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Enhanced Heliotracking Control for Box-Type Solar Cookers: Adaptable to Various Locations*

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Abstract— **Box-type solar cookers are portable renewable cooking devices that can replace polluting fuels in small households and remote areas, providing health benefits for women while also benefiting the environment. However, a long cooking time hinders widespread adoption. While researchers have investigated many approaches to shorten cooking time including passive tracking mechanisms, active tracking has been mostly overlooked. The aim is to introduce a new two-axis tracking mechanism for box-type solar cookers (BTSC) and design a control strategy to automatically detect and follow the sun's position at any location. The effectiveness of tracking is evaluated based on an optimal orientation ratio, the first figure of merit (F_1), the second figure of merit (F_2), and cooking power. Suitable tracking intervals for maximizing energy output are determined by balancing actuator energy consumption with discrete tracking step which demonstrate that active cooker tracking is feasible and yields well.**

I. INTRODUCTION

Daily food preparation is a widespread practice requiring considerable energy. In developing countries, fuels like wood, charcoal, dung, kerosene, and agricultural waste are still widely used, contributing to deforestation and environmental pollution and adversely affecting health. Among alternative renewable sources, solar cookers that work on solar energy stand out as cost-effective, environmentally friendly, and low-maintenance devices [1]. They are specifically designed for cooking food by boiling method and can operate at a maximum of 100°C [2]. The proposed cooker can also warm food and beverages, and be utilized for milk or water pasteurization. Solar cookers come in three varieties: box-type solar cookers (BTSC), parabolic-type solar cookers (PTSC), and panel solar cookers (PSC). This study focuses on a BTSC due to compact size, practicality, straightforward design, and affordability as desired in remote areas.

Existing models of BTSC are less popular due to higher cooking time, fixed time range for cooking (working only in day time), less awareness, etc. The primary limitation is the lack of a tracking mechanism for efficient sunlight capture. Manual tracking necessitates standing in the sunlight during the operation, a principal drawback of existing models of BTSCs. Different techniques are applied to make the solar cooker user-friendly, fast-cooking, maximum thermal efficiency, lighter, smaller, and economical. Several studies indicate that strategic and integrated tracking can reduce cooking time.

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The active tracking mechanisms for small box-type solar cookers are not found in the literature studied. However, the last ten years of literature sources have identified four tracking methods: manual control, weight-driven with gravity, pendulum-driven with gravity, the utilization of external domestic electric power, and external PV panels.

This study focuses on an active tracking mechanism. The spatial footprint of reflected rays is larger in continuous tracking than in discrete tracking. However, active continuous tracking requires greater actuator energy consumption, while passive discrete tracking does not achieve optimal reflected rays. Hence active discrete tracking with battery-powered or using grid electric-powered tracking actuators [**?**], is chosen for this study. This study sets the following objectives to create an efficient cooker tracking system: (i) to analyze the effectiveness of tracking through optimum orientation ratio (ii) to check the feasibility of half-hour discrete steps of tracking to optimize radiations; (iii) to calculate thermal performance with first figure of merit and second figure of merit. (iv) to calculate the consumption of electromechanical actuators and the net yield of solar irradiation. The solar data helps assess the performance of the newly created solar cooker at Ahmedabad, Gujarat, India. Two different cooker configurations- namely, configuration 1 (C_1) with a fixed reflector angle and configuration 2 (C_2) with a tracking reflector and tracking base set at an optimal angle.

II. CONSTRUCTION OF NEW DESIGN OF COOKER

A proposed design of BTSC is shown in Figure 1 (a), it comprises an outer box, an inner box (absorber tray), a sole glass cover, a thermal insulating layer, a reflector, cooking vessels, and a thermoelectric generator (TEG)-mounted heat sink. For this project, a conceptual design is crafted using Autodesk Fusion 360 with the specified dimensions of the inner box being 400×400×125, the outer box is 460×460×160, and the overall body extreme dimension is 616×502×175 that of the (L×W×H). All sizes are in mm, and L, W, and H stand for length, width, and height, respectively. According to IS 13429 Part-1 (Second Revision in 2020) standards, a thickness of 0.5 mm for aluminum is recommended, resulting in a weight of 15.45 kg. To cater to users in remote areas, hilly communities, and adventure enthusiasts, the tracking actuators are integrated within the cooker assembly to ensure compactness and facilitate easy transportation and installation. The absorber is constructed from aluminum and is coated with black paint for maximum heating. It functions to absorb solar radiation and transfer heat to the cooking utensils made of aluminum due to the

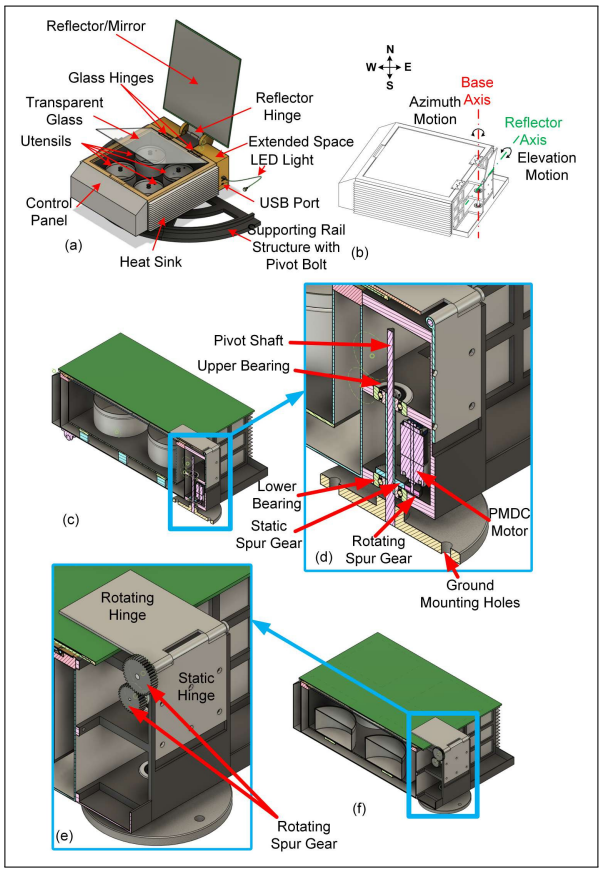


Fig. 1. Solar cooker tracking angles: (a) direction of direct and reflected rays; (b) various angles

thermal efficiency of an aluminum cooking vessel, which achieved 15.4% more than stainless steel [4]. A glass lid seals the absorber tray. Thermal insulating material fills the space between the outer box and the inner tray, extending to the tray's bottom, to minimize heat loss. The reflector is employed in a solar cooker to enhance radiation over the aperture area (A_a). When sunlight strikes the reflector, it reflects and penetrates the inner tray through the glass lid. The selected drive system must satisfy two primary requirements: (i) ensuring that the cooker base remains stationary while stirring the food, and (ii) maintaining the optimal angle of the cooker base and reflector despite wind gusts or stirring. A power-off load latching system with a worm gearbox is adopted to meet these criteria. Figure 1 (b) illustrates the design of the tracking axis, with the horizontal axis used for rotating the reflector and the vertical axis for rotating the cooker base. A full load of load motor driving torque is calculated using Newton's law of motion. The effective necessary torque is the summation of static and dynamic torque to overcome the cooker's friction losses, gravity, and load. The calculated required torque of the base joint and reflector joint is 6.18 Nm and 6.55 Nm respectively. Figure 1(c to f) illustrates the deployment of the base and reflector actuators in the rear part of the cooker. In Figure 1 (c) and (f) the cut section of the cooker illustrates the base and reflector actuator deployment respectively. Figure 1 (d) enlarged view of the base actuator comprises PMDC motor with worm gear[**?**], pivot shaft, ball bearing, spur gear, and ground mounting plate. The ground mounting plate is fixed on the ground and PMDC is fixed on the extended chassis. The cooker base rotates when the motor is excited through a rotating gear and static gear which is fixed on the pivot shaft. Figure 1 (e) enlarged view of reflector actuator comprises static hinge plate, rotating hinged plate, second PMDC motor with worm gearbox, and to transmit motor drive two rotating spur gear. In this mechanism motor and static hinge plate are fixed on the extended chassis and the rotating hinge plate is free to rotate and a mirror is attached to it.

III. Analytics of Tracking Angle

A single reflector with proper tracking collects direct and reflected rays over the aperture area of the cooker as shown in Figure 2 (a) and, subsequently, the cooker's temperature, contingent upon the optimal alignment of the cooker [3]. A procedure is delineated to determine a reflector and an

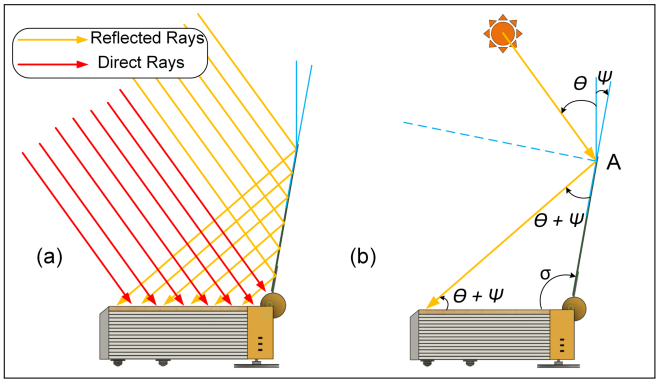


Fig. 2. Solar cooker tracking angles: (a) direction of direct and reflected rays; (b) various angles

orientation angle, both influenced by the sun's zenith angle and the azimuth angle. The reflector's height equals the length of its horizontal active area of the aperture. The zenith angle varies according to the solar elevation angle in the sky. The optimum reflector angle depends on the zenith angle, increasing the incident rays; consequently, reflected rays increase, and intercepting rays also increase over the active area of the solar cooker—the small movement of the reflector w.r.t. the vertical axis (ψ) as shown in Figure 2(b):

$$\psi = \frac{\pi - (\frac{\pi}{2} + 2\theta)}{3}. \tag{1}$$

The equation for determining the optimal reflector angle relative to the horizontal plane is derived with the help of basic trigonometry and the law of reflectivity 2. The basic reflection principles were used for calculating the angle for collecting the maximum amount of sun rays

$$\sigma_{opt} = \frac{\pi}{2} + (\psi). \tag{2}$$

The cooker base movement is essential to catch the reflected rays over the aperture area (A_a) and depends on the solar azimuth angle (γ_s). Therefore, the optimum orientation of the cooker's base angle (δ_{opt}) is the azimuth angle itself.

The south axis convention is used to measure azimuth angle, so the center line of the south-facing cooker becomes the reference, the east part becomes negative, and the west part a positive angle (3).

$$\xi_{opt} = \begin{cases} -\gamma_s, & \text{for due east,} \\ 0, & \text{for culmination,} \\ \gamma_s, & \text{for due west.} \end{cases} \quad (3)$$

The maximum reflector angles are determined through (2), but for the maximum base angles, (3) is valid up to the $E-W$ line. Above that line, the base angle is added by the correction factor $\varepsilon = \mp\,\pi \pm |\delta|$, before noon hours ε_m=$-\pi+\delta$. and the afternoon hours, ε_e=$\pi-\delta$. The maximum range of

TABLE I

MAXIMUM BASE AND REFLECTOR ANGLE RANGE AT THE SITE.

Year Day	Sunrise (hh:mm)	Culmination (hh:mm)	Sunset (hh:mm)	σ_{Max} (deg.)	ξ_{Max} (deg.)
299	06:40	12:23	18:06	95.64	$\pm$ 102.60

base and reflector angles helps determine the position of the dead stopper for the reflector, the base structure's peripheral length, and the actuators' maximum energy consumption.

IV. EXPERIMENT AND CONTROL ALGORITHM

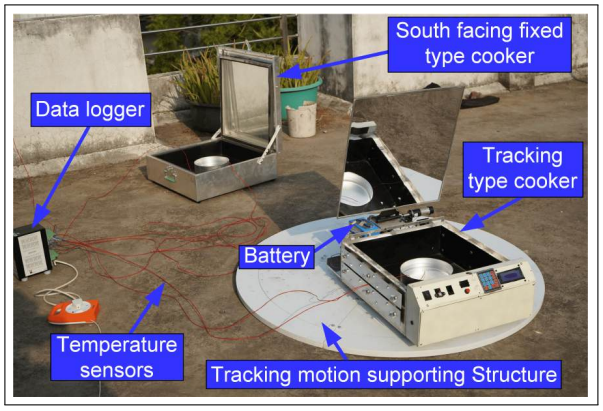


Fig. 3. Solar cooker tracking control block diagram: (a) onboard calculator; (b) closed loop diagram

The PMDC equivalent motor parameters are obtained using the online calculator provided by the Faulhaber company. To ensure smooth motion position control loop and

TABLE II

SELECTED PMDC MOTOR EQUIVALENT PARAMETERS

Name of Parameter	Base Motor	Reflector Motor
Armature resistance (R_a)	210 $m\Omega$	663 $m\Omega$
Armature inductance (L_a)	0.06 mH	0.18 mH
Torque constant K_T	31.82 mNm/A	39.8 mNm/A
Speed constant K_N	300 min^{-1}/V	240 min^{-1}/V
Rotor inertia (J_R)	164 $g\ cm^2$	120 $g\ cm^2$
No load speed (N_0)	5400 min^{-1}	5800 min^{-1}

current control loop in the controller tuned and corresponding controller gain are shown in Table III.

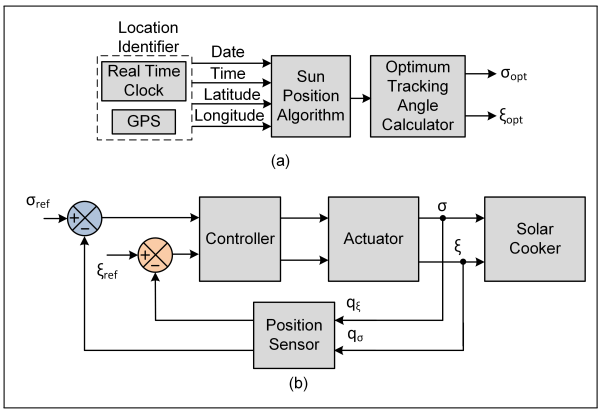


Fig. 4. Solar cooker tracking angles: (a) direction of direct and reflected rays; (b) various angles

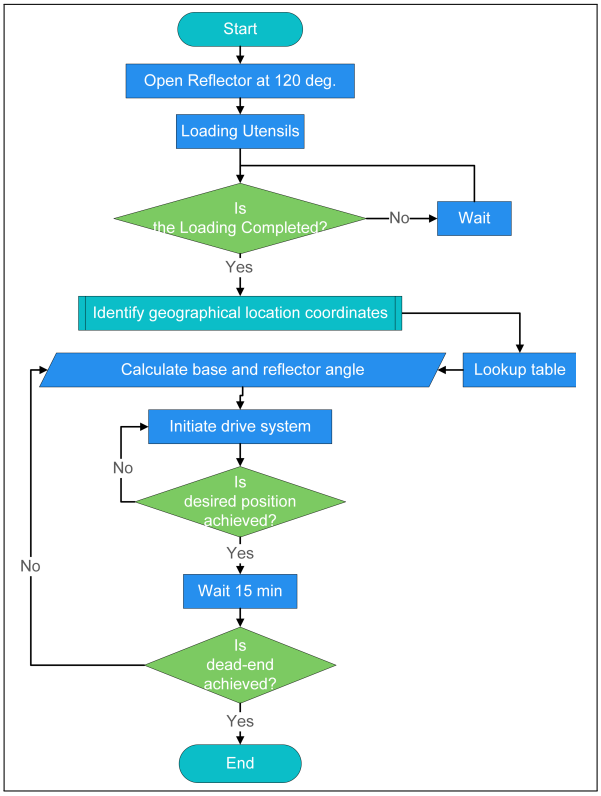


Fig. 5. Control flow chart

V. RESULTS AND DISCUSSION

On October 25, the selected site provides a useful cooking period of 9 hours and 30 minutes for proposed configuration 2, from 8:00 AM to 5:30 PM considering average irradiance. Cooking is effective when irradiance exceeds 500 W/m^2 [5]. The purpose of choosing this date is to determine the maximum consumption and yield values for the year. Table I compares the instantaneous simulated maximum irradiance, average irradiance, and average irradiance power for cooker C_1 and C_2. The irradiance power is calculated at each discrete time by multiplying the average solar irradiance by the aperture area (A_a). The tracking angle is validated using Figure 1, which shows the traced ray at 11:00 for

TABLE III

CONTROLLER PARAMETERS

Name of Feedback	Proportional Gain (K_P)	Integral Gain (K_I)
Position loop	100	0.4
Current loop	5	0.1

both configurations. Figure 1 (a) for C_1 shows capture of only direct sunrays, while Figure 1 (b) for C_2 shows capture of both direct and reflected sunrays, optimizing the capture through the aperture area (A_a). Figures 1 (c) and (d) illustrate the maximum irradiation received by the apertures of C_1 and C_2, respectively. Throughout the day, C_2 shows a percentage improvement in average solar irradiance from 41.92% to 74.30%. The cooking period for C_1 is approximately 5 hours, from 10:30 AM to 3:00 PM, whereas for C_2 it is about 9 hours and 30 minutes, from 8:00 AM to 5:30 PM. The cooking period for C_2 exceeds that of C_1 by 55%.

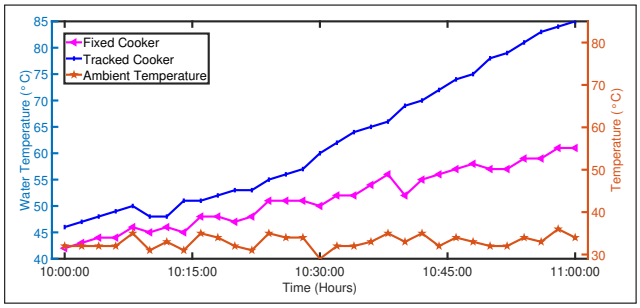


Fig. 6. Experimental results of pot water and chamber temperature of fixed and tracked solar cooker

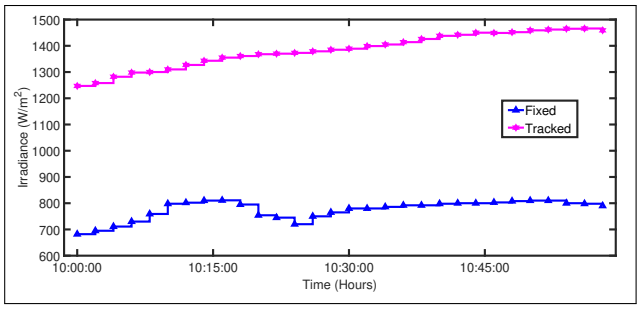


Fig. 7. Solar insolation over selected site

VI. COST ESTIMATION

The expenses for various components of the tracking mechanism are outlined in Table IV. The retrofitting cost of the tracking mechanism for the standard size, as recommended by IS 13429 Part 1, second revision, is $80, bringing the total cost of the cooker to $150.

TABLE IV

COST ESTIMATION OF THE TRACKING MECHANISM IN PROPOSED BTSC

Cooker component description	Cost ($)
Outer box	10
Inner box	10
Glazing	03
Thermal insulation	05
Heat sink with TEG	15
Reflector with bracket	07
Reflector and glazing hinge	08
Extended chassis	10
PMDC motor	12
Ball bearings	05
Castor wheel	05
Supporting rail	08
Wooden frame	04
Rear cover	03
Control panel	07
Manufacturing cost, fasteners, and other miscellaneous	38
Total	150

VII. CONCLUSIONS

The 25 October 2024 day is selected to perform the experiment to get maximum consumption. In line with the objectives outlined in this study, the following outcomes are achieved through simulation.

1) Throughout the day, C_2 improves average solar irradiance from 41.92% to 74.30% than C_1.
2) The cooking period of C_2 obtained about 9 hours and 30 minutes, which is 55% more than that of C_1.
3) The average energy improvement obtained is 62 to 63% than C_1.
4) The proposed tracking cooker operates on both battery power and domestic electricity, with consumption of 429.42 mAh and 0.87 Wh, respectively, over 24 tracking steps, resulting in a net energy yield of 1256.72 Wh. These statistics demonstrate that electromechanical active cooker tracking is feasible and provides a good yield.

The outcomes are useful for the researchers as a reference consumption for their own cooker model. The study considered only irradiance energy over the aperture area (A_a) i.e. solar insolation. The outcomes from simulating the solar cooker show great promise. In our upcoming endeavors, we will construct a prototype for testing and validating the simulation results with proposed tracking powered with self-generated electricity. Due to backlash and play between drive and driven gear, the position feedback is happens and hence wrong position is achieved. Such a problem is identified as a future work.

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