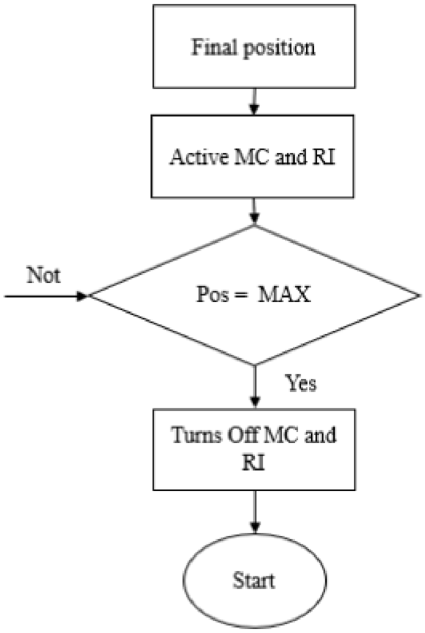


Fig 9. Final position algorithm of the SSPTC prototype

Additionally, a code is developed through the Python programming language for the Raspberry, in order to create communication with the ESP32 control module, allowing the development of an interface to monitor in real time the intrinsic variables in the process, applying the LabVIEW software collecting the information coming from the Raspberry PI 3 (See Fig. 10). It is important to note that the LabVIEW tool is only responsible for displaying the process variables, which implies that the system can operate without the need for a PC since the control is carried out directly by the ESP32.

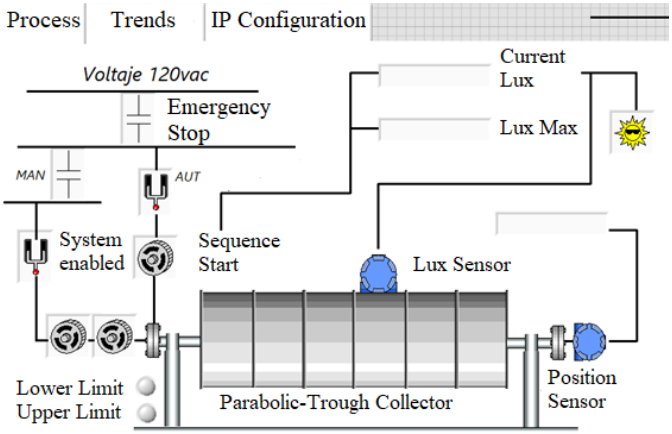


Fig 10. Graphical Interface in LabVIEW raspberry system connected to ESP32 sensor

III. RESULTS Y DISCUSSION

A. *Deviation Error*

The percentage error of the LUX measurement (Solar radiation measurement sensor) is determined by means of a comparative verification process, using an AMEC brand standard luxmeter. Instrument model CA811. The reading error can be determined from (1).

$$\text{Error} = \frac{\text{Standard measure} - \text{Labview measure}}{\text{Standard measure}} \qquad (1)$$

Table V shows the daily average values in LUX, which were taken into account in the experimentation process to determine the difference or the percentage error of the solar measurement sensor. The data was collected through the use of the Graphical Interface developed in LabVIEW to visualize the intrinsic variables in the process, applying (1) and it is concluded that:

- The maximum average percentage of error of the solar radiation measurement system is 0.73%, a value that reflects the accuracy of the measurements implemented in the solar path tracking system.

TABLE V
DATA TO DETERMINE THE MAXIMUM LUX MEASUREMENT ERROR OF THE SOLAR MEASUREMENT SENSOR

Day	Average		
	Standard	LabVIEW	Error %
1	1560	1555	0.32
2	1830	1825	0.27
3	1250	1245	0.40
4	5570	5565	0.09
5	3225	3220	0.16
6	689	684	0.73
7	725	720	0.69
	Máximum error		0.73

B. *Automatic tracking system*

The calculation of the system performance can be determined by applying (2) or using (3), based on a constant and the algebraic difference between the input temperature (T input) and the output temperature (T output).

$$\eta_{th} = \frac{\dot{m}*C_p*(T_o-T_i)}{A_a*G_b*\eta_o} \qquad (2)$$

Where:

- $\dot{m}$: mass Flow
- C_p: Specific heat of water.
- A_a: Collector opening area.
- G_b: Direct solar radiation
- η_o: optical Efficiency.

$$\eta_{th} = 1.124 * (T_o - T_i) \qquad (3)$$

Table VI presents the daily average values of inlet temperature and outlet temperature of the experimental tests developed with the SSPTC prototype, as well as the performance value applying (3).

Fig. 11 shows the trend of the SSPTC inlet and outlet average temperature values and Fig. 12 shows the performance trend, concluding:

- The inlet and outlet temperatures differ on average by 56 ° C during the test days, evidencing the stability in the solar tracking system developed.
- The performance of the SSPTC system is in a range of 49.5% and 54%, evidencing an appropriate technology model developed with materials that present favourable optical characteristics for the construction of decentralized PTC.

TABLE VI
PERFORMANCE AND TEMPERATURE VALUES INLET AND OUTLET OF THE EXPERIMENTAL TESTS OF THE AUTOMATIC SOLAR TRACKING SYSTEM

Day	Average		
	T input °C	T output °C	Performance %
1	66	112	51.7
2	65	111	51.7
3	63	112	55.1
4	65	113	54.0
5	65	110	50.6
6	64	110	51.7
7	65	109	49.5
8	66	111	50.6
9	65	110	50.6
10	64	112	54.0
10	64	112	54.0

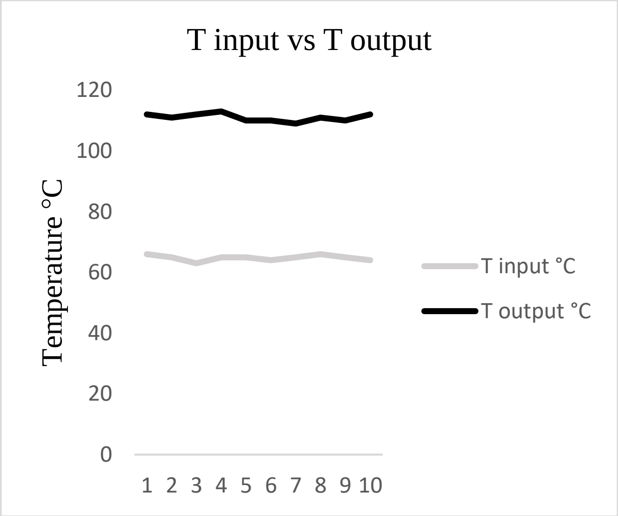


Fig 11. Graph average temperature trend of SSPC inlet and outlet

Table VII shows the average performance values of the initial SSPTC prototype, developed by the GISEAC research group [36] and the SSPTC system with solar path tracking. further, Fig. 13 presents the trend graph of the final average performance values with the data presented in Table VII and concludes:

The efficiency achieved by the SSPTC prototype increased to 51.95% compared to the initial prototype developed, which had an efficiency of 31.32%.

TABLE VII
AVERAGE PERFORMANCE VALUES OF THE AUTOMATIC AND MANUAL SYSTEM OF THE SSPTC PROTOTYPE

Automatic system	51.95
Manual system	34.32

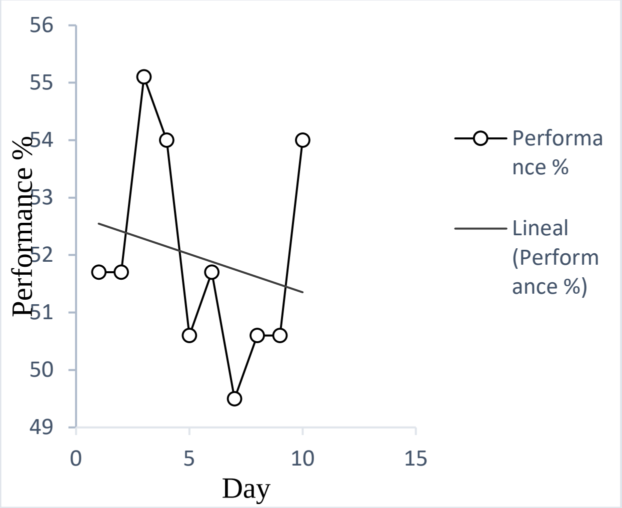


Fig 12. Trend graph of the average performance of the SSPTC

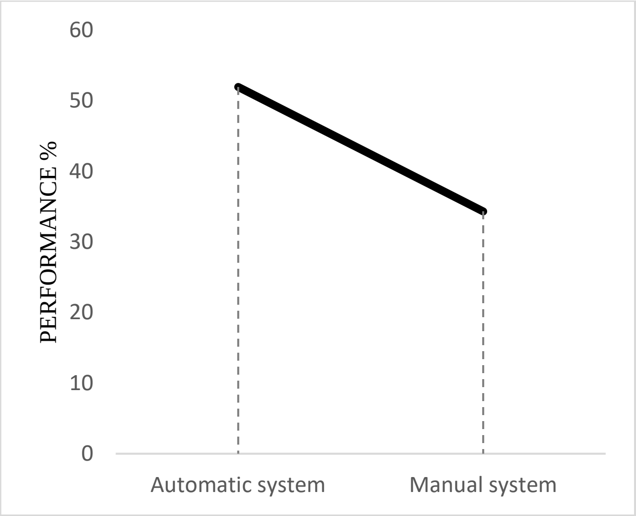


Fig 13. Average performance trend graph of the automatic and manual system of the SSPTC prototype

IV. CONCLUSION

The present work dimensioned, implemented and experimented a single axis solar trajectory tracking system for a small scale handcrafted parabolic-trough collector prototype. A control algorithm was developed to follow the position of the sun during the day by applying a closed loop. The system can follow the solar path throughout the day, so it can be applied in various urban or rural areas with weather conditions similar to those in the city of Bucaramanga, Colombia, or in better conditions.

The hardware of the solar tracking system is governed by an ESP32 module and a Raspberry PI3 microcontroller, with specific characteristics of a system under the Appropriate Technology concept, based on low energy consumption, availability of auxiliary elements in the region, easy operation and maintenance. Additionally, a visualization and monitoring system was developed through the LabVIEW tool.

The performance of the implemented system was evaluated experimentally in terms of power absorbed by the receiver tube, evaluating the average values of the device's inlet and outlet temperatures. Additionally, the value of the automatic tracking error was determined. Thus, it is concluded:

- The influence of the maximum solar tracking error is less than 1%, due to this, it is evident that it does not significantly affect the performance of the device.
- The maximum solar tracking error is acceptable and is the product of the load of the collector's reflection area, the friction of the shaft, the resistance of the mechanical accessories used in the assembly, and the wind speed and direction of the location where the installation was carried out. experimentation process.
- The performance of the automated solar tracking system was 51.95%, exceeding by a value greater than 40% the manual tracking system initially built, showing an increase in the levels of power absorbed by the receiver tube when the angular position of the system, is aligned with the location of the sun.

Finally, the proposed system presents an attractive low-cost alternative for the development of low-scale systems of parabolic-cylinder collectors with solar tracking on one axis, applying the concept of appropriate technology. The system presents high levels of efficiency, being a profitable alternative for the implementation of renewable technologies in areas with similar operating conditions to those presented in this work.

ACKNOWLEDGMENT

The authors acknowledge the contributions of J.A. Forero-Monsalve and BA Jaimes-Grimaldos in the project of "Development of an automated sun tracking system to give movement to a parabolic cylindrical solar collector through the implementation of an Esp32 chip and a Servomotor, monitored by a Raspberry minicomputer", which was the basis for the development of the article.

REFERENCES

[1] V. K. Jebasingh y G. M. J. Herbert, "A review of solar parabolic trough collector", *Renew. Sustain. Energy Rev.*, vol. 54, pp. 1085-1091, feb. 2016, DOI: 10.1016/j.rser.2015.10.043.

[2] B. E. Tarazona-Romero, A. Campos-Celador, y Y. A. Maldonado-Muñoz, "Can solar desalination be small and beautiful? A critical review of existing technology under the appropriate technology paradigm", *Energy Res. Soc. Sci.*, vol. 88, p. 102510, jun. 2022, DOI: 10.1016/j.erss.2022.102510.

[3] A. Z. Hafez *et al.*, "Design analysis of solar parabolic trough thermal collectors", *Renew. Sustain. Energy Rev.*, vol. 82, pp. 1215-1260, feb. 2018, DOI: 10.1016/j.rser.2017.09.010.

[4] B. E. Tarazona-Romero, A. C. Celador, C. L. S. Rodriguez, J. G. A. Villabona, y A. D. R. Quintero, "Design and construction of a solar tracking system for Linear Fresnel Concentrator", *Period. Eng. Nat. Sci. PEN*, vol. 9, n.º 4, Art. n.º 4, oct. 2021, DOI: 10.21533/pen.v9i4.1988.

[5] A. Herez, H. El Hage, T. Lemenand, M. Ramadan, y M. Khaled, "Review on photovoltaic/thermal hybrid solar collectors: Classifications, applications and new systems", *Sol. Energy*, vol. 207, pp. 1321-1347, sep. 2020, DOI: 10.1016/j.solener.2020.07.062.

[6] R. Kumar y M. A. Rosen, "A critical review of photovoltaic–thermal solar collectors for air heating", *Appl. Energy*, vol. 88, n.º 11, pp. 3603-3614, nov. 2011, DOI: 10.1016/j.apenergy.2011.04.044.

[7] B. E. Tarazona-Romero, A. Campos-Celador, O. Lengerke-Perez, N. Y. Castillo-Leon, y A. D. Rincon-Quintero, "Appropriate Technology for Solar Thermal Desalination by Concentration Applied the Humidification-Dehumidification Method", en *Applied Technologies*, Cham, 2023, pp. 415-428. DOI: 10.1007/978-3-031-24971-6_30.

[8] B. E. Tarazona-Romero, Á. Campos Celador, Y. A. Muñoz Maldonado, C. Sandoval Rodríguez, y J. G. Ascanio Villabona, "Prototype of lineal solar collector Fresnel", *Visión Electrónica*, vol. 14, n.º 1, p. 4, 2020. DOI: 10.14483/22484728.16013

[9] K. Lovegrove y W. Stein, "Chapter 1 - Introduction to concentrating solar power technology", en *Concentrating Solar Power Technology (Second Edition)*, K. Lovegrove y W. Stein, Eds. Woodhead Publishing, 2021, pp. 3-17. DOI: 10.1016/B978-0-12-819970-1.00012-8.

[10] B. E. Tarazona-Romero, A. Campos-Celador, Y. A. Muñoz-Maldonado, J. G. Ascanio-Villabona, M. A. Duran-Sarmiento, y A. D. Rincón-Quintero, "Development of a Fresnel Artisanal System for the Production of Hot Water or Steam", en *Recent Advances in Electrical Engineering, Electronics and Energy*, Cham, 2021, pp. 196-209. DOI: 10.1007/978-3-030-72212-8_15.

[11] W.-D. Steinmann, "Thermal energy storage systems for concentrating solar power plants", 2021, pp. 399-440. DOI: 10.1016/B978-0-12-819970-1.00008-6.

[12] H. Price *et al.*, "Chapter 20 - Concentrating solar power best practices", en *Concentrating Solar Power Technology (Second Edition)*, K. Lovegrove y W. Stein, Eds. Woodhead Publishing, 2021, pp. 725-757. DOI: 10.1016/B978-0-12-819970-1.00020-7.

[13] P. V. Gharat, S. S. Bhalekar, V. H. Dalvi, S. V. Panse, S. P. Deshmukh, y J. B. Joshi, "Chronological development of innovations in reflector systems of parabolic trough solar collector (PTC) - A review", *Renew. Sustain. Energy Rev.*, vol. 145, p. 111002, jul. 2021, DOI: 10.1016/j.rser.2021.111002.

[14] E. Z. Moya, "7 - Parabolic-trough concentrating solar power (CSP) systems", en *Concentrating Solar Power Technology*, K. Lovegrove y W. Stein, Eds. Woodhead Publishing, 2012, pp. 197-239. DOI: 10.1533/9780857096173.2.197.

[15] E. Z. Moya, "Chapter 7 - Parabolic-trough concentrating solar power systems", en *Concentrating Solar Power Technology (Second Edition)*, K. Lovegrove y W. Stein, Eds. Woodhead Publishing, 2021, pp. 219-266. DOI: 10.1016/B978-0-12-819970-1.00009-8.

[16] E. Zarza-Moya, "7 - Concentrating Solar Thermal Power", en *A Comprehensive Guide to Solar Energy Systems*, T. M. Letcher y V. M. Fthenakis, Eds. Academic Press, 2018, pp. 127-148. DOI: 10.1016/B978-0-12-811479-7.00007-5.

[17] G. Barone, A. Buonomano, C. Forzano, y A. Palombo, "Chapter 6 - Solar thermal collectors", en *Solar Hydrogen Production*, F. Calise, M. D. D'Accadia, M. Santarelli, A. Lanzini, y D. Ferrero, Eds. Academic Press, 2019, pp. 151-178. DOI: 10.1016/B978-0-12-814853-2.00006-0.

[18] C. B. Anfinsen, "Solar Energy", *Science*, vol. 192, n.º 4236, pp. 202-202, abr. 1976, DOI: 10.1126/science.192.4236.202.

[19] B. E. Tarazona-Romero, "Evaluation of the incidence of optical and physical characteristics on the performance of a Fresnel Linear Collector prototype", *Period. Eng. Nat. Sci. PEN*, vol. 11, n.º 1, Art. n.º 1, feb. 2023, DOI: 10.21533/pen.v11i1.3105.

[20] M. Malekan, A. Khosravi, y M. El Haj Assad, "Chapter 6 - Parabolic trough solar collectors", en *Design and Performance Optimization of Renewable Energy Systems*, M. E. H. Assad y M. A. Rosen, Eds. Academic Press, 2021, pp. 85-100. DOI: 10.1016/B978-0-12-821602-6.00007-9.

[21] J. Fredriksson, M. Eickhoff, L. Giese, y M. Herzog, "A comparison and evaluation of innovative parabolic trough collector concepts for large-scale application", *Sol. Energy*, vol. 215, pp. 266-310, feb. 2021, DOI: 10.1016/j.solener.2020.12.017.

[22] S. Toghyani, E. Baniasadi, y E. Afshari, "Thermodynamic analysis and optimization of an integrated Rankine power cycle and nano-fluid based parabolic trough solar collector", *Energy Convers. Manag.*, vol. 121, pp. 93-104, ago. 2016, DOI: 10.1016/j.enconman.2016.05.029.

[23] R. Silva, M. Pérez, M. Berenguel, L. Valenzuela, y E. Zarza, "Uncertainty and global sensitivity analysis in the design of parabolic-trough direct steam generation plants for process heat applications", *Appl. Energy*, vol. 121, pp. 233-244, may 2014, DOI: 10.1016/j.apenergy.2014.01.095.

[24] R. V. Padilla, A. Fontalvo, G. Demirkaya, A. Martinez, y A. G. Quiroga, "Exergy analysis of parabolic trough solar receiver", *Appl. Therm. Eng.*, vol. 67, n.º 1, pp. 579-586, jun. 2014, DOI: 10.1016/j.applthermaleng.2014.03.053.

[25] S. Peng, H. Hong, H. Jin, y Z. Zhang, "A new rotatable-axis tracking solar parabolic-trough collector for solar-hybrid coal-fired power plants", *Sol. Energy*, vol. 98, pp. 492-502, dic. 2013, DOI: 10.1016/j.solener.2013.09.039.

[26] Natraj, B. N. Rao, y K. S. Reddy, "Wind load and structural analysis for standalone solar parabolic trough collector", *Renew. Energy*, vol. 173, pp. 688-703, ago. 2021, DOI: 10.1016/j.renene.2021.04.007.

[27] S. A. Kalogirou, "A detailed thermal model of a parabolic trough collector receiver", *Energy*, vol. 48, n.º 1, pp. 298-306, dic. 2012, DOI: 10.1016/j.energy.2012.06.023.

[28] F. I. Nascimento, E. W. Zavaleta-Aguilar, y J. R. Simões-Moreira, "Algorithm for sizing parabolic-trough solar collectors", *Therm. Sci. Eng. Prog.*, p. 100932, abr. 2021, DOI: 10.1016/j.tsep.2021.100932.

[29] A. Z. Hafez *et al.*, "Design analysis of solar parabolic trough thermal collectors", *Renew. Sustain. Energy Rev.*, vol. 82, pp. 1215-1260, feb. 2018, DOI: 10.1016/j.rser.2017.09.010.

[30] W. Qu, R. Wang, H. Hong, J. Sun, y H. Jin, "Test of a solar parabolic trough collector with rotatable axis tracking", *Appl. Energy*, vol. 207, pp. 7-17, dic. 2017, DOI: 10.1016/j.apenergy.2017.05.114.

[31] Y. Yao, Y. Hu, S. Gao, G. Yang, y J. Du, "A multipurpose dual-axis solar tracker with two tracking strategies", *Renew. Energy*, vol. 72, pp. 88-98, dic. 2014, DOI: 10.1016/j.renene.2014.07.002.

[32] M. S. Al-Soud, E. Abdallah, A. Akayleh, S. Abdallah, y E. S. Hrayshat, "A parabolic solar cooker with automatic two axes sun tracking system", *Appl. Energy*, vol. 87, n.º 2, pp. 463-470, feb. 2010, DOI: 10.1016/j.apenergy.2009.08.035.

[33] W. Schiel y T. Keck, "Chapter 9 - Parabolic dish concentrating solar power systems", en *Concentrating Solar Power Technology (Second Edition)*, K. Lovegrove y W. Stein, Eds. Woodhead Publishing, 2021, pp. 311-355. DOI: 10.1016/B978-0-12-819970-1.00007-4.

[34] C. Chang, "5 - Tracking solar collection technologies for solar heating and cooling systems", en *Advances in Solar Heating and Cooling*, R. Z. Wang y T. S. Ge, Eds. Woodhead Publishing, 2016, pp. 81-93. DOI: 10.1016/B978-0-08-100301-5.00005-9.

[35] D. Sakthivadivel, K. Balaji, D. Dsilva Winfred Rufuss, S. Iniyan, y L. Suganthi, "Chapter 1 - Solar energy technologies: principles and applications", en *Renewable-Energy-Driven Future*, J. Ren, Ed. Academic Press, 2021, pp. 3-42. DOI: 10.1016/B978-0-12-820539-6.00001-7.

[36] J. D. Aequez Florez y M. Y. Almeida Lozano, "Diseño y construcción de un prototipo de colector solar cilíndrico parabólico para la producción de vapor teniendo en cuenta las condiciones climáticas de la zona en las que se encuentra las unidades tecnologías de Santander", Pregrado, Unidades Tecnologicas de Santader, Bucaramanga, 2019.

Brayan Eduardo Tarazona Romero, was born in Floridablanca, Santander, Colombia in 1992. He received the Engineering degree in electromechanical from the Unidades Tecnológicas de Santander, Colombia, in 2015, the Magister degree in Renewable energy and energetic efficiency from the Universidad a Distancia de Madrid, España, in 2018 and currently study a Ph.D. in Energy efficiency and sustainability in engineering and architecture from Universidad del Pais Vasco, España. From 2016 to 2018, he was a professor at the Unidades Tecnológicas de Santander, Colombia. In 2019 he was a parttime research professor at the Unidades Tecnológicas de Santander, Colombia. Currently, he is a full-time research

professor at the Unidades Tecnológicas de Santander, Colombia. His research interests include automation and industrial control, renewable energy, alternative solar thermal alternative solar desalination systems. Mr. Brayan´s attached to the Research Group on Energy Systems, Control and Automation GISEAC (Unidades Tecnológicas de Santander). He is previously recognized as a Minciencias, Colombia as a Junior investigator.
ORCID: https://orcid.org/0000-0001-6099-0921

Javier Gonzalo Ascanio Villabona, was born in Bucaramanga, Santander, Colombia in 1990. He received the Engineering degree in electromechanical from the Unidades Tecnológicas de Santander, Colombia, in 2015, the Magister degree in Renewable energy and energetic efficiency from the Universidad a Distancia de Madrid, España, in 2018 and currently study a Ph.D. in Energy efficiency and sustainability in engineering and architecture from Universidad del Pais Vasco, España. From 2015 to 2016, he was a professor of Unidades Tecnológicas de Santander (UTS). From 2017 to 2018 he was a part-time research professor UTS, Colombia. Since 2019 to Currently, he is a full-time research professor at the Technological Units of Santander, Colombia. His research interest area is the renewable energy, energetic efficiency and the conductive materials analysis. Mr. Javier´s attached to the Research Group on Energy Systems, Control and Automation GISEAC of the Unidades Tecnológicas de Santander. He is previously recognized as a Minciencias, Colombia as a Junior investigator. Since 2018 he is the leader of the EVOTEC research hotbed, at the Unidades Tecnológicas de Santander.
ORCID: https://orcid.org/0000-0003-1749-5399

Arly Darío Rincón Quintero was born in Aguachica, Cesar, Colombia in 1982. He received the degree in mechanical engineering from Francisco de Paula Santander University, Colombia, in 2005 and the degree Master in Energy Efficiency and Sustainability from the University of the Basque Country UPV/EHU, Bilbao, España, in 2013. He is currently pursuing the Ph.D. degree in Energy efficiency and sustainability in engineering and architecture with Basque Country UPV/EHU, Bilbao, España. He is a senior researcher before Minciencias, Colombia associate professor at the Unidades Tecnológicas de Santander, in the Faculty of Natural Sciences and Engineering.
ORCID: https://orcid.org/0000-0002- 4479-5613

Camilo L. Sandoval R, is an Electronic Engineer, Master in Electronic Engineering and Ph.D (c) in Electronics and Telecommunications from the Universidad del Pais Vasco. Leader of the research group in energy systems, automation and control GISEAC of the (Unidades Tecnológicas de Santander) UTS. His areas of interest are: automatic control, signal processing and pattern recognition, applied to the analysis of materials and structures, and biomedical engineering. With 14 publications, more than 100 directed engineering degree works and more than 30 participations as a speaker in scientific and academic events. Consultant specialized in automatic control systems, participation in various technological development and innovation projects. He is recognized as an Associate Researcher (I) according to the Ministry of Science, Technology and Innovation of the Republic of Colombia, from 2018 to the present.
ORCID: https://orcid.org/0000-0001-8584-0137