Solar Panel Device for Temporary Road Sign Lighting

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Abstract

This proposal presents a solar powered light fixture designed to attach non-retroreflective temporary road signs, aimed at addressing the critical need for enhanced visibility during the night. While Canadian roads are currently populated with signage relying on retroreflective coatings to ensure visibility for drivers, there are numerous other contexts where sign visibility without the need for headlights is crucial. As such a portable solar attachment is proposed for luminating signage using solar energy harvested over daylight hours. The solar powered light fixture will combine solar panel technology, energy efficient LED lights, mechanical rotation components and software modeling to accurately and periodically predict the location of the sun while dynamically tilting the panel at the calculated optimal angle to ensure maximum energy captured from the sun. Due to the natural energy consumption of the rotation component, calculation and testing will determine the period at which the motor will rotate the panel, optimizing the energy captured from the sun versus the total energy expended by the mechanism. The primary objective of this product is to ambitiously develop an intuitive solution that has a straightforward installation process and usage to light up temporary road signs in the northern hemisphere.

Introduction

This proposal's objective is to outline the design and prototype process of an automated single axis solar tracker mechanism that includes manual calibration components to power a light that illuminates temporary construction road signs in low-light and night-time environments to increase visibility, while maintaining ease of use in a variety of conditions.

Driving at night is more dangerous than in daytime due to factors such as reduced visibility, depth perception, and awareness [1]. Half of all traffic deaths occur at night despite only a quarter of drivers being on the road during this period [1]. Road construction zones are considered to be particularly hazardous as they disrupt traffic flow and force cars to detour [2]. Alongside this, night construction is prevalent, as it allows for work to be carried out outside of peak driving hours. An Illinois study showed that nighttime construction is five times more hazardous than daytime construction [2].

Road sign visibility has been shown to directly contribute to driving safety and accident prevention [3]. While regulations that control parameters such as retroreflectivity, observation angle, and viewable distance [4], are enforced during the installation of permanent road signs, temporary construction road signs are frequently repositioned by construction workers in dense traffic situations [5], making them prone to installation errors that can reduce their visibility and sabotage their intended effect.

Current solutions such as dynamic message boards with programmable LEDs, and flashing beacons require power sources such as rechargeable batteries or are wired to the power grid which may not be suitable for remote locations [5]. Retroreflective signs and markers reflect light from existing sources such as car head and auxiliary lights. However, studies have shown that these signs may still be difficult to read due to poor positioning, low ambient light, and brighter visual distractions [6]. Solar powered lights, with fixed mechanisms, have been developed for more permanent road signs. These designs usually feature a solar panel mounted to the top of the sign's pole and have either embedded or external LEDs mounted above or below the sign but have a large cost and are not easy to move for conditions such as temporary work.

Roadside construction signs are typically diamond or rectangular signs between 36 to 48 inches [5] in width and height. These signs would require a portable mechanism that could be mounted and dismounted by users without altering their structure, integrity, or balance. This setup process should be able to be reasonably completed by a construction worker without overwhelming complexity to prevent interruptions with the roadwork. Moreover, the mechanism must be weather-resistant and withstand dirt, water, and external forces such as wind. It would need to generate enough power to recharge its internal battery and illuminate the sign through the night in winter solstice conditions. Lights should increase the sign's visibility without excessively distracting drivers or impeding incoming traffic from the opposite direction with the bled light staying below regulation light pollution levels for roadways.

Design concept

The device is made up of three subsystems: a mechanical system which mounts the product to the sign, an electrical system to capture power using the solar panel and light up the sign, and a software system to control the solar panel's orientation and maximize the power captured. The design for the mechanical system and electrical system can be found in Figure 1 and Figure 2 respectively.

In terms of the software or algorithmic requirements, the solar panel should be south facing with an azimuth of 180 degrees. Given that the intended users are located in the northern hemisphere, this orientation would ideally allow the panel to receive direct sunlight during the day [7]. A physical or digital compass could be used to measure the azimuth and check if it is within 180 ± 1 degree, which would be considered a successful orientation. Users should also be given the optimal axial tilt of the solar panel so they can make manual adjustments accordingly. This requires the development of a software interface that takes the installer's longitude, latitude, and time zone as input, in addition to the expected time that the device is intended to remain on the sign, and returns the optimal axial tilt as output. The interface should be user-friendly and intuitive for construction workers. Since the device is a single axis tracking system, the user will manually adjust the axial tilt angle of the solar panel using a quick release lever mechanism, which holds the solar panel to a desired tilt angle, and use the built-in accelerometer to measure the angle of tilt to verify axial tilt angle is aligned with the optimal axial tilt angle. In addition, the solar panel must rotate dynamically according to the position of the sun. A firmware would be required to calculate the theoretical optimal rotation angle following the procedure described in a technical report [8] in a variable time interval. The actual time interval will be determined later after testing, and the solar panel would move accordingly to the optimal rotation angle. The power left over after calculating and adjusting the rotation angle of the solar panel has to be sufficient to illuminate the sign throughout the night. Besides, if the energy captured by the single axis tracking system is greater than the energy captured by the fixed axis tracking system, the requirement is considered to be a success.

In terms of the mechanical requirement, two mounts are required, the light mount and the solar panel mount, to secure the solar panel on the sign. The mount will leverage the existing base of the sign and has to be able to adjust to various sign types in order to reduce material needs and provide a universal method to install the mechanism. The solar panel mount should be attached to the sign post to maximize stability in cases of wind or extreme weather that may sway the sign. A dual bracketing support will be used to attach the bar of the mount to the sign post, creating enough tension to hold its place. For added support, the bar will also be bolted to the sign post. As a safety requirement, the mount along with the sign must withstand 64 km/h which takes into account extreme winds in the northern hemisphere and is in line with safety requirements for road signage [9]. The device should also be able to accommodate for various sign heights. The bar attached to the sign post will have a quick release lever mechanism to extend and shorten the height of the solar panel in order for the solar panel to be in direct sunlight as well as allow for maximum rotation. The manual tilt angle rotation will be fixed by a quick release lever mechanism that will be under the tracking axis of rotation. The success metric is determined by ensuring that the bar that holds up the solar panel reaches higher than the tallest temporary construction signage. According to industry standards, the higher the speed limit of the road, the larger the standard sign size. High speed roadways require signage of 1.2 x 1.2 meters, and low speed roadways require signage of 0.762 x 0.762 meters [10], therefore the bar must extend and shrink to accommodate both of these dimensions. Both the light mount and the solar panel mount will be connected to the same double bracketing support for ease of installation. A sliding mounting bracket will be used to attach and detach the light fixture to the battery and wiring enclosure. Taking into consideration the need for frequent mounting and dismounting, the device should be easy to set up and transported. The success of the ease of installation of the device will be based on whether the entire mechanism can be set up and calibrated within 10 minutes. Considering the device will be mounted on the sign in different weather conditions, the battery and other electrical components have to be stored in a waterproof enclosure that will be 3D modeled and printed. The effectiveness of the waterproof enclosure will be determined against the Ingress Protection Testing, which is an international standard for testing protection against water. The result of the test must be that the enclosure withstands the testing required to be categorized as an IPX4 rating [11].

The primary focus of the electrical system is to harness solar power and distribute it to various components. These components include LEDs, an ESP32 microcontroller, an accelerometer for tilt angle measurement, and a stepper motor for single-axis tracking. According to Outdoor Advertising Association of America (OAAA), the recommended sign brightness is approximately 325 nits, which is equivalent to the brightness of 325 candle lights per meter squared [12]. The LED is chosen after considering a high value of brightness per unit energy and the price. In selecting the LED, we took into account both high brightness per unit energy and cost considerations. The power calculation involves dividing the sign brightness by the LED brightness rating, resulting in a rounded up value of 5W. In the worst-case scenario, during a winter night in Waterloo, Ontario, the LEDs need to remain lit for 15 hours [13], which is approximately 75Wh per day. After considering the power dissipation of the current limiting resistor, the device has to supply at least 90Wh per day. On the other hand, to store excess solar energy gathered during sunny days and fill up the inadequate energy captured during cloudy days, a battery is required. Therefore, the system includes 450Wh of battery capacity, which can sustain power consumption for at least 5 nights. Since a 25cm^2 solar panel can only generate a maximum output of 0.5W, a larger solar panel capable of capturing more power is necessary. As a result, a dual 24V-30W solar panel design is chosen as the energy source, providing 540Wh on a winter day, which is more than sufficient to power the LEDs for at least 5 nights during winter.

During the summer months, the daylight time can extend beyond 15 hours [14], providing ample opportunity for solar panels to gather energy. In fact, the panels can collect up to a remarkable 900Wh of energy during this period. However, this abundance of energy may surpass the storage capacity of the batteries used in the system. To address this potential issue, the energy levels of the batteries are monitored by a microcontroller. When the batteries reach their maximum capacity, the microcontroller disconnects the solar panel from the remainder of the circuit. This ensures that the batteries are not damaged by excess energy and aligns with the personal electrical safety generation recommendations suggested by IESO [15]. Furthermore, the microcontroller will act as the brain of the entire device. It governs the charging process, tracks the sun by controlling the motor's rotation, and activates the LED circuit in the evening.

With regards to the limitations, weather conditions are one of the major inhibitors to efficient energy capturing. The power captured by solar panels varies drastically as weather conditions change. On cloudy days, solar panels can typically produce 10% - 25% of its typical power capacity [16], which could impact the defined use case. An example of a direct impact of bad weather may be that the LED may not receive enough power to emit light throughout the night, potentially leading to drivers overlooking critical signage on the road. However, this issue is alleviated by increasing the battery capacity of the device. Furthermore, the optimal orientation of the panel being used is not the actual optimal orientation of the solar panel because the system is a single axis tracking system. Since the tilt angle is fixed, the captured power is not maximized. However, single axial tracking instead of a dual axial tracking is chosen because a dual axial tracking system requires significantly more computation, increasing the energy consumption, defeating the purpose of capturing power using tracking altogether. Another limitation would be the device would not be able to accommodate signs that are excluded from the standard heights outlined in previously cited resources, and the size of the sign that the device can light up is constrained by the brightness of the LED lights.

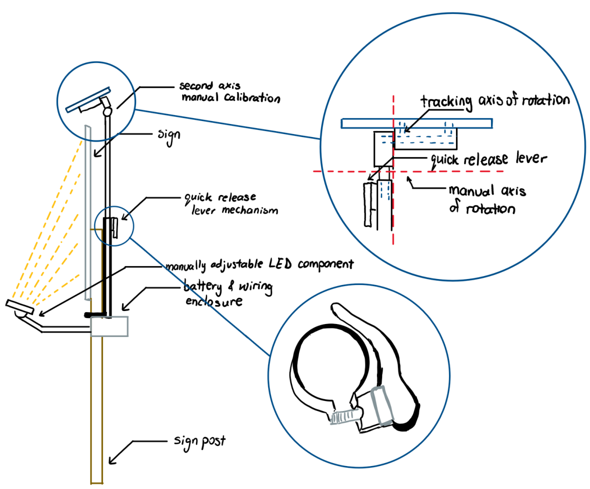

Figure 1: Mechanical Design Diagram

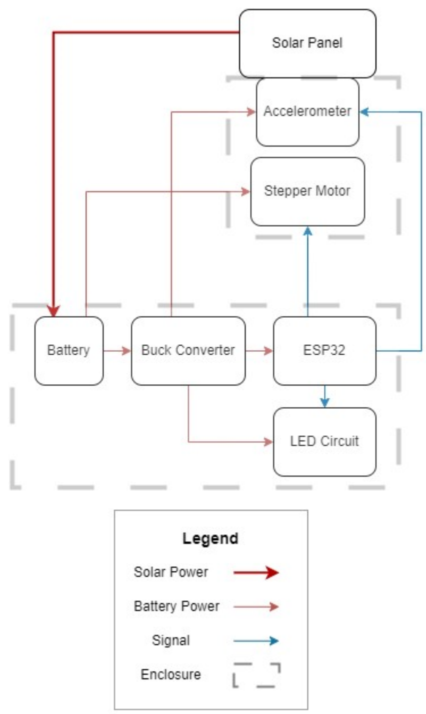

Figure 2: Electrical Block Diagram

Prototype plan

When considering the creation of our product there are various areas of concern that are not able to be verified through analytic methods alone. As such a prototype plan is put forward to help provide data on the various aspects of the device that may behave in unexpected ways or those that are not susceptible to available modeling techniques. While the total range of assumptions that could be validated with a prototype is large for this prototype, an investigation of the most critical three will be undergone. The first issue to be analyzed will be the user experience specifically focusing on setup and teardown of the device when it is to be moved between differing locations and mounting types. Secondly, an analysis of total circuit efficiency will be undergone using a two system approach both when the prototyped is set to behave as a fixed system as well as when it is set to behave as a tracking system, this analysis will also have total energy consumption gathered based on differing conditions to identify operational figures for optimization analysis. Finally, we will evaluate various system attachment methods, specifically direct screw techniques and bracketed mounting, for system stability, ease of installation, removal, and resilience to external factors.

Firstly our prototype design will allow us to analyze how a user will respond to the setup phase of our product allowing us to identify potential issues and areas for improved clarity before we finalize a design. This phase will be focused on exploratory testing and will be using a cluster sampled group design focusing on allowing users to simulate setting up the device in a new environment as well as removing the device after setup. Our sample groups will be selected through volunteer trials with equal numbers of participant selected from highly technically adept, technically literate, and technically illiterate categories following this the sample users will be randomly split into three groups comparing a physical approach to device setup involving markings and assistive devices such as an attached compass, a group that will work with an electronic interface for setup of the same device, and a group that is only considering the setup of a fixed tilt system. After the testing is completed users will be asked to complete a survey detailing a rating of the product ease of use from one to five, a question asking for the most difficult and simplest aspect of the process as well as a general comment section detailing what the user was thinking during the process. Following this we will take the user feedback in the survey and will use what we have learned to work iteratively on our design identifying what general method would be superior or if a hybrid should be considered as well as allowing for specific redesign areas of focus when considering the user impact of our design. Additionally we will work to determine the usability cost if any of implementing a tracking system considering that the added complexity may be a deterrent to certain portions of the user base.

Alongside this we will be using the prototype for the collection of live real operation data and technical specifications that could not be accurately modeled without some electrical prototyping. Chief among this will be a focus on the energy consumption of the system when operated with various features as well as a secondary electrical analysis to identify efficiencies of various components in differing operating conditions. The first area of focus on this front is the issue of tracking vs fixed systems. Our prototype will be designed with full tracking capabilities along with an external arm that when fixed to the panel mount will allow for the panel to stay fixed in place and stable without any need for the motor to even hold torque. Through this various test cases will be run spanning over the course of three days each method will be tested in alternating increments of two hours over the course of a day to identify its overall operational statistics including total potential power generation, power consumption statistics and efficiency. Days will be selected based on varying weather such as cloudy, sunny, and rainy to identify how the system will respond to differing conditions in the field, and specific hours each method will be tested on will be compared to the theoretical data in order to keep a relative view of the data to avoid skews based on short term factors.

The time interval to adjust the rotation angle of the solar panel is one of the critical factors that affect the power efficiency. Calculating the optimal rotation angle and moving the motor to the associated angle require power, but the optimal rotation angle would capture more power because the angle of incidence is minimized. Therefore, a balance between the frequency of which the solar panel rotation angle is adjusted and the optimal rotation angle is required. The optimal time interval at which the power efficiency is maximized can be determined by conducting tests of the prototype. The actual energy consumed to calculate the optimal rotation angle, energy consumed to move the motor, and dimension of the panel will be measured during the prototype testing. After capturing the data, the optimal time interval can be determined numerically. The optimal time interval changes as time and location changes, the optimal time interval being determined is assumed to be on 1st June, 2023, which around the middle of a year, in Waterloo, Canada, which has a time zone of GMT-4, and we assume to have the latitude of 43.5 and longitude of -80.5.

Furthermore, testing on the axial tilt angle is needed, this is to ensure the power loss due to the discrepancy in the actual axial tilt angle and the optimal axial tilt angle is not too significant such that the power captured by the solar panel can still be able to light up the sign for the entire night. To determine the maximum time for which the axial tilt angle is valid, firstly, the theoretical optimal axial tilt angle is graphed out throughout the year. Then, the theoretical axial tilt angle for the prototype testing date is being calculated, the axial tilt angle with the largest difference with the theoretical axial tilt throughout the year is identified and being used to measure the actual power captured during the day. Considering the solar panel used in the prototype might be smaller than the solar panel used in the actual device, the actual power measured is scaled up to the expected power captured using a solar panel with the same size as the actual device. Finally, the scaled up power is being compared with the minimum power needed to light up the signs for the entire night based off of a longest canadian night of 15 hours [13].

However, the charging circuit efficiency will not be tested in the prototype stage due to the complexity of the circuit PID control system [17] and the efficiency can be easily improved using an off-the-shelf charging controller.

Finally our prototype will work to validate the various approaches to device affixation to various types of signage and through the application of user testing to determine the user response to our various approaches to affixation techniques, users will be selected similarly to the investigation with panel alignment with the key difference that there will only be two groups for this piece of the investigation one that will be working with a bracket mounting system and one that will work with a screw mounted approach, each group will have to affix the system to various types of signage and supports specifically a wooden beam, a U-bar, an X-bar, and a metal beam. After each user affixes the device to the dummy sign our team will run a stress test on the device measuring how it responds to forces shaking the sign from the apex to simulate wind strain, forces striking the pole directly to simulate collisions with passerby, and finally rotational torque to identify how well the system can hold its orientation. Following this a survey will also be provided to the participants asking them to evaluate, how easy the process was from 1-5, the easiest and hardest parts of the process, and how concerned they are about potential impacts the system would have on the racking. After completing all of the testing for each of the three key questions we seek to answer on this design cycle we will use the data to redesign and implement any feedback we have received to work towards a design that can achieve clarity in user interaction, improved operational efficiency, and high resilience to environmental factors.

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