

COB-2023-1152

A BIOINSPIRED SOLAR TRACKER ACTUATED BY SHAPE MEMORY ALLOY

João Gabriel Andrade da Rocha

Guilherme Amaral do Prado Campos

Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, CEFET/RJ - Department of Mechanical Engineering, Rio de Janeiro, Brazil

joao.rocha@aluno.cefet-rj.br; guilherme.campos@cefet-rj.br

Arthur Adeodato

Instituto Politécnico, Universidade Estadual do Rio de Janeiro (UERJ), R. Hormindo Silva, 25 - Lagoinha, Nova Friburgo - RJ, 28625-570.

arthuradeodato@iprj.uerj.br

Abstract. *Solar panels have been extensively used as a clean and sustainable method for energy conversion, leading to significant developments and research on photovoltaic (PV) cells. PV technology converts sunlight into electrical energy when photons from the sun are absorbed by a PV cell, causing electrons to be excited from the valence band to the conduction band of the semiconductor material. This process generates a voltage difference between the two sides of the cell, producing an electrical current. However, the efficiency of PV cells is highly dependent on the angle at which the sunlight strikes the cell's surface. Among other factors, it is essential to keep the PV cells at the right angle to the incoming sunlight to maximize the energy output in PV energy conversion. One promising approach to address this challenge is using shape memory alloys (SMAs). SMAs are smart materials that exhibit remarkable shape recovery properties when subjected to specific temperature variations. These properties make SMAs ideal for solar trackers, allowing them to orient the PV panels to follow the sun's movement throughout the day. This paper presents a bioinspired mechanism for solar tracking using SMAs elements mimicking a sunflower movement. The proposed mechanism employs a two restitution elements of a shape memory alloy to control the panel orientation. The SMA phase transformation can happen when heated by the sun's rays, promoting its contract and pull-on. This movement is then transmitted to the PV panel, causing it to rotate and track the sun's movement as a sunflower. The feasibility of the proposed mechanism is evaluated through computational simulations which can contribute to the development of an experimental prototype. The current stage of development is shown as a proof of concept. A constitutive model with assumed phase transformation represents the SMA thermomechanical behavior, and different configurations are evaluated. The results show that the intelligent mechanism can follow the sun conferring adaptability characteristics when compared to static PV panels. This research presents a promising solution for improving the efficiency of PV energy conversion using shape memory alloys.*

Keywords: *Photovoltaic Energy, Bioinspired Design, Shape Memory Alloys, Intelligent Systems.*

1. INTRODUCTION

Photovoltaic (PV) solar energy has experienced an attractive growth year after year in the global scenario, mainly associated to governmental incentives, high electricity prices, and the reduction in the cost of installing PV systems. According to the official data from the Associação Brasileira de Energia Solar Fotovoltaica (ABSOLAR), the installed capacity of distributed PV generation systems (micro and/or mini-generation in homes) and centralized (solar power plants) is approximately 32 GW, i.e., solar energy has become the second source of the Brazilian electricity matrix (ABSOLAR, 2023).

Considering the popularization of the PV systems and solar energy, it is essential to highlight that most of the PV systems are of the fixed type. It means, they are static in relation to their orientation and do not follow the movement of the sun. Alternatively, the most recent solar plants use movement systems in the PV modules to follow the sun throughout the day. This movement can be performed through active, passive, or semi-passive systems (Mousazadeh *et al.*, 2009; Hafez *et al.*, 2018; Awasthi *et al.*, 2020). Figure 1 shows the percentage of types of drive systems used in photovoltaic solar trackers. It can be seen that 95% of the trackers are active; that is, they have one or two actuators responsible for moving the PV modules.

Solar trackers can have different efficiencies compared to fixed systems due to the following factors: solar radiation, level of cloudiness throughout the year, latitude, and temperature (Campos and da Silva, 2020). Therefore, the behavior of solar radiation throughout the year or day becomes a predominant factor in the decision. In the case of Brazil, macro

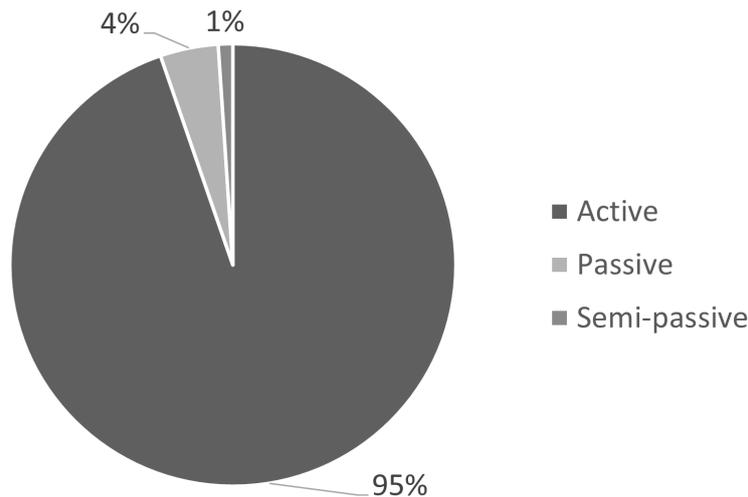


Figure 1: Types of drive systems in solar trackers adapted from Awasthi *et al.* (2020).

data can be obtained through the Brazilian Atlas of Solar Energy, which presents solar irradiation maps whose values vary from 2117 Wh/m².day in the worst place and time of the year to 7289 Wh/m².day in the best place and time of the year, that is, the worst in Brazil is better than the solar irradiation in Germany in any place or time.

The displacement of the Sun throughout the day impacts the angle of incidence of solar rays on the surfaces of photovoltaic panels, thus varying energy generation throughout the day. In addition, other factors can reduce the efficiency of the modules, such as temperature, dirt, incorrect positioning, and an environment close to the coast, among others (Pillai and Rajasekar, 2018).

Recently, intelligent mechanisms of actuation have been employed conferring adaptability characteristics with the objective to increase even more the efficiency of PV unit cells. Smart materials comes up as a great alternative due to their multi physical coupling and capacity of softening actuation. For instances, this paper proposes the use of a shape memory alloy mechanism to activate the PV panel and control its orientation. Shape memory alloys (SMA) became famous in the early 1990 due to their reversible martensite phase transformation and thermomechanical coupling (Lagoudas, 2008; Savi, 2015). Several efforts have been done to mathematical describe the constitutive behavior of SMAs over stress and temperature fields. Tanaka *et al.* (1986); Liang and Rogers (1990); Brinson (1993) present a class of models with an assumed kinetics on phase transformation considering martensite phase transformation. Further, Oliveira *et al.* (2018); Dornelas *et al.* (2021b, 2020, 2021a) developed the model concerning fundamental phenomena as transformation induced plasticity and fatigue over distinct martensite phases. Adeodato *et al.* (2022) proposed a model for strain prescribed problems in SMAs with great contribution in dynamical problems. This model also provides the option to adjust the phase transformation path according to experimental data by two additional independent parameters.

In this way, the shape memory effect have been used in sensing and actuation devices in technological application in industry such as: aerospace (Leal and Savi, 2018), robotic (Fonseca and Savi, 2020; Fonseca *et al.*, 2022), control (Savi *et al.*, 2012; Costa *et al.*, 2019), and biomedical (Machado and Savi, 2003; Petrini *et al.*, 2005; Petrini and Migliavacca, 2011; Ali *et al.*, 2019). Riad *et al.* (2017) conducted a numerical study in order to explore the effect of the sun's radiation on SMA actuators. Further, Riad *et al.* (2019) proposed an intelligent SMA bio inspired solar tracker in a flower shape. Different conditions of temperature were evaluated enhancing the ability of the solar system in various conditions tracking the sun. Riad *et al.* (2020) provides an investigation around a SMA solar tracker employing a single SMA element. The authors explored the two-way effect and shown an increase of energy production about 39% compared to a fixed system. Experimental investigations have been performed by Degeratu *et al.* (2014) allowing to prove the concept and contribute to the assembly of SMA solar trackers.

In the present work, the focus is to develop a bio inspired system that would be able to follow the Sun as a passive type actuator. The PV panel would be able to move according to the SMA temperature variation provided by the environment. Two antagonistic SMA springs are proposed performing the shape memory effect of contraction in opposite directions. The Adeodato *et al.* (2022) model is employed to describe the thermomechanical coupling in the SMA elements. Numerical simulations are carried out considering the ambient temperature, the incidence of the solar sun during the day, and the panel's angle of orientation. An experimental prototype is under development and it is present as an illustrative design. The result demonstrate the ability to shape memory alloys to actuate solar panels.

2. MATHEMATICAL MODEL

This section provides the basis for the mathematical description of the proposed bioinspired solar tracker actuated by shape memory alloys and the sun's light. The assumptions are mentioned with the constitutive equations adopted to represent the shape memory effect.

A traditional solar panel can be considered a base to support the panel, and it cannot shift its orientation or move around the base. Usually, its orientation is set according to the weather and geographical conditions to optimize energy conversion.

The energy conversion is highly sensitive to several factors, such as the panel's temperature, luminosity, and angle orientation. For instance, this paper proposes to investigate using the shape memory effect to actuate the solar panel, alter its panel angle, and, therefore, track the sun.

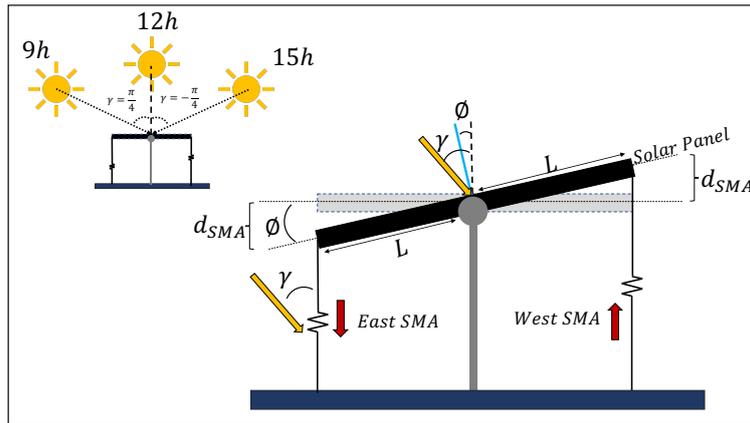


Figure 2: Bioinspired solar tracker actuated by shape memory alloy concept design.

Opposing now a static solar panel, an orthogonal and vertical vector can be defined from the bottom to the top (see Fig. 2). In this sense, the sunlight strikes the panel with an angle of γ . Considering now the solar panel is allowed to re-orientate, an angle ϕ can be defined as in Eq. 1 and the objective here is to track $\phi = \gamma$ according to the temperature where the SMA actuators are submitted. It is important to note that γ also represents the angle at which the sun's ray strikes the SMA element. This phenomenon is intrinsic for an SMA solar tracker design promoting an additional increase in the SMA actuator's temperatures beyond the ambient temperature changes. In this paper, it is assumed that, among the ambient temperature, which may vary from 293 to 305 K, the incidence of solar rays can promote an increase of 30 K (see Fig. 5).

$$\phi = \arcsin\left(\frac{d_{SMA}}{L}\right) \quad (1)$$

This work with the sun rising at 6 o'clock with an ambient temperature below A_s and the sun setting at 18 o'clock with the same ambient temperature. At that moment, the sun's ray strikes the solar panel with an angle of $\gamma = \pi/2$. Note that this is the moment with less solar energy available from the lightning day period. In order to guarantee the structural design, this project is imitated to actuate the SMA from 9 o'clock ($\gamma = \pi/4$) to 15 o'clock ($\gamma = -\pi/4$).

The temperature is low at sunrise, so no phase transformation is allowed. When the sun starts to move, the sun's ray first strikes the east SMA element, promoting an increase in temperature and allowing phase transformation. In particular, at 9 o'clock, the east SMA element experiences a high incidence of the sun's rays due to $\gamma = \pi/4$. At noon, $\gamma = 0$, both actuators are covered by the panel and are submitted to the same temperature condition, finishing the SMA's first cycles of thermomechanical load and beginning the second. The forces the actuators promote are equal, so $\phi = 0$. Finally, at 15 o'clock, the sun strikes the SMA oriented to the west with $\gamma = -\pi/4$ making the same effect on the opposite side, finishing the second cycle at 18 o'clock.

In order to represent the thermomechanical coupling present in SMAs, the kinetics of phase transformation is assumed according to Adeodato *et al.* (2022). Therefore, it is possible to represent the phase transformation induced by temperature effects considering different proprieties for each phase.

Evaluating a one-dimensional SMA model, a proof body submitted to uniaxial load, the energy balance, thermodynamics principles, and Clausius-Duhem inequality, the thermomechanical coupling can be represented by internal state variables (ϵ, β, T) . Therefore, ϵ represents the strain and β the martensite volume fraction governed by σ and T states. The constitutive equation, combining these principles, is represented as:

$$\dot{\sigma} = E\dot{\epsilon} + \alpha\dot{\beta} + \Theta\dot{T} \quad (2)$$

where E represents Young's modulus, Θ the thermal dilatation coefficient, and $\alpha = -E\epsilon_R$ with ϵ_R as the maximum recoverable strain. In this regard, the critical phase transformations temperatures are referred as M_s , M_f , A_s , and A_f , and the critical stresses for martensite reorientation are σ_s and σ_f .

The martensite volume fraction (β) is expressed in terms of the martensite volume fraction initial conditions β_0 and the hardening functions $f_M(\tilde{T})$ and $f_A(\tilde{T})$ as follows:

$$\beta = \beta_0 + (1 - \beta_0)f_M(\tilde{T}) \quad A \rightarrow M \quad (3)$$

$$\beta = \beta_0 f_A(\tilde{T}) \quad M \rightarrow A \quad (4)$$

where \tilde{T} is a normalized temperature defined as:

$$\tilde{T}_M = \frac{M_s - T}{M_s - M_f} \quad A \rightarrow M \quad (5)$$

$$\tilde{T}_A = \frac{A_f - T}{A_f - A_s} \quad M \rightarrow A \quad (6)$$

The hardening functions $f_M(\tilde{T}_M)$ and $f_A(\tilde{T}_A)$ are expressed by two successive second-order polynomial equations each as:

$$f_M(\tilde{T}) = \begin{cases} a_1\tilde{T}_M^2 & 0 \leq \tilde{T} \leq B_M \\ a_2\tilde{T}_M^2 + b_2\tilde{T}_M + c_2 & B_M < \tilde{T} \leq 1 \end{cases} \quad (7)$$

$$f_A(\tilde{T}) = \begin{cases} a_3\tilde{T}_A^2 + b_3\tilde{T}_A + c_3 & 1 \leq \tilde{T} \leq B_A \\ a_4\tilde{T}_A^2 & B_A < \tilde{T} \leq 0 \end{cases} \quad (8)$$

Where $0 < B_M < 1$ and $0 < B_A < 1$ are controlling parameters for forward and reverse transformations, respectively, defining the start and finish of the polynomial curve. For forward phase transformation, the coefficients are set as: $a_1 = \frac{1}{B_M}$, $a_2 = \frac{1}{B_M-1}$, $b_2 = \frac{-2}{B_M-1}$, $c_2 = \frac{B_M}{B_M-1}$ while for reverse transformation, the value of the coefficients are: $a_3 = \frac{1}{B_A-1}$, $b_3 = \frac{-2}{B_A-1}$, $c_3 = \frac{B_A}{B_A-1}$, $a_4 = \frac{1}{B_A}$.

Therefore, the shape memory effect can be simulated with the assistance of a computational software and Table 1 shows the SMA constitutive parameters employed in this work. The parameters are taken from experimental analyses performed in Adeodato *et al.* (2022) for a shape memory alloy commercial sample.

Table 1: SMA constitutive parameters from Adeodato *et al.* (2022).

$M_s(K)$	$M_f(K)$	$A_s(K)$	$A_f(K)$	$\sigma_s(MPa)$	$\sigma_f(MPa)$
314	308	316	324	90.6	285.5
$E_A(GPa)$	$E_M(GPa)$	$C_a(MPa)$	$C_m(MPa)$	ϵ_R	$B_A = B_M$
43.2	18.9	7	6.5	0.06	0.5

The next section provides the prototype concepts and design.

3. PROTOTYPE SETUP

This project is bioinspired by the movement of a sunflower and respecting Heliotropism. That is, it is the movement in relation to the Sun that happens due to a system of contraction and extension of the wall of the proposed mechanism, thus giving an angle to the part of the head of the panel and leaving it as perpendicular orientation as possible related to the sun. This section deals with the conception and assembly of the proposed mechanism as a proof of concept.

The prototype design present a central angular mechanism allowing the movement of the panel related to the base. In the connection between the sheets, hinges were added between the two PV solar panels to allow freedom of movement, allowing adjustment for the best possible solar incidence angle. Fig. 3 and 4 shows the prototype design indicating the position of the SMA elements in the angular mechanism.

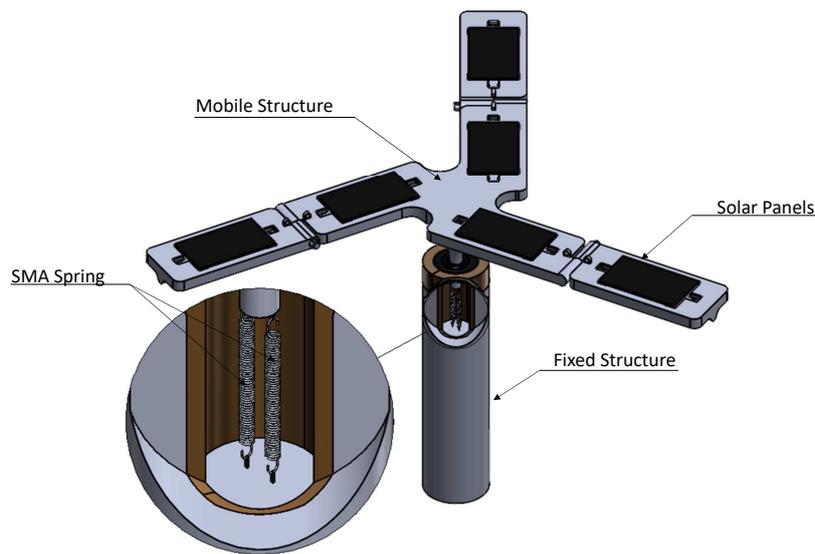


Figure 3: Bio-inspired solar tracker actuated by shape memory alloy concept design.

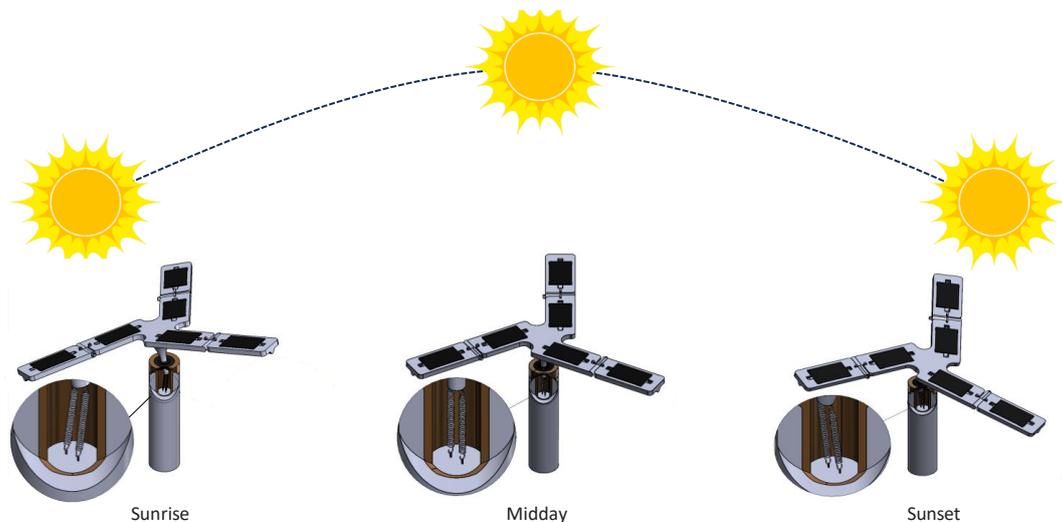


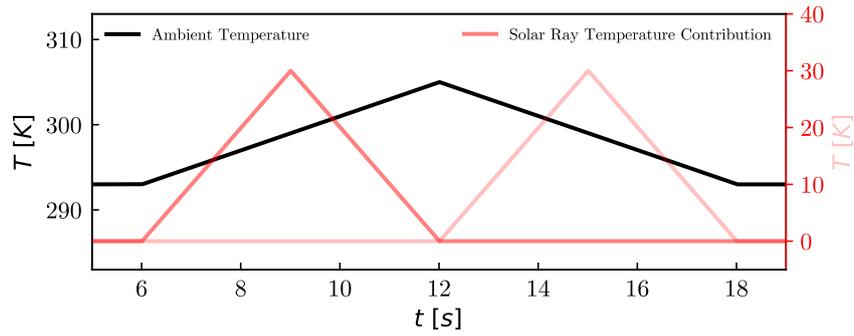
Figure 4: Position by Bio-inspired solar tracker throughout the day.

4. RESULTS

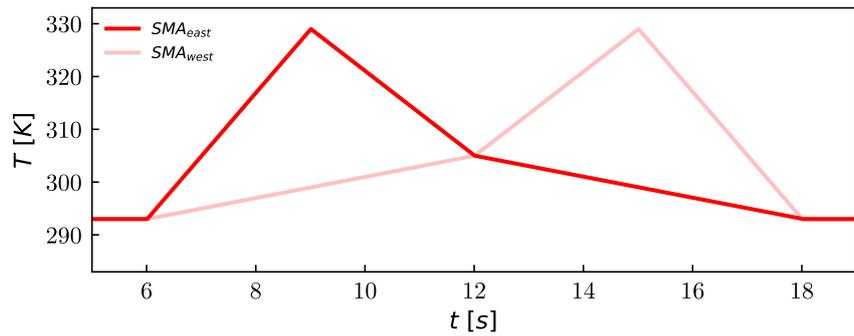
This section provides the results of the bio-inspired solar tracker actuated by shape memory alloys. The results are attributed to qualitative analyses as a proof of concept to use the SMA shape memory effect to track the sun. The mathematical model of Adeodato *et al.* (2022) is adopted with the hypothesis and assumptions in made on Section 2.

In this sense, Figure 5 presents the temperature variation assumed in this paper. Figure 5(a) is attributed to environmental conditions showing the ambient temperature variation and the contribution of the incidence of solar rays. Figure 5(b) deals with the temperature in which east and west SMA actuators are submitted during the lighting period of the day as the sum of the ambient temperature and the solar ray contribution.

Figure 6 shows in a 3D diagram the first cycle of both actuators. The pre-processing of SMA actuators is in gray and consists of pre-deformation and coupling to the panel. The first thermomechanical cycle for east and west actuators is rendered in red. So, from 6 to 9 o'clock, the temperature in the east SMA actuator increases, promoting its shape recovery. Consequently, the west SMA actuator, which is not submitted to a thermal load at this moment, is mechanically loaded and presents a linear elastic behavior with constant elastic modulus $E = E_M$. After 9 o'clock, the temperature in the east



(a)



(b)

Figure 5: SMA thermo cycles for a lightning day period. Temperature \times time diagrams.

SMA actuator decreases, returning to the initial point at 12 o'clock.

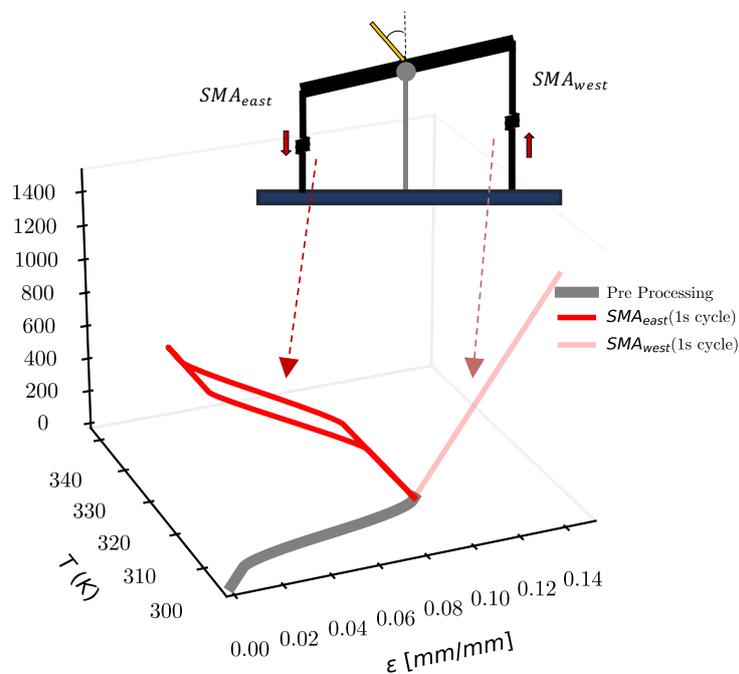


Figure 6: Tri-dimensional Stress \times Strain \times Temperature diagram for the first thermo cycle (from 6 to 12 o'clock). Shape memory effect with assisted stress for the east SMA element and linear response for west SMA element.

Figure 7(a), (b), and (c) provide information about SMA strain (ϵ), martensite volume fraction (β), and panel angle (ϕ), respectively. The first and the second cycles are highlighted, exhibiting each SMA actuator's state and the panel

angle's path (ϕ).

Finally, Figure 8 exposes the strain \times temperature diagram where it is possible to observe the shape memory effect with assisted stress for the first and second cycles. The total strain is not recovered since the opposite SMA element provides resistance to the movement. The shape memory effect happens in the first cycle in the east SMA actuator, while the west SMA actuator experiences it in the second cycle.

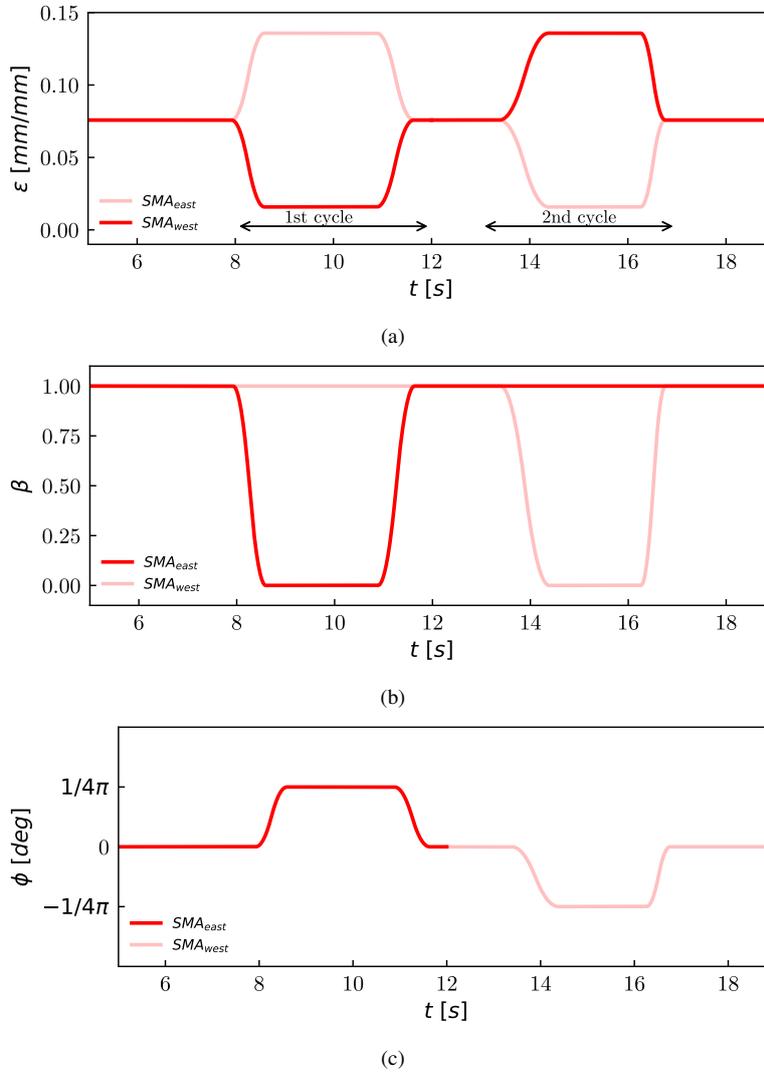


Figure 7: Day response of SMA east and west actuators representative variables.

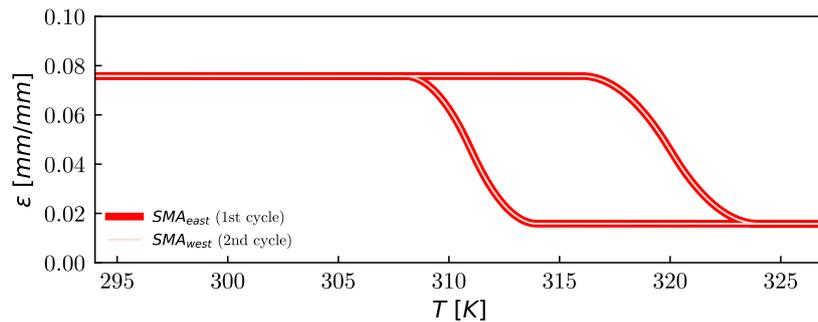


Figure 8: Strain \times Temperature diagram. East and west SMA actuators recoverable strain.

5. CONCLUSION

The use of solar energy and the search for more efficient ways of using this renewable source are essential practices for energy production that is less harmful to the environment.

The idea of artificial heliotropism was incorporated into this work due to its energy and time-saving advantage by eliminating the need to study solar incidence.

The conceptual prototype, composed of SMA, allows the movement of the structure concerning the sun with a satisfactory angular variation, generating greater use by maintaining the best angle of incidence with the solar cells and enhancing the efficiency of energy capture. Therefore, this project has characteristics that make it more advantageous than fixed solar panels in terms of better energy efficiency.

6. REFERENCES

- ABSOLAR, 2023. “Panorama da solar fotovoltaica no brasil e no mundo”. Technical report.
- Adeodato, A., Vignoli, L.L., Paiva, A., Monteiro, L.L., Pacheco, P.M. and Savi, M.A., 2022. “A shape memory alloy constitutive model with polynomial phase transformation kinetics”. *Shape Memory and Superelasticity*, pp. 1–18.
- Ali, F., Raza, W., Li, X., Gul, H. and Kim, K., 2019. “Piezoelectric energy harvesters for biomedical applications”. *Nano Energy*, Vol. 19.
- Awasthi, A., Shukla, A.K., SR, M.M., Dondariya, C., Shukla, K., Porwal, D. and Richhariya, G., 2020. “Review on sun tracking technology in solar pv system”. *Energy Reports*, Vol. 6, pp. 392–405.
- Brinson, L.C., 1993. “One-dimensional constitutive behavior of shape memory alloys: Thermomechanical derivation with non-constant material functions and redefined martensite internal variable”. *Journal of Intelligent Material Systems and Structures*, Vol. 4, No. 2, pp. 229–242. URL <https://doi.org/10.1177/1045389X9300400213>.
- Campos, G.A.d.P. and da Silva, J.P.G., 2020. “Rastreador solar impresso: Um projeto open source”. In *Congresso Brasileiro de Energia Solar-CBENS*.
- Costa, D.D.A., Savi, M.A., de Paula, A.S. and Bernardini, D., 2019. “Chaos control of a shape memory alloy structure using thermal constrained actuation”. *International Journal of Non-Linear Mechanics*, Vol. 111, pp. 106–118. URL <https://doi.org/10.1016/j.ijnonlinmec.2019.02.006>.
- Degeratu, S., Alboteanu, L., Rizescu, S., Coman, D., Bizdoaca, N.G. and Caramida, C., 2014. “Active solar panel tracking system actuated by shape memory alloy springs”. In *2014 International Conference on Applied and Theoretical Electricity (ICATE)*. IEEE, pp. 1–5.
- Dornelas, V.M., de Oliveira, S.A. and Savi, M.A., 2020. “A macroscopic description of shape memory alloy functional fatigue”. *International Journal of Mechanical Sciences*, Vol. 170. URL <https://doi.org/10.1016/j.ijmecsci.2019.105345>.
- Dornelas, V.M., de Oliveira, S.A., Savi, M.A., Pacheco, P.M.C.L. and de Souza, L.F.G., 2021a. “Fatigue on shape memory alloys: Experimental observations and constitutive modeling”. *International Journal of Solids and Structures*, Vol. 213, pp. 1–24. URL <https://doi.org/10.1016/j.ijsolstr.2020.11.023>.
- Dornelas, V.M., Oliveira, S.A., Savi, M.A. and Pacheco, P.M.C.L., 2021b. “Numerical investigations of shape memory alloy fatigue”. *Metals*, Vol. 11, No. 10, p. 1558.
- Fonseca, L.M. and Savi, M.A., 2020. “Nonlinear dynamics of an autonomous robot with deformable origami wheels”. *International Journal of Non-Linear Mechanics*, Vol. 125, p. 103533. URL <https://doi.org/10.1016/j.ijnonlinmec.2020.103533>.
- Fonseca, L.M., Rodrigues, G.V. and Savi, M.A., 2022. “An overview of the mechanical description of origami-inspired systems and structures”. *International Journal of Mechanical Sciences*, Vol. 223, p. 107316.
- Hafez, A., Yousef, A. and Harag, N., 2018. “Solar tracking systems: Technologies and trackers drive types—a review”. *Renewable and Sustainable Energy Reviews*, Vol. 91, pp. 754–782.
- Lagoudas, D., 2008. *Shape Memory Alloys*. Springer, United States of America.
- Leal, P.B.C. and Savi, M.A., 2018. “Shape memory alloy-based mechanism for aeronautical application: Theory, optimization and experiment”. *Aerospace Science and Technology*, Vol. 76, pp. 155–163. URL <http://www.sciencedirect.com/science/article/pii/S1270963817316954>.
- Liang, C. and Rogers, C.A., 1990. “One-dimensional thermomechanical constitutive relations for shape memory materials”. *Journal of intelligent material systems and structures*, Vol. 8, No. 4, pp. 285–302. URL <https://doi.org/10.1177/1045389X9700800402>.
- Machado, L. and Savi, M., 2003. “Medical applications of shape memory alloys”. *Brazilian journal of medical and biological research*, Vol. 36, pp. 683–691.
- Mousazadeh, H., Keyhani, A., Javadi, A., Mobli, H., Abrinia, K. and Sharifi, A., 2009. “A review of principle and sun-tracking methods for maximizing solar systems output”. *Renewable and sustainable energy reviews*, Vol. 13, No. 8, pp. 1800–1818.
- Oliveira, S.d.A., Dornelas, V.M., Savi, M.A., Pacheco, P.M.C. and Paiva, A., 2018. “A phenomenological description of

- shape memory alloy transformation induced plasticity”. *Meccanica*, Vol. 53, pp. 2503–2523.
- Petrini, L. and Migliavacca, F., 2011. “Biomedical applications of shape memory alloys”. *Journal of Metallurgy*, Vol. 2011. URL <https://doi.org/10.1155/2011/501483>.
- Petrini, L., Migliavacca, F., Massarotti, P., Schievano, S., Dubini, G. and Auricchio, F., 2005. “Computational studies of shape memory alloy behavior in biomedical applications”. *Journal of Biomechanical Engineering*, Vol. 127, No. 4, pp. 716–725. URL <https://doi.org/10.1115/1.1934203>.
- Pillai, D.S. and Rajasekar, N., 2018. “A comprehensive review on protection challenges and fault diagnosis in pv systems”. *Renewable and Sustainable Energy Reviews*, Vol. 91, pp. 18–40.
- Riad, A., Alhamany, A. and Benzohra, M., 2017. “The shape memory alloy actuator controlled by the sun’s radiation”. *Materials Research Express*, Vol. 4, No. 7, p. 075701.
- Riad, A., Benzohra, M., Mansouri, M. and Alhamany, A., 2019. “Design of sunflower system based on shape memory alloy actuator”. In *Lecture Notes in Real-Time Intelligent Systems*. Springer, pp. 45–54.
- Riad, A., Zohra, M.B., Alhamany, A. and Mansouri, M., 2020. “Bio-sun tracker engineering self-driven by thermo-mechanical actuator for photovoltaic solar systems”. *Case Studies in Thermal Engineering*, Vol. 21, p. 100709.
- Savi, M.A., 2015. “Nonlinear dynamics and chaos in shape memory alloy systems”. *International Journal of Non-Linear Mechanics*, Vol. 70. URL <https://doi.org/10.1016/j.ijnonlinmec.2014.06.001>.
- Savi, M.A., Pinto, F.H.I.P., Viola, F., de Paula, A. S. Bernardini, D., Litak, G. and Rega, G., 2012. “Using 0–1 test to diagnose chaos on shape memory alloy dynamical systems”. *International Journal of Solids and Structures*, pp. 32–42.
- Tanaka, K., Nishimura, F., Matsui, M., Tobushi, H. and Lin, P., 1986. “Phenomenological analysis of plateaus on stress-strain hysteresis in tiny shape memory alloy wires”. *Mechanics of Materials*, Vol. 24, No. 1, p. 1930. URL [https://doi.org/10.1016/0167-6636\(96\)00030-0](https://doi.org/10.1016/0167-6636(96)00030-0).

7. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this paper.