P-ISSN 2586-9000
E-ISSN 2586-9027
Homepage : *https://tci-thaijo.org/index.php/SciTechAsia* Science & Technology Asia
Vol.28 No.2 April - June 2023 Page: [174-182]
Original research article

Novel Approach to Solar Tracking Using 3D Printed Swiss Lever Escapement

Abul Kashem Tahmid Shahriar*, Sappinandana Akamphon

Department of Mechanical Engineering, Faculty of Engineering, Thammasat University, Pathum Thani 12120, Thailand

Received 10 November 2022; Received in revised form 6 February 2023
Accepted 10 April 2023; Available online 14 June 2023

ABSTRACT

A novel modular solar tracking system for use with in-situ materials is presented in this article. The tracker rotates at a fixed rate of 15° per hour using a 3D printed Swiss level escapement actuated by moment imbalance about the connecting pivot. Previous studies have shown that a fixed rotation system can increase efficiency by 20-30%, and experimental evaluation shows support for potentiality. The device can be made within 1,200 Thai Baht in total if primarily 3D printed, and can be assembled with relative ease by anyone using commonly available fasteners. The design is open-source, and possibilities for further development are discussed in the article.

Keywords: 3D printing; In-situ; Open hardware; Open source hardware; Solar tracking

1. Introduction

Reliable access to energy has been a key hindrance in the development progress of many least developed countries (LDCs). This energy scarcity is most prominent in rural locations where access to grid energy is not available. In response, LDCs have utilised off-grid solar energy to alleviate the impact of energy poverty. In such circumstances, the addition of a solar tracking system could further benefit such regions from their available solar panels as reviews have shown that single and dual axis trackers can increase the yearly energy yield of solar panels as much as 20% to 40% [1].

Yet despite the benefits, per Global Innovation Index's report on local market and business sophistication worldwide, accessibility of such systems remains out of reach in much of the developing world where they would be most impactful [2]. Moreover, tracking systems are not recommended for use in smaller or rural solar systems as the current price to performance ratio for available trackers is either not cost effective or involves complicated processes

*Corresponding author: tahmid.shahriar@gmail.com doi: xx.xxxxx/scitechasia.xxxx.xx

that require advanced knowledge or skills [3, 4]. Although Talavera et al. does note that one-axis tracking system can be cost-competitive in smaller arrays and that under some conditions a single axis tracker could prove to be better than a fixed system [3].

To mitigate this, Rizk et al. demonstrates the effectiveness of a stepper motor based simple, single axis tracker achieving upwards to 30% power increase [5]. While Fathabadi et al. designed an offline sensor-less system capable of two axis tracking with a tracking error of 0.43°[6]. To further develop the cost competitiveness, passive tracking systems try to reduce the cost incurred by electronic components used in active trackers. Clifford et al. used aluminium-steel bimetallic strips to develop and test a system capable of up to 23% efficiency increase in locations within 10° to 20° from the equator [7]. Similarly, Poulek demonstrated the possibilities of using Shape Memory Alloy as viable passive actuators in tracking systems [8]. Notable weaknesses in these system are their limitation on where they can be used effectively. One of the most simple and cost effective approaches has been the Sunsaluter, which uses weight differential to emulate the solar rotation [9]. Most notably, Jain et al. published a tracking system for solar concentrators based on a pendulum mechanism [10, 11]. Although novel designs, both systems are highly susceptible to external forces with the latter also being restricted to the fabrication limitations of 1978.

This presents a gap in the availability of low-cost tracking systems that can perform with reliability and can be manufactured locally with ease. Additionally, the lack of systems that do not require advanced theories such as electromechanical actuators or thermal properties of bi-metallic strips, excludes communities with limited education from utilizing the system without outside assistance. Access to such systems would reduce barriers to entry, increasing the efficiency of available solar panels and providing additional energy generation for communities relying on solar energy either fully or partially.

As such, this paper presents a novel mechanical solar tracking system that utilises a 3D printed hairspring and Swiss lever escapement, an elementary mechanism commonly found in mechanical watches and children's toys, to provide a fixed rate of rotation to any attached solar panel. It is designed to take advantage of the emerging commercialisation of 3D printing technology in developing countries to simplify the complicated manufacturing process of hairsprings [12], while also accommodating traditional fabrication methods for the other components. The design principal is explored in Section 2 and theoretical models of primary system components are thoroughly considered and evaluated in Section 2.1. The design is then prototyped and tested to verify its rate of rotation; results are discussed in Section 2.4 along with cost comparisons. Finally, conclusions are drawn up and possible future improvements are considered at the end.

The scope of this paper aims to demonstrate a working 3D printed, single axis system capable of rotating at a fixed rate using the Swiss lever escapement to regulate its speed. Theories and design criteria of the lever escapements as well as clockwork mechanisms are thoroughly researched and previously explained well in various published mediums [13–15].

The system adheres to open hardware guidelines [16, 17] and follows a simplicity metric defined by Krayner et al. to enhance accessibility, utilising minimal features in the CAD models of its components. [18].

2. Design and Methodology

The system design uses a simple reduction gear train and a Swiss lever escapement. The tracker is to be attached underneath a symmetrical frame with a west favoured offset to the center of gravity. This imbalance provides the torque required by the gear train to actuate. Simultaneously the Swiss lever escapement maintains a fixed oscillation with assistance from the hairspring and balance wheel, and governs the rate of rotation of the gear train at 15° per hour, an approximation of the average solar angular velocity at the equator [19] rounded up to the nearest integer. An isometric view of the tracking system's exploded schematic is shown in Fig. 1, along with the complete design documentation made available under a GNU General Public License (GPL) 3.0 as open source hardware on OSF [20].

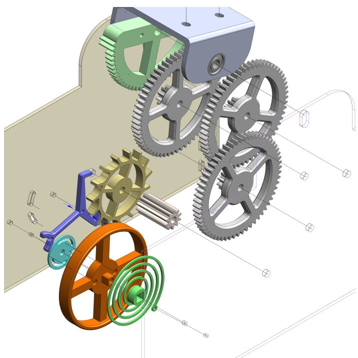

Fig. 1. Isometric view of complete design with transparent case highlighting the Swiss lever escapement and gear train.

The primary factors that set apart this design can be itemised as follows:

- The most important feature that maintains the tracker's reliability is the Swiss lever mechanism, which supports the gear train to keep a steady, fixed rate of rotation approximate to the sun's along the required axis.
- The system components are designed such that when printing via a commercial FFF 3D printer, material use is minimised without compromising strength.
- The design and theory simplicity lets the system be easily distributed and utilised in rural LDCs, lowering the skill barrier necessary to achieve efficiency gain through tracking.

2.1 Swiss lever escapement mechanism

For approximate tracking, the system would require to rotate the attached solar panel at a rate of 15° per hour. To achieve this, the complete design of the system can be divided into two recursive stages, the escapement mechanism and the gear train, working in tandem to maintain the rotation.

In the Swiss lever escapement, the Balance is the timekeeping core comprising a Balance Wheel and a Hairspring connected to a Pallet-fork which controls the gear train's rate of rotation based on the Balance's oscillation frequency. This frequency, f_{n0}, of the Balance is governed by the stiffness of the Hairspring, k_0, and the moment of inertia of the Balance Wheel, I, as shown in Eq. 2.1.

$$f_{n0} = \frac{1}{2\pi}\sqrt{\frac{k_0}{I}} \qquad (2.1)$$

$$k_0 = \frac{Eht^3}{12L} \qquad (2.2)$$

Generally, the required spring constant of the hairspring is found using Eq. 2.1 and is used to determine the spring's dimensions. But due to the manufacturing nature of 3D printing, this value shown to be unreliable and further experimental iteration, detailed in Section 2.3, was required to finalise the design. The balance was designed to maintain an approximate 4-5Hz oscillation frequency resulting in approximately 20 rotations per minute(rpm) of the 15 teeth escapement gear used to regulate the gear train.

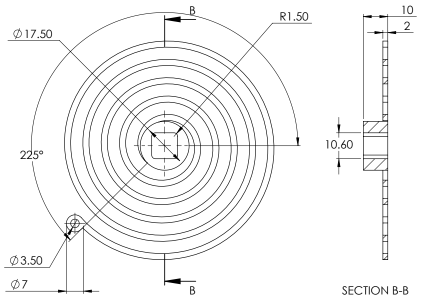

Fig. 2. A detailed diagram showing the dimensions of the 3D printed hairspring used in the prototype.

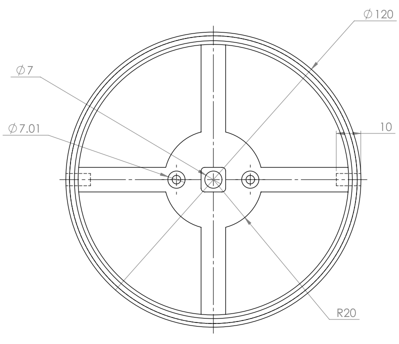

Fig. 3. The balance wheel is designed to allow for the oscillation frequency to be adjusted via 2 M5 screws of identical length on either side.

2.2 Gear train

To reduce the escapement gear's 20rpm speed to match the desired 15°/hr, the gear train was designed with a reduction ratio of 1:1447 over 4 stages of identical gear and pinion pairs to minimise complexity through gear homogeneity, while maintaining a manageable space footprint. The final gear, with 67 teeth, directly connects to the pivot attached to the center of mass of the solar panel mount.

The gear train reduces the rotation allowed by the escapement and matches it to the desired 15°/hr. Furthermore, to allow for craft production methods and raw material to be used, Module 2 gears were used in evaluation process.

2.3 Prototype manufacture

The lever escapement and gear train components were 3D printed using a stock Flashforge Finder 3D Printer with 1.75mm eSun Pla+ Grey and White filaments. The parts were sliced using Ultimaker Cura 4.8 slicer, at 0.18mm layer height and 20% infill density using a gyroid pattern. Detailed print information is made available on the OSF repository [20]. Additionally, the gear and pinion pairs were printed as a single component to reduce the likelihood of mechanical failures.

Material selection for ancillary components was determined by local availability. As such, the printed parts were assembled inside an acrylic case with generic fasteners and stainless steel rods as gear shaft. To reduce friction, ball bearings supported the gear shaft running through the pivot, thus connecting panel mounting rails to the tracking system via an aluminium flat bar. An optional constant force spring of 1kgf was used to provide a fixed actuation force for ease of simplifying the evaluation process.

2.4 Prototype evaluation

Single axis tracking systems have been previously measured and compared in various studies as discussed in Section 1; the prototype evaluation was streamlined to verify the rate of rotation of the system compared to that of the solar hour. To further verify the accuracy and capabilities of the proposed design, the aforementioned prototype had a 120W solar panel with a dimension of 680mm x 1020mm x 30mm mounted atop and evaluated in a fixed indoor environment at room temperature of 26°C. The constructed system was evaluated at the geographical location of (14.0696°N, 100.6050°E) and measured at a 15 minute interval using 2 hours of footage from a 120 frames per second camera capturing the angle of the solar panel relative to its starting position displayed on a digital protractor with a <0.10° accuracy, as shown in Fig. 4.

A pilot study estimating the possible energy output while accounting for any above error rate was also conducted using the horizontal irradiance value obtained with a Remote Solar Detector connected to a Prova 1011 PV Analyser. Simultaneously, the aforementioned solar panel was also connected to the analyser to measure the reference energy output of a panel fixed at a 14° south facing tilt. The estimations are calculated assuming an isotropic sky model and a surface albedo of 0.2.

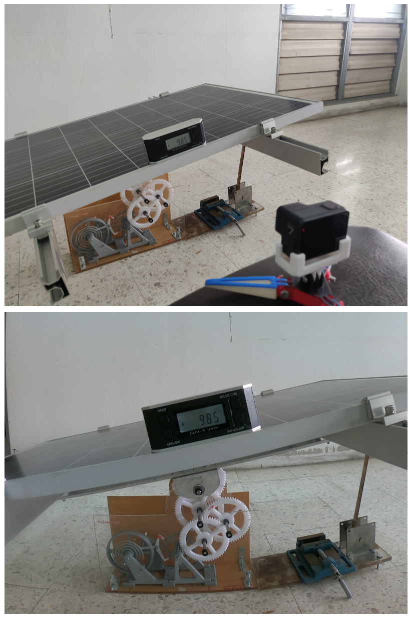

Fig. 4. Isometric view (up) and camera view (down) of the test setup for the presented system using a <0.10° accuracy digital protractor and a GoPro 7 Black set to 120 frames per second.

3. Results and Discussions

3.1 Performance

Table 1 shows the adjusted absolute angles of the tests conducted to measure the operational ability of the system. On average the system was able to maintain an acceptable rate of rotation with an average error of ±0.50 from the desired angle at each 15 minute interval, which could be attributed to backlash and periodic energy loss in the hairspring resulting in uneven oscillation period.

From the estimated energy output shown in Fig. 6, it is seen that under similar conditions, the proposed tracking system would be capable of performing at least 10% more efficiently when compared to a fixed system tilted at an angle equal to the local latitude.

Table 1. Change in panel angle measured at 15 min intervals for 2 hours in 4 tests, with solar hour angle for comparison.

Time (mins)	Angle (°)					
	Test 1	Test 2	Test 3	Test 4	Solar Hour	Avg Error
0	0	0	0	0	0	0
15	3.55	3.8	3.9	3.5	3.75	0.06
30	7.75	7.6	8.05	7.35	7.5	-0.19
45	11.95	11.45	12	11.55	11.25	-0.49
60	15.15	15.35	15.85	15.35	15	-0.43
75	18.35	19.2	19.65	18.7	18.75	-0.23
90	22.3	22.95	23.3	22.5	22.5	-0.26
105	26.45	26.5	27.05	26.5	26.25	-0.38
120	30.55	30.25	30.75	30.35	30	-0.48

3.2 Cost comparison

The presented system, fabricated with 3D printed components, has a cost of THB 1,200 or approximately USD 36, making it a low-cost option compared to other previously discussed designs. The cost could be further reduced if locally available

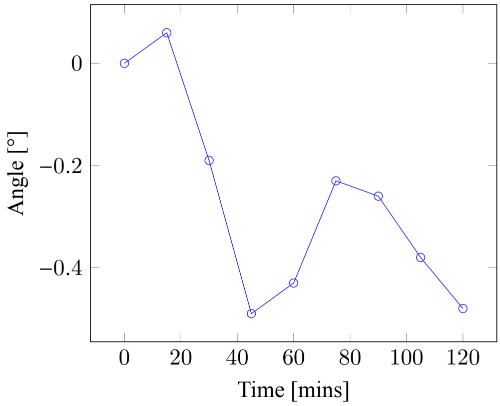

Fig. 5. The average absolute error remained within ±0.5 range of the target angles at each interval.

materials, such as wood, are used for some components, excluding the hairspring. In comparison, other systems such as the sensorless active tracker by Fathabadi, estimated to cost USD 190, and the passive tracking system by Poulek, costing upwards of USD 95 [6, 8]. The design presented in this paper is thus approximately one-third the cost of the cheapest alternative. Furthermore, the cost of Clifford and Eastwood's system is not provided in their work [7]. This makes the presented design a cost-effective solution for rural regions of LDCs that face both energy poverty and limited economic purchasing power.

4. Conclusions

To alleviate the adversity of energy poverty and improve efficiency of available solar panels in rural regions of least developed countries, this paper presents a novel and open-source design for a mechanical single axis solar tracker, utilising primarily 3D-printed components. The fabrication cost of the complete system via 3D printing was approximately THB 1,200 and was verified to effectively perform the role of a single axis tracker rotating at a fixed rate. The design features a fully mechanical system with zero electrical components, keeping the complexity and cost to a minimum. This approach also allows for easy deployment with minimal technical expertise, making it accessible to users in rural least developed countries who may lack the technical capability to operate and maintain commercial solar trackers. The absolute error on average showed only ±0.50 difference from the targeted value. Accounting for this error, the tracker is estimated to be able to perform approximately 10% more efficiently than a fixed solar panel tilted at an angle equal to the latitude of the test location.

As the system relies on 3D printed components that experiences continuous dynamic load, a longitudinal study investigating the durability and longevity of the system would be beneficial in further understanding the feasibility of additive manufacturing using PLA+, as well as the operational reliability of this material.

The current version of the system requires the user to reset the solar panel each day, which is a simple process that involves lifting the panel, disengaging it from the gear train, and returning it to its starting position. In addition, the conducted tests have shown the system to require minimal maintenance; however a real-world study over a longer period of time would give a clearer understanding of its reliability.

Such future work should also focus on testing the device's energy efficiency with the addition of a secondary seasonal tilt angle. Additionally, expanding the system to support a secondary axis under similar design philosophy, as well as developing an end of day return mechanism would also greatly improve its utility. Alternative materials for the hairspring such as wood, acrylic and spring steel would provide more versatility in material choice and further im-

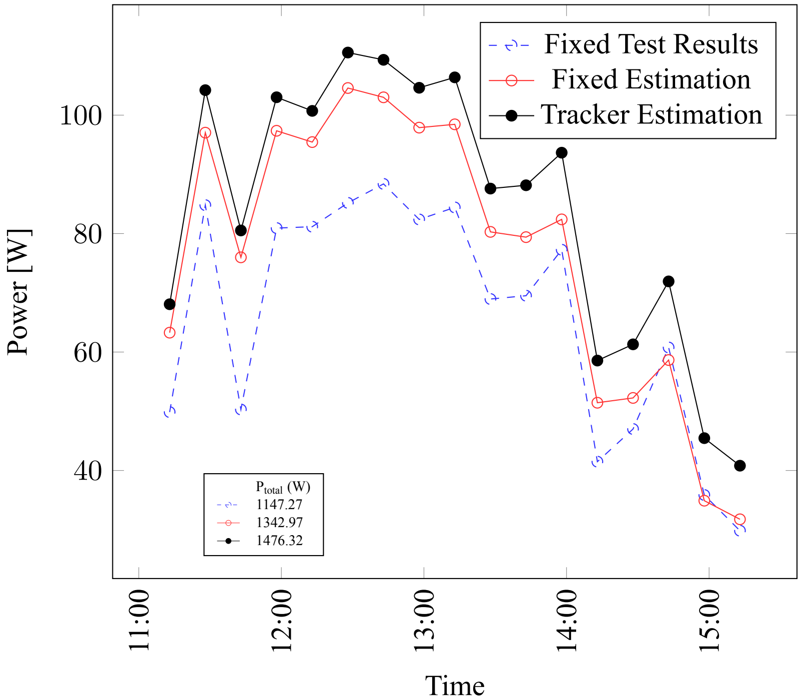

Fig. 6. Comparison of estimated maximum energy output at 14° south-facing tilt (red), and the proposed tracking system (black) calculated using reference power output of test solar panel at a fixed 14° south-facing tilt measured on June 10th, 2022 (blue)[21].

prove the system's design.

5. Acknowledgement

The authors would like to thank the Faculty of Engineering, Thammasat University for providing the necessary funds and support for this research.

References

[1] Mousazadeh H, Keyhani A, Javadi A, Mobli H, Abrinia K, Sharifi A. A review of principle and sun-tracking methods for maximizing solar systems output. Renewable and Sustainable Energy Reviews. 2009 Oct;13(8):1800–1818.

[2] Dutta S, Lanvin B, Wunsch-Vincent S, León LR. Global innovation index 2021 : Tracking innovation through the COVID-19 crisis. Global Innovation Index. 2021:xviii, 206 pages. Available from: `http://tind.wipo.int/record/44315` [cited 2022-10-10].

[3] Talavera DL, Muñoz-Cerón E, Ferrer-Rodríguez JP, Pérez-Higueras PJ. Assessment of cost-competitiveness and profitability of fixed and tracking photovoltaic systems: The case of five specific sites. Renewable Energy. 2019;134:902–913. Available from: `http://www.sciencedirect.com/science/article/pii/S0960148118314101` [cited 2022-10-08].

[4] Vermaak HJ. Techno-economic Analysis of Solar Tracking Systems in South Africa. Energy Procedia. 2014;61:2435–2438. International Conference on Applied Energy, ICAE2014. Available from: `https://www.sciencedirect.com/science/article/pii/S1876610214030471` [cited 2022-10-08].

[5] Rizk J, Chaiko Y. Solar Tracking System: More Efficient Use of Solar Panels. International Journal of Electrical and Computer Engineering. 2008;2(5):784 – 786. Available from: https://publications.waset.org/vol/17 [cited 2022-10-10].

[6] Fathabadi H. Novel high efficient offline sensorless dual-axis solar tracker for using in photovoltaic systems and solar concentrators. Renewable Energy. 2016;95:485 – 494. Available from: http://www.sciencedirect.com/science/article/pii/S0960148116303652.

[7] Clifford MJ, Eastwood D. Design of a novel passive solar tracker. Solar Energy. 2004 Sept;77(3):269–280.

[8] Poulek V. Testing the new solar tracker with shape memory alloy actors. In: Proceedings of 1994 IEEE 1st World Conference on Photovoltaic Energy Conversion - WCPEC (A Joint Conference of PVSC, PVSEC and PSEC). vol. 1. IEEE; 2002. p. 1131–1133.

[9] SunSaluter. SunSaluter [Internet]. Sunsaluter; 2017 [cited 2022 Oct 10]. Available from: http://www.sunsaluter.com/.

[10] Gupta KC, Mirakhur RK, Sathe AP. A SIMPLE SOLAR TRACKING SYSTEM. In: de Winter F, Cox M, editors. Sun: Mankind's Future Source of Energy. Pergamon; 1978. p. 1336–1340. Available from: https://www.sciencedirect.com/science/article/pii/B9781483284071502622.

[11] Gupta KC, Jain PK, Borania CH, Sathe AP. A clockwork driven one axis tracking system. In: Proceedings of the NSEC; 1979. p. 114–117.

[12] Ishengoma FR, Mtaho AB. 3D Printing: Developing Countries Perspectives. International Journal of Computer Applications. 2014 10;104:30–34. Available from: http://research.ijcaonline.org/volume104/number11/pxc3899329.pdf.

[13] Grossmann M. Prize Essay on the Construction of a Simple But Mechanically Perfect Watch. Watkins, Richard; 2002. OCLC: 225996017.

[14] Glasgow D. Watch and Clock Making. Cassell; 1885.

[15] Du R, Xie L. The Mechanics of Mechanical Watches and Clocks. vol. 21. Springer Berlin Heidelberg; 2013. DOI: 10.1007/978-3-642-29308-5. Available from: http://link.springer.com/10.1007/978-3-642-29308-5_2 [cited 2018-08-10].

[16] Gibb A. Building Open Source Hardware: DIY Manufacturing for Hackers and Makers. Addison-Wesley Professional; 2014.

[17] Oberloier S, Pearce JM. General Design Procedure for Free and Open-Source Hardware for Scientific Equipment. Designs. 2018;2(1). Available from: https://www.mdpi.com/2411-9660/2/1/2.

[18] Krayner N, Katz R. Measuring Simplicity in Mechanical Design. Procedia Manufacturing. 2018 Jan;21:878–889. Available from: http://www.sciencedirect.com/science/article/pii/S2351978918302361.

[19] Snodgrass HB, Ulrich RK. Rotation of Doppler features in the solar photosphere. The Astrophysical Journal. 1990;351. Available from: https://articles.adsabs.harvard.edu/pdf/1990ApJ...351..309S [cited 2022-10-10].

[20] Shahriar AKT. Clockwork Solar Tracker [Internet]. OSF; 2022 [cited 2022 Oct 08]. Available from: https:

//osf.io/8q7pn/?view_only=1209989f1e75411facf10173b11f5621.

[21] Shahriar AKT. Design and Development of Mechanical Solar Tracker [Master's Thesis]. Thammasat University. Pathum Thani, Thailand; 2022.