Design, Implementation, and Experimental Validation of a Low-Cost Autonomous Coelostat System for High-Stability White-Light Solar Imaging

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Abstract

This research work presents the design, implementation, and experimental testing of a low-cost autonomous coelostat. The coelostat uses a two-mirror system to keep the reflected sunbeam in a fixed position, while compensating for the Sun's apparent motion in the sky. The coelostat control system is realized using a dsPIC33FJ128GP802 microcontroller in combination with a Raspberry Pi computer-based user interface, implementing an open-loop predictive tracking algorithm based on the NREL Solar Position Algorithm (SPA). With the introduction of the proposed design, there is no need for moving telescopes or optical sensors for feedback, therefore, the mechanical complexity and alignment of the optical components can be reduced significantly. A prototype of the coelostat with three gear-reduced axes of stepper motors (1:410) was developed and tested outdoors. A maximum beam displacement of less than 1 mm at a 3 m projection distance was observed, resulting in a tracking accuracy of 0.5–1.0 arcmin. These results prove that the proposed coelostat is compact, reliable, and affordable instrument for solar white light imaging and spectroscopy as well as educational applications.

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1. Introduction

Solar white-light imagery is mainly used in observing photospheric phenomena like sunspots, faculae, and granules. Monitoring the above photospheric phenomena plays an important role in studying solar activity, long-term solar variability, and educating the general public [1], [2]. Monitoring the above photospheric phenomena plays an important role in observing the solar activity and space weather, as well as educating the general public.

Effective solar imagery needs precise correction for earth's rotation in order to keep the solar image stable for a long period of time. Such setups are relatively expensive, need periodic adjustment, and might cause mechanical vibrations leading to poor stability of the images during long-term observations [3].

A coelostat provides a convenient and efficient way of reflecting the sun's rays onto an immovable optical axis by using two plane mirrors. As the mirrors move but the telescope and other instruments remain in place, the entire optical system is simpler and more stable and easily combinable with other equipment such as imaging and spectrographic devices [4], [5]. This architecture is particularly attractive for compact observatories, educational facilities, and public outreach installations where reliability, ease of operation, and low maintenance are important design considerations.

The recent progress in embedded controls, embedded instrumentation and autonomous tracking algorithms has facilitated the realization of compact solar tracking systems. Besides, some recent works have successfully demonstrated new and better prediction and sensorless algorithms that achieve reliable tracking without the need for optical feedback sensors [6], [7]. In particular, the SPA of NREL is able to predict with great accuracy the position of the sun using astronomical calculations. This together with precise gear-reduced stepper motors allows the prediction-based tracking of the sun continuously in an open-loop manner without any optical feedback sensors.

However, despite all these advances, there have been only few studies regarding compact autonomous coelostats for presenting the sustained white light imaging of the Sun. Most studies are about photovoltaic trackers or larger-scale heliostats and solar telescopes that are too costly for use in compact learning environments. Also, there has not been enough testing for stability of the beam over sustained periods of time.

This research study reports on the development of a low cost autonomous two-mirror coelostat system for highly stable solar white-light imaging. The system incorporates the use of three separately controlled, gear-reduced stepper motors actuated by a dsPIC33FJ128GP802 digital signal controller. In addition, a Raspberry Pi graphical user interface is used to monitor and control in real-time the motors of the proposed system and also to display live observations of the sun and its globally referenced images. Sun tracking is performed using an in-built implementation of NREL's SPA algorithm, which allows the use of open loop predictive control with no computational errors. Experimental testing was conducted under clear sky conditions at the Kodaikanal Solar Observatory. Measurement of beam displacements during long observational time intervals reveals a sub-millimeter beam stability at a projection distance of 3 meters which corresponds to an angular tracking accuracy of 0.5-1.0 arc-minutes. Therefore, the proposed approach demonstrates reliable long-term sun tracking while being low cost and robust in nature.

2. System Design and Methodology

The proposed autonomous coelostat system enables constant and stable imaging of the Sun using white light, whereby the constant output optical beam is retained despite the apparent diurnal motion of the Sun. In contrast to traditional equatorial and altazimuth telescope mounting, where the whole optical system has to keep moving, the proposed solar tracker retains the position of the Sun through orientation control of two plane mirrors. Consequently, the telescope, imaging device, projection system, and additional optical systems can be held still for the whole duration of observation.

The architecture of the designed system is depicted in Figure 1. The design involves four parts: an opto-mechanical coelostat device, a motion control module, a computer for supervision, and a graphical user interface (GUI). The motion control in real time is implemented using dsPIC33FJ128GP802 digital signal controller, whereas the supervision is carried out by Raspberry Pi, which involves human-computer interaction and visualization.

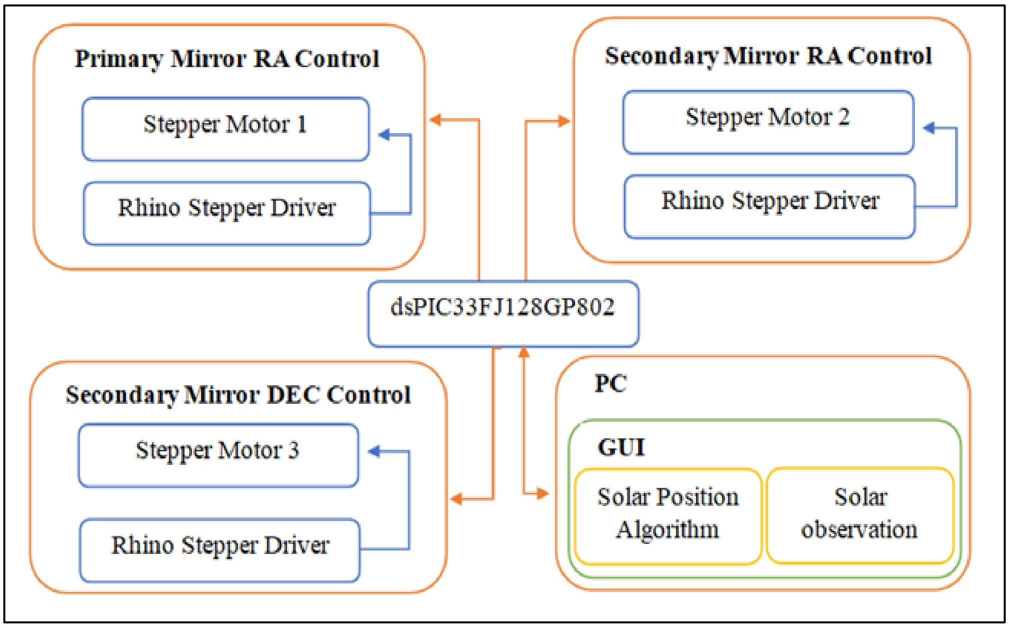

Figure 1. Block diagram of the autonomous coelostat system

Three stepper motors are powered separately by the embedded controller using Rhino motor drivers. The stepper motors control the rotation of the primary mirror and the rotation of two perpendicular axes of the secondary mirror and enable the degrees of freedom needed to keep the reflected beam stationary [10]. The motor drivers provide regulated current pulses, whereas the gear reduction systems enable the angle resolution needed for accurate positioning of the mirrors. A serial connection allows communication between the Raspberry Pi and the embedded controller for transmitting commands and system data.

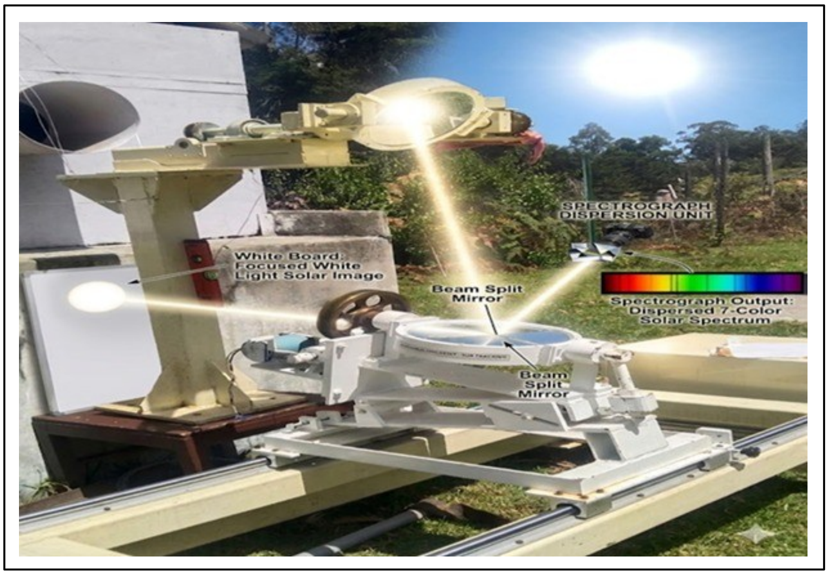

Figure 2. Optical configuration of the proposed coelostat.

The optical configuration of the designed coelostat is shown in Figure 2. Solar radiation enters the system and is reflected from the main mirror (M1), which corrects the apparent movement of the Sun. Then the light beam is directed by the secondary mirror (M2) along a certain optical axis. All optics except the mirrors are not moving when the device tracks the Sun, which reduces the level of structural vibrations and allows avoiding the alignment of the telescope multiple times.

There is a beam splitter located in the optical path, dividing the reflected beam into two separate beams. One of the beams produces the image of the sun using the white light on the projection screen, which is used in education and public relations, while the other produces a beam directed at a diffraction grating towards a stationary telescope used in spectroscopy. Thus, this configuration allows performing imaging and spectral measurements simultaneously, without any extra mechanisms for moving the system. The positioning of the mirrors depends on the law of reflection, where the normal line to the mirror divides the angles of incidence and reflection.

Apparent Sun Positioning can be determined through the NREL's SPA, which gives a very accurate measurement of solar azimuth and Zenith angles considering corrections for astronomical and atmospheric effects. The positioning algorithm uses the geographical coordinates of the observer, the date and time, and calculates the instantaneous sun position, which is then used to determine the necessary mirror positioning for the dual mirrors coelostat geometry. Due to the high level of computational accuracy of the SPA, tracking effectiveness is mainly limited by the mechanical properties of the positioning system.

The coelostat uses an open-loop predictive tracking approach [8] wherein the mirror angles are updated based on the computed solar angles without any optical feedback system. At the time of functioning, the computer determines the position of the Sun and sends out commands for adjusting the mirrors based on the mirror angle values. The motor steps are determined based on the mechanical transmission ratio of the drive mechanisms used. The controller produces synchronized pulse train to move the mirrors and thereby corrects the solar motion. The angular motion of the Sun being roughly constant at 〘15〙 ^∘ h^(-1), minor adjustments can be made continuously to ensure that the beam is steered. A ratio of 1:410 ensures that there are enough degrees of freedom to adjust without any errors due to the tracking process.

3. Mathematical Modeling

The apparent position of the Sun is determined using the National Renewable Energy Laboratory (NREL) Solar Position Algorithm (SPA). The embedded implementation computes the solar hour angle, solar declination, and solar zenith angle from the geographical location, date, and time. These parameters are subsequently transformed into the required mirror orientations to maintain a stationary reflected beam.

The solar hour angle is expressed as

$$H = 15(LST - 12), \tag{1}$$

where LST is the local solar time expressed in hours. The solar declination angle is approximated by

$$\delta = 23.45^{\circ}\sin\left[\frac{360}{365}(d - 81)\right] \tag{2}$$

where d denotes the day of the year.

The apparent position of the Sun is represented by the solar zenith angle (θ_z) and solar azimuth angle (γ_s), which are computed using the NREL's SPA. The solar zenith angle is given by

$$\cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos H \tag{3}$$

where ϕ is the observer's latitude, δ is the solar declination angle, and H is the hour angle. The corresponding solar azimuth angle is obtained from

$$\gamma_s = \tan^{-1}\left(\frac{\sin H}{\cos H\sin\phi - \tan\delta\cos\phi}\right), \tag{4}$$

The solar zenith and azimuth angles obtained from the SPA provide the fundamental inputs for determining the required mirror orientations and have been widely adopted in precision solar tracking applications [9].

For the two-mirror coelostat, the orientation of each mirror is determined according to the law of reflection, where the mirror normal bisects the angle between the incident and reflected rays. Let s denote the unit vector corresponding to the incident solar ray and o denote the desired outgoing beam directed along the fixed telescope axis. The mirror normal vector is therefore expressed as

$$\mathrm{n} = \frac{\mathrm{s} + \mathrm{o}}{\|\mathrm{s} + \mathrm{o}\|}, \tag{5}$$

where n is the unit normal vector of the reflecting mirror. This vector formulation enables direct computation of the mirror orientations required to maintain a stationary reflected beam as the solar position changes throughout the day.

The tracking accuracy of the system is evaluated by relating the angular pointing error of the mirrors to the displacement of the projected solar image. For a projection screen located at a distance L, the beam displacement is

$$\Delta x = L \cdot \tan(2\Delta\theta) \approx 2\mathrm{L}\Delta\theta \tag{6}$$

where $\Delta\theta$ represents the mirror pointing error. Since the tracking errors are very small, the small-angle approximation can be applied,

$$\Delta x \approx 2L\Delta\theta. \tag{7}$$

For a stepper motor having an output angular resolution θ_{step}, the worst-case quantization error is approximated as

$$\Delta\theta_{\mathrm{step}} = \frac{\theta_{\mathrm{step}}}{2}, \tag{8}$$

which represents the maximum positioning uncertainty associated with one motor step.

The angular positioning capability of the coelostat is determined by the stepper motor resolution and the mechanical gear reduction. The prototype employs stepper motors with a fundamental step angle of 1.8° and a gear reduction ratio of 1:410. The resulting mechanical resolution is

$$\theta_r = \frac{1.8°}{410} = 0.00439°, \tag{9}$$

which corresponds to

$$\theta_r = 0.263 \text{ arcmin}. \tag{10}$$

Converting to arcminutes:

$$0.00439 \times 60 = 0.2634 \text{ arcmin} \tag{11}$$

The worst-case quantization error is half-step:

$$\Delta\theta_{\mathrm{step}} = \frac{0.00439°}{2} \times 60 = 0.1317 \text{ arcmin} \tag{12}$$

Considering that the optical correction is shared by the two-mirror configuration, the effective tracking resolution of the system is approximately 0.13 arcmin, which is substantially smaller than the apparent solar motion of approximately $15^{\circ}\mathrm{h}^{-1}$. Consequently, the system is capable of producing smooth incremental mirror adjustments while maintaining a stable reflected beam during continuous operation.

4. Experimental Setup

The concept of an autonomous coelostat was built and tested experimentally in outdoor operational modes to confirm its ability to perform tracking and provide optical stabilization and autonomy in operation. As seen in Figure 3, the design includes the optical assembly of two mirrors, electronic control devices, the motorized mechanism for motion and the controlling computer in one compact unit for white-light solar observations. The mechanics were designed to ensure sufficient rigidity to minimize vibrations.

Figure 3. Stepper motor with 1:410 gear reduction assembly used in the coelostat.

The experiments have been carried out at the Kodaikanal Solar Observatory, Tamil Nadu, India, where the geographic location of the observatory has served as an input for the NREL's SPA. Before conducting the test, the optical components have been aligned so that the output beam would be established along the axis of the telescope. Once the alignment was done, the system ran independently.

Figure 4. Installed coelostat system in museum environment.

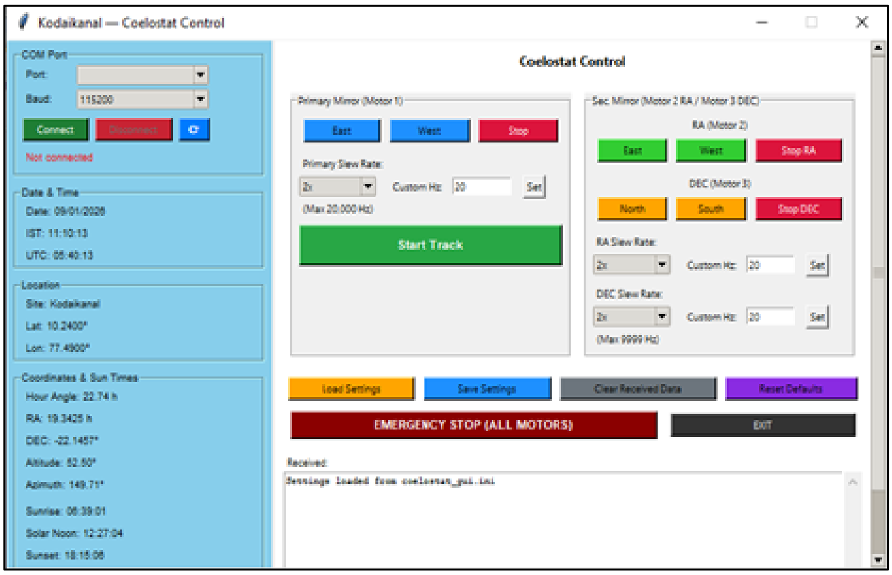

Figure 5. Graphical user interface for coelostat control.

As illustrated in Figure.5, tracking was monitored using a graphical user interface (GUI) specially designed and implemented on the Raspberry Pi platform. This GUI not only shows the position of the sun, orientation of the mirrors, state of the motor, and system mode but also provides means of manual positioning, tracking, and emergency control. In the meantime, the GUI allows monitoring of the real-time projection of the sun's image during operation.

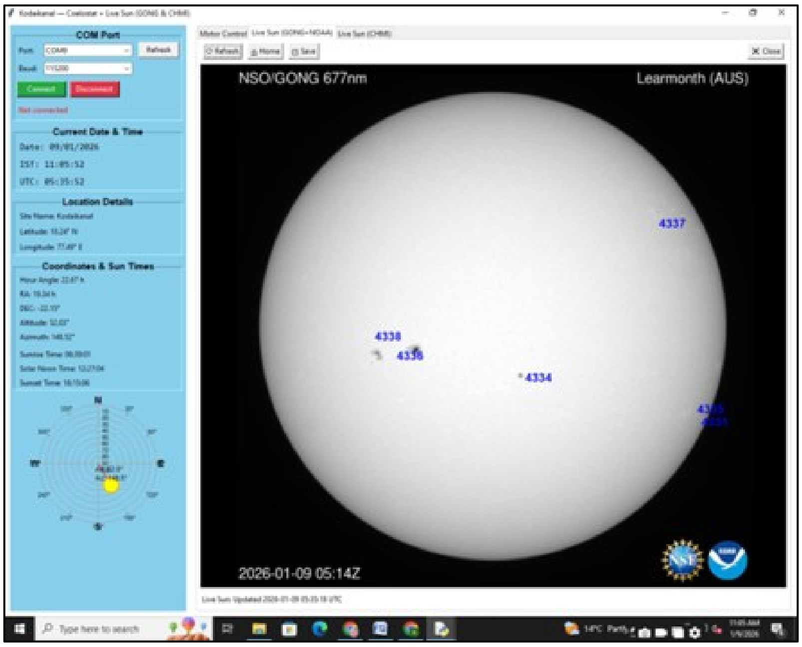

Figure 6. Reference solar image with Active Region labelling.

Figure 7. Experimental projection setup.

The experimental arrangements are illustrated in Figure 6 and Figure 7. The reflected solar beam was directed at a stationary screen situated roughly 3 m away from the optical components. The position of the projected solar image was tracked using a reference grid. As both the screen and the telescope did not move during the experiments, the movement of the projected solar image reflected the total tracking error of the coelostat.

The prototype was tested continuously under clear sky conditions to analyze the system's stability and ability to track autonomously. During all the experiments, the controller inside the device adjusted the mirror positions based on the coordinates calculated by the program, while the supervisor computer monitored the work of the system. In addition to measuring the displacement of the beam, the experiment included a qualitative evaluation of the optical system's work.

5. Results and Discussion

Experimentation was carried out to determine the tracking precision, beam stability, and autonomy of the developed autonomous coelostat. The autonomous coelostat was operated for a long period of time after the completion of the initial optical calibration stage where the controller updates the positions of the mirrors according to the coordinates of the sun calculated by the NREL's SPA. The solar beam reflected off the mirrors remained aligned to the optical axis throughout the entire experiment without any need for manual adjustment.

Quantitative results related to the performance of the proposed system are presented in Table 1. According to the measurements carried out experimentally, the designed coelostat provided stable solar tracking, with the maximum displacement of the beam being less than 1 mm at a projection distance of about 3 m, which corresponds to tracking accuracy of 0.5–1.0 arcmin.

Table 1. Tracking performance summary

Parameter	Value
Projection distance	3 m
Beam displacement	<1 mm
RMS stability	0.5–1.0 arcmin
Motor step angle	1.8°
Gear reduction ratio	1:410
Effective motor resolution	0.13 arcmin

As shown in Table 1, the measured value of the beam displacement was well within the acceptable threshold for stable projection of solar images. The discrepancy between the theoretical resolution (0.13 arcmin) and the measured tracking accuracy (0.5–1.0 arcmin) is mainly due to real mechanical restrictions such as gearbox backlash, bearing play, flexibility of the structure, and mirror misalignment. The accuracy of computations in the SPA algorithm being far superior to the mechanical resolution of the prototype, the total pointing error depends mainly on mechanical features of the tracker.

Figure 5 and 6 provide examples of typical white light images of the sun obtained using the tracker during the autonomous mode operation. The projected solar image did not exhibit any wobble or distortion during the tracking phase. Likewise, the graphical user interface provided in Figure 4 consistently provided the calculated positions of the sun and mirror angles throughout the entire process, ensuring that the connection between the supervisor computer and embedded control computer was continuous.

One of the distinguishing features of the proposed system design is that the only moving parts will be the two reflecting mirrors used to track the sun, and the telescope, screen, and other optical equipment will not move at all. The advantage of such an arrangement is that it reduces the mechanical complexity, avoids the need for constant re-alignment of optics, and allows other instruments such as spectroscopes to be easily incorporated into the system.

6. Conclusion

The development, implementation, and testing of an efficient and cost-effective autonomous coelostat have been successfully accomplished for perofming continuous white-light imaging of the Sun. The proposed approach utilizes an optical setup with two mirrors along with the embedded control algorithm that employs the NREL's SPA and precise gearing stepper motor drives to keep the reflected beam fixed. The experimental analysis shows stable autonomous tracking with the maximum displacement of the beam not exceeding 1 mm at the projection distance of 3 m, corresponding to the tracking accuracy of about 0.5-1.0 arcmin. The good correspondence between analytical model and the experimental results indicates the efficiency of the proposed concept, showing that any remaining tracking error is caused mainly by the mechanical imperfections rather than computation accuracy. The stationary optical configuration makes instrument installation much easier. Due to its simplicity, reliability, and cost-effectiveness, the developed coelostat can be successfully applied in solar observatories and educational establishments, as well as in public outreach.

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