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SOL: A Compact, Portable, Telescopic, Soft-Robotic Sun-Tracking Mechanism for Improved Solar Power Production

Bryan Busby, Shifei Duan, Marcus Thompson and Minas Liarokapis

***Abstract*— Solar power is becoming an increasingly popular option for energy production in commercial and private applications. While installing solar panels (photovoltaic cells) in a stationary configuration is simple and inexpensive, such a setup fails to maximise their potential solar energy production. Single- and dual-axis sun trackers automatically adjust the tilt angle of photovoltaic cells so as to directly face towards sun, but these also come with their own drawbacks such as increased cost and weight. This paper presents SOL, a soft-robotic, dual-axis, sun-tracking mechanism for improved solar panel efficiency. The proposed design was built to be compact, portable, and lightweight, and it utilises closed-loop control for the intelligent actuation of a set of soft telescopic structures that raise and tilt the solar panels in the direction of the sun. The performance of the proposed solar tracking platform was experimentally validated in terms of its maximum elevation at different azimuths and its ability to balance different loads. The result is a device that provides solar panel users with an accessible, affordable, and convenient means of increasing the efficiency of their solar energy system.**

I. INTRODUCTION

With the knowledge of the environmental harm, economic instability and increasing scarcity of non-renewable energy sources such as fossil fuels, human efforts have steered recent energy research in the direction of renewable alternatives. Solar power, in particular, has become one of the most popular solutions for renewable energy production, reaching a global value of 4.41 billion USD in 2022 [1]. Unlike wind- and water-based systems, solar (or photovoltaic) systems can be adapted for commercial and home / personal use as well as industrial application, and the technology is even beginning to see implementation in complex automotive applications (as in the case of the Hyundai Ioniq 5 [2] and Lightyear One cars [3]).

This capability for miniaturisation has led to the exploration of methods of maximising and increasing the efficiency of solar systems. Solar panels generate the most power when they are angled such that they directly face towards the sun, and this optimal angle varies significantly depending on the geographical region, season, and climate of the location in which the solar arrays are being installed [4], [5]. The simplest way of addressing this challenge is by setting up static solar panels such that they face the sun at its average annual zenith (usually corresponding to the sun's noon position in the seasons of spring and autumn). This compromise, however, significantly reduces the power generation efficiency of solar systems [6], and sun-tracking mechanisms have been developed to address this need for optimised solar power generation.

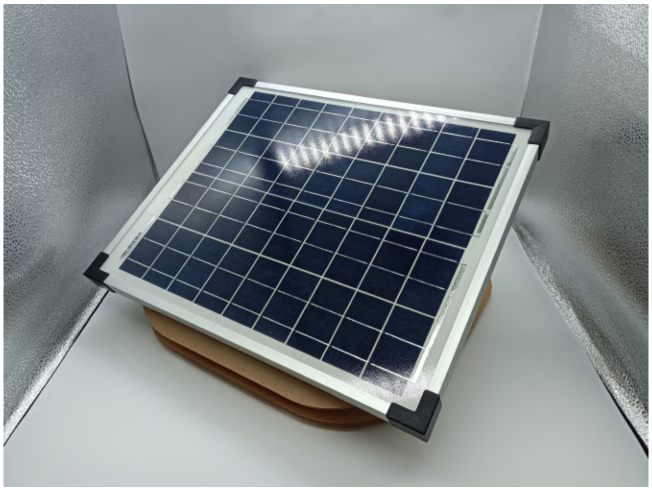

Fig. 1: The SOL is a compact and portable prototype for a dual-axis solar tracking mechanism based on telescopic, soft-robotic structures.

Although capable of producing between 10% and 100% more power than static systems [7], single- and dual-axis solutions are not without their own disadvantages. Although dual-axis systems are more efficient than single-axis solutions in terms of energy-generating performance, these come at a steep cost [8], [9]. For one, active sun-tracking systems will have parasitic losses due to requiring power to maintain the optimal tilt angle of the solar panel. The additional hardware required to automatically adjust tilt angle also requires climate protection [10], necessitating designs that are large, bulky, and require professional installation and maintenance. Even consumer-grade sun-tracking systems such as the EcoFlow Solar Tracker [11] have a footprint and weight that make them cumbersome for humans to relocate their solar panels at will.

In this paper, we present the design, development, and experimental validation of SOL, a compact, scalable, portable, soft-robotic platform for sun-tracking applications that allows for optimisation of the power generation capabilities of solar panels. The proposed device utilises a set of pneumatically-actuated, telescopic soft-robotic structures in combination with a PID controller so as to angle the attached solar panel to a specified elevation angle.

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The remainder of the paper is organised as follows. Section II discusses the related work and the state-of-the-art in sun-tracking solar systems, Section III presents the design of the proposed sun-tracking mechanism, Section IV discusses the experimental validation of the sun tracking system, and Section V concludes the paper.

II. RELATED WORK

The energy yield of a stationary solar panel is severely limited due to the daily and seasonal variations in the sun's position in the sky. Sun-tracking systems have been developed to combat this loss of efficiency from two angles: i) by adjusting azimuth to keep the solar panels directly facing the sun as it follows its daily path, and ii) by adjusting the elevation angle in line with the seasonal variations in the sun's path. The former can be resolved with simple single-axis solar tracking mechanisms. Single-axis systems exhibit significant cost-effectiveness and improved performance compared to their stationary counterparts but still lose some efficiency due to only directly following the *average* daily path of the sun. Dual-axis solar trackers, on the other hand, look to resolve both of these challenges but involve increased cost and complexity.

A. Single-Axis and Dual-Axes Solar Trackers

As their names suggest, single-axis sun-tracking systems rotate about only one axis in order to align their solar panels with the sun (usually at a fixed elevation), while dual-axis systems utilise two axes of rotation (both azimuth and elevation). Due their simplicity and low cost, single-axis solar trackers tend to be employed in industrial or large commercial solar arrays, such as the EzTracker series provided by Clenergy [12]. Their single axis of rotation allows for solar panels to be joined together in long lines that track the sun's daily path from east to west. Single-axis solar trackers have also been explored for use with smaller scale photovoltaic cells [13]. However, since single-axis tracking mechanisms yield increasing economic payoff in larger quantities, their usage in small, private applications is very limited. Additionally, from a performance perspective, single-axis solar trackers largely pale in comparison to their dual-axis counterparts [4], [6], [14].

Dual-axis solar tracking systems adjust both the azimuth (rotation about the vertical axis) and elevation (angle relative to the horizontal plane) to achieve optimal absorption of solar energy. In [15] and [16] prototypes were developed for PLC-driven dual-axis sun tracking systems, while companies such as Heliomotion provide dual-axis solutions to the commercial and industrial markets [17]. The EcoFlow Solar Tracker is marketed as a consumer-grade dual-axis sun tracker and - while lacking the intelligence of an industrial-level system - has proven sufficient for private use [11].

However, the improved performance provided by increasing the degrees of rotation of a solar array comes at the cost of complexity, maintenance and, well... cost. A study conducted by [8] determined that dual-axis systems have a significantly reduced economic payoff as opposed to single-axis units, especially for smaller solar arrays. From a technical standpoint, it is difficult to arrange dual-axis solar panels in large arrays like those made with single-axis solutions.

Fig. 2: An individual telescopic structure of the proposed soft robotic sun tracking mechanism. Left subfigure shows an assembled telescopic structure. Right subfigure shows an exploded view of the telescopic structure assembly's four main components.

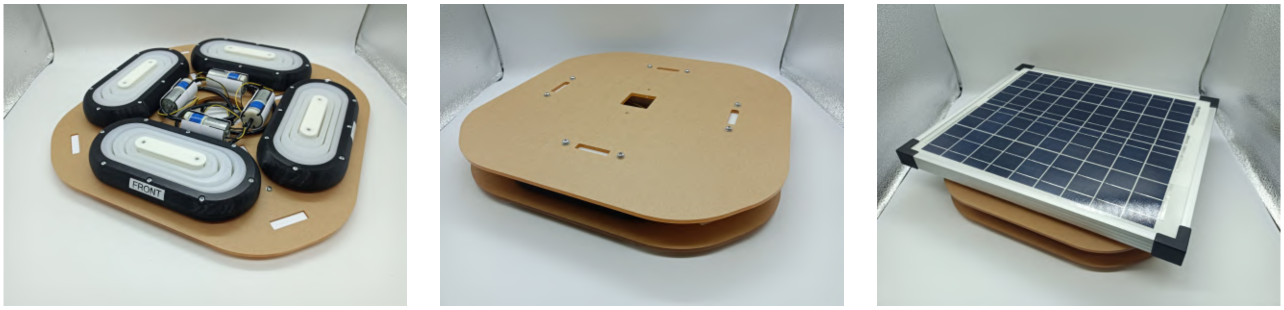
B. Load-Bearing Soft Robots

Soft robotics has seen recent and rising popularity in the science and technology field, and has begun to be explored in load-bearing applications. These explorations of soft robotic capabilities in load-bearing applications are primarily in medical and assistive technology and tend to employ a bellow-like structure. In [18] and [19] authors proposed pneumatically-actuated cushions for assisting patients in changing from sitting to standing positions or adjusting posture, while [20] and [21] utilised similar soft structures for providing patients with limb support and rehabilitation.

Another new development in load-bearing soft robotics - and of particular interest for this paper - is in the application of robotic grasping and manipulation: the telescopic structures. These inflatable structures can be pneumatically actuated to produce a considerable enough amount of force so that grippers equipped with them have been capable of grasping a wide variety of objects and geometries [22], [23], [24], [25]. While this type of structure has only been developed for and experimentally assessed in the bounds of small scale robotic grippers, telescopic structures can be modified to meet the demands of tasks that involve larger and heavier loads.

III. DESIGNS

The proposed solar tracking device consists of a platform actuated by a ring of inflatable structures. Without solar panels attached, the prototype measures 400 mm by 400mm by 50 mm in length, width and height, respectively, and weighs 3.5 kg, making it small and lightweight enough for one person to carry and store with ease. At an total cost of approximately US$154.39, the device was manufactured with inexpensive components, materials and methods, consisting of two acrylic sheets (though these could easily be substituted with another material such as wood), components 3D-printed with commonly available polylactic acid (PLA) plastic, and



(a) Bottom segment (b) Top plate attached (c) Solar panel attached

Fig. 3: Full assembly of the SOL solar tracker. The bottom sub-assembly (consisting of the four pairs of telescopic structures and air pumps) includes mounting points atop the center of each telescopic structure where the top acrylic plate is affixed. Once the IMU is secured to the center of the top plate, the solar panel is mounted on top of the completed assembly.

Fig. 4: The bottom platform assembly as a 3D CAD render. Four telescopic structures are arranged in a ring on an acrylic base surrounding the four air pumps used to pneumatically actuate them.

four sets of inflatable structures molded using soft urethane rubber. The DC-motor-based air pumps and Arduino-based electronics employed in the actuation and control of the solar tracking device were easily sourced at US$84.96.

A. Telescopic Structures

The actuation mechanism of the proposed solar tracking device is based on the telescopic structures developed in [24]. As shown in Figure 2, each telescopic structure is comprised of four main components from the bottom up: i) a rigid, 3D-printed base, ii) a soft urethane rubber gasket, iii) an inflatable, urethane rubber telescopic component, and iv) a rigid, 3D-printed collar. The inflatable telescopic component and the gasket are molded from Smooth-On's soft urethane rubber, Dragon Skin™ 30 using two separate 3D-printed molds. Once set, these soft rubber components are then fastened between the 3D-printed collar and base using a set of eight nuts and bolts. The base and collar act as flanges, compressing the perimeters of the telescopic component and the gasket together to prevent air leakage from the system. Inlets molded into the bottom of the gasket allow for easy connection to air pumps and pressure sensing systems via pneumatic tubing.

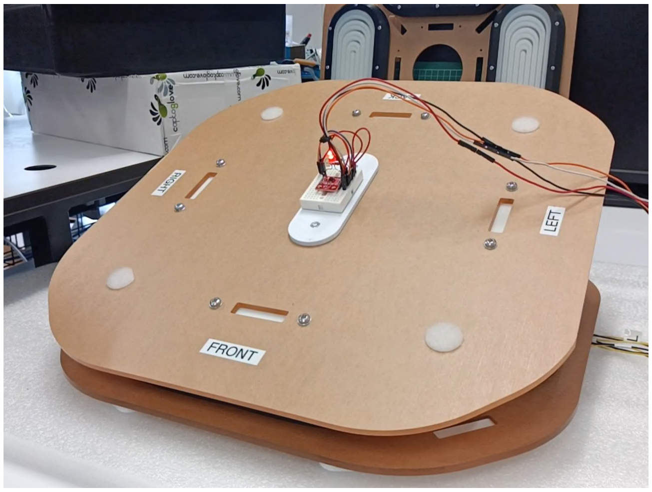


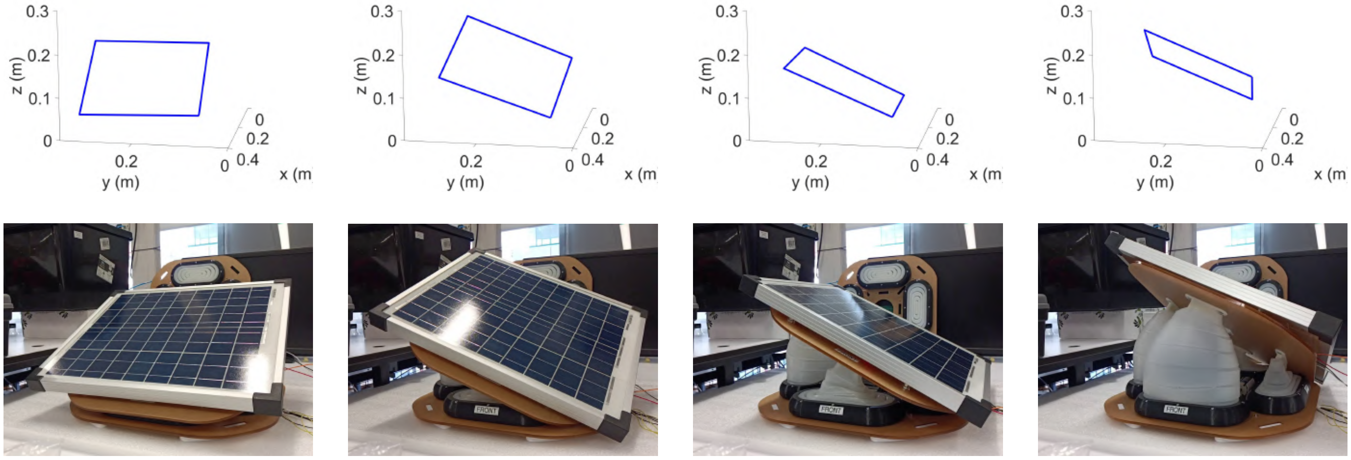
Fig. 5: Setup of the solar tracking device for experimental validation of maximum elevation angles. The IMU was mounted in the center of the top plate and Polhemus motion tracking sensors were attached to the corners.

B. Solar Tracker Prototype

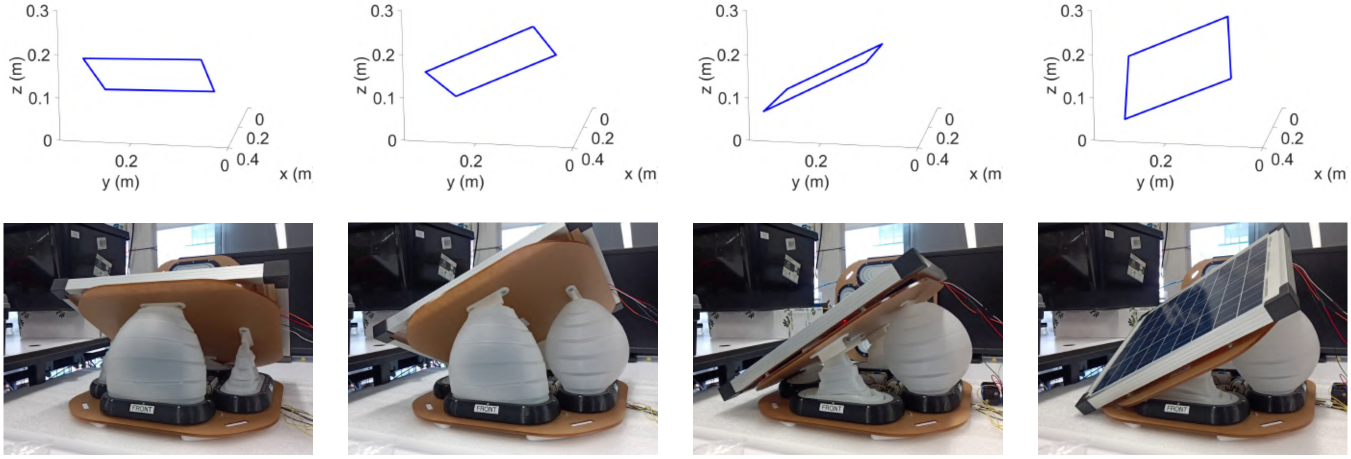
Four of the aforementioned telescopic structures were manufactured and then affixed to a 4.5 mm thick, 400 mm square acrylic base in a ring formation. Four Conjoin CJP37 air pumps employed for the pneumatic actuation of these telescopic structures were arranged in the middle of this base platform. All tubing and wiring attached to these pumps was directed through a circular cavity in the center of the acrylic sheet. As demonstrated in Figures 4 and 3, this produced a very compact assembly with potential room for additional electronic and pneumatic components.

C. Balance Controller

To control the flow rate of the Conjoin air pumps and the resulting elevation angles, an MPU9250 inertia measurement unit, an Arduino Mega 2560 and a Duinotech Motor Shield were utilised. The MPU9250, comprised of a gyroscope, accelerometer and magnetometer, was used to retrieve the real-time roll, pitch and yaw data of the prototype solar



(a) 0° azimuth (b) 45° azimuth (c) 90° azimuth (d) 135° azimuth



(e) 180° azimuth (f) 225° azimuth (g) 270° azimuth (h) 315° azimuth

Fig. 6: Maximum elevation tests for eight target orientations, each separated by 45° of azimuth. While the 0°-, 90°-, 180°- and 270°-azimuth orientations primarily utilised only one telescopic structure to raise the solar panel, the 45°-, 135°-, 225°- and 315°-azimuth orientations employed two telescopic structures and therefore achieved slightly higher elevation. Graphical representations of the Polhemus sensor positions at peak elevations confirm this observation.

tracker. A simple PID control program was developed to control the air flow rate of the pumps based on the roll (about the x-axis running from the back to the front) and pitch (about the y-axis running from left to right).

IV. EXPERIMENTS AND RESULTS

Two sets of experiments were conducted with the prototype solar tracker: i) the evaluation of its maximum achievable elevation angles and ii) the assessment of its performance in raising and balancing different static loads.

A. *Elevation Angle Experiments*

The azimuth range for the elevation experiments was set to eight discrete orientations circling counterclockwise from the front of the device, each separated by 45° of azimuth. A target elevation of 45° was set for each orientation and the displacement of the top plate of the device was tracked using an array of four Polhemus motion tracking sensors placed on each corner of the top plate. The solar tracking device was actuated until no further visible changes in elevation were observed for approximately 10 seconds before the telescopic structures were then deflated and the top plate was reset to the zero position. The MPU9250 circuitry was mounted in the center of the top plate prior to attaching a solar panel onto the device. The real-time pitch and roll data of the IMU was transmitted to the Arduino Mega 2560 board to aid the PID controller in determining the telescopic structures to be inflated and the required air flow rate for each structure.

The photovoltaic cell used in these experiments was a Powertech 20W Solar Panel measuring 430 mm by 350 mm by 25 mm in length, width and depth, respectively, and weighing approximately 2 kg.

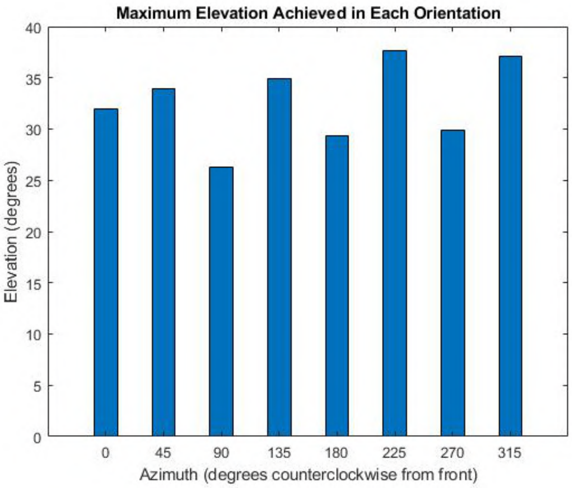


Fig. 7: Bar graph summarising the maximum elevation angles calculated for each orientation, and confirming that higher elevations were achieved by the device at 45°, 135°, 225° and 315° azimuth than at 0°, 90°, 180° and 270° azimuth.

The prototype solar tracker was easily capable of elevating the solar panel past 25° in all eight orientations, although it yielded a visibly greater elevation in the 45°, 135°, 225° and 315°-azimuth orientations than in the 0°, 90°, 180° and 270°-azimuth orientations. In the case of the former, two telescopic structures were inflated to elevate the solar panel, while in the case of the latter only one telescopic structure was primarily actuated, as illustrated in Figure 6. This disparity was made apparent in the 3D plots of the maximum displacements measured by the Polhemus trackers in each orientation, as well as in the resulting peak elevation angle calculations (depicted in Figure 7). While the peak elevation angles range between 26.3° and 37.6°, the elevations achieved at 45°, 135°, 225° and 315° azimuth (mean 35.9°) averaged 6.6° higher than those at 0°, 90°, 180° and 270° azimuth (mean 29.4°).

In Auckland, New Zealand (latitude -36.8, longitude 174.8), the optimum elevation angle varies significantly with the season, between 16.1° in the summer and 46.1° in the winter. While the proposed solar tracking device is limited to up to 37.6° of elevation, the design parameters of the telescopic structures can be easily modified to increase their peak extension heights and thereby accommodate such extreme variations in the sun's seasonal path at locations further from the equator.

In terms of the continuity of the rates of change of elevation of the solar tracker, Figure 8 illustrates the elevation over time in each orientation. It can be observed that the rate of change of elevation was roughly linear in the first 12-19 seconds of the experiments, however this was followed by a slight reduction in elevation rate and, in some cases, sudden fluctuations in elevation angle. As the telescopic structures inflated past the midpoint of their extension, they were prone to sudden deflections caused by their rings "popping out" and reconfiguring the structure for maximum support.

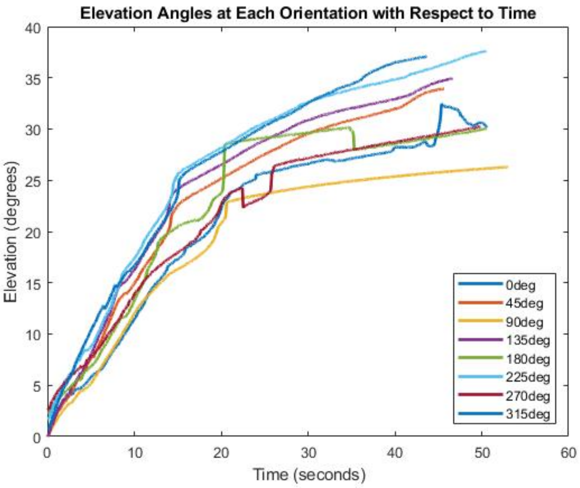


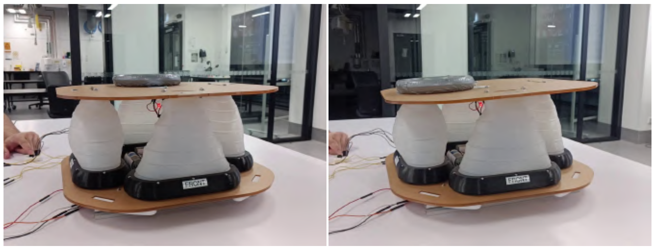
Fig. 8: Line graph showing how the elevation of the device changes when inflating. The rate of elevation change is roughly linear in the first 12-19 seconds of inflation of the telescopic structures before reducing slightly or plateauing.

B. Load-Balancing Experiments

In addition to the previous experiments assessing the solar tracker's ability to elevate a 2 kg solar panel, the device's ability to raise and maintain the level of heavier loads was also analysed. Masses of 1.25 kg, 2.5 kg, 5 kg, 10 kg and 20 kg were placed atop the center of the top plate of the device and raised to their maximum possible height. In the cases of the 1.25 kg and 2.5 kg loads, these masses were also placed on the front, left, back and right sides of the top plate at a displacement of 100 mm from the center. The target angle

(a) Load at 0°

(b) Load at 90°



(c) Load at 180°

(d) Load at 270°

Fig. 9: Testing the self-balancing capabilities of the solar tracker with a 2.5 kg load. The device was generally able to maintain less than 2° of deviation from the horizontal plane.

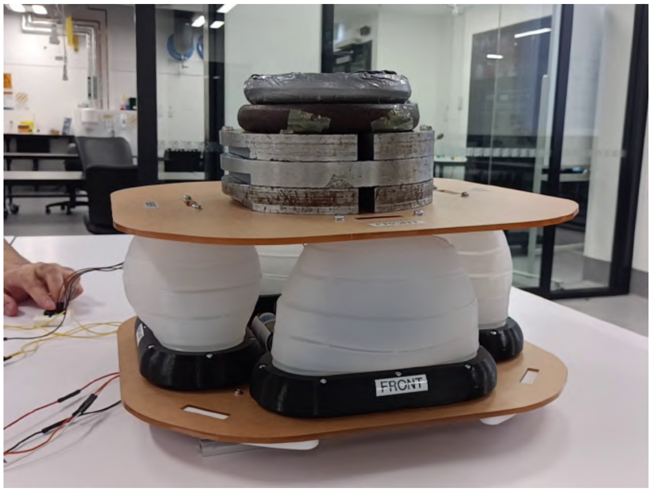


Fig. 10: The solar tracking device was capable of lifting and balancing a 20 kg load, demonstrating the prototype's potential for use with larger or heavier solar panels.

of the top plate was set to 0° elevation, and the level of the top plate was observed.

The device proved to be very efficient in executing the task of lifting and balancing all the employed loads placed at its center, including the 20 kg mass, as depicted in Figure 10. For the loads displaced 100 mm from the center, the device generally maintained the level of the top plate with less than 2° deviation from the horizontal as it raised the loads. The top plate did, however, begin to sag significantly to the loaded side at the peak height of the telescopic structures, and this droop was noticeable in the case of the 2.5 kg mass tests (the top plate tilted by up 5° in some cases), as illustrated in Figure 9.

V. CONCLUSIONS

In this paper, the development and experimental validation of a compact, portable, telescopic, soft-robotic sun-tracking mechanism was discussed and analysed. It was found that the design is capable of not only operating as a dual-axis solar tracker for angles up to 37.6°, but also being adapted for larger solar arrays that weigh up to 20 kg, despite costing only US$155. Limitations to the prototype's maximum achievable elevation angle and load-balancing capabilities, while present in the current design, can be rectified with slight modifications to the telescopic structures and air pumps with higher operating pressures and flow rates.

The experimental validation of the proposed solar tracking platform showcased its ability to achieve maximum elevation at various azimuths while effectively balancing different loads. This innovation offers solar panel users an accessible, affordable, and convenient solution to enhance the efficiency of their solar energy systems. In a world increasingly focused on sustainable energy sources, SOL presents a promising step forward in the quest to optimize solar power production. Its adaptable and cost-effective design brings us closer to harnessing the full potential of solar energy, contributing to a more environmentally friendly and energy-efficient future.

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