ELECTENG 700A: Research Project

Sunlink II: Light-Based Wireless Communication Using Sunlight

Technical Report

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1 Introduction to the Technical Subsystem

This report details the technical development and design strategy for the sun-tracking subsystem of the Sunlink II project — a system intended to facilitate robust, passive visible light communication (VLC) using direct sunlight. While the project explores scalable VLC using modulated sunlight, this subsystem focuses on enabling dynamic, real-time alignment with the Sun's position through a dual-axis mechanical tracking system.

Unlike existing fixed-angle or manually aligned VLC systems, the proposed subsystem incorporates motorised tracking controlled by a closed-loop feedback system. While light sensors capture sun position offsets, control algorithms continuously adjust the azimuth and elevation of the transmitting or receiving surface to maintain alignment. This enables the system to ensure consistent signal quality throughout the day, even as the Sun moves across the sky.

The subsystem integrates sensing, actuation, and embedded control components to form a lightweight, scalable module that can be deployed in distributed communication nodes. Its real-time responsiveness and directional adaptability are key enablers for future VLC networks operating entirely within artificial light or RF infrastructure.

2 System Architecture and Design Rationale

The sun-tracking subsystem is built around a dual-axis pan-tilt configuration, consisting of two motor-actuated joints: one for azimuthal (horizontal) tracking and another for elevation (vertical) adjustment. This arrangement allows the system to follow the Sun's changing position throughout the day and across seasons. The key hardware components include:

- Motors:
  A NEMA 17 stepper motor is used as the primary actuator for azimuth tracking, driven by an A4988 stepper driver to enable precise position control via micro-stepping. A backup 28BY-48 stepper motor driven by an ULN2003 controller is planned for elevation control. Providing redundancy and flexibility for testing different configurations.

- Microcontroller:
  The MSP-EXP430FR2433 launch pad from Texas Instruments was selected due to its integrated support for motor control applications, low power consumption, and sufficient GPIO/ADC interfaces for sensor inputs and motor control logic. It operates at 3.3V and supports analog and digital peripheral connections, making it well-suited for this embedded control task.

- Sensors:
  Light direction is detected using a combination of Light-Dependent Resistors (LDRs) and photo diodes arranged in a quadrant configuration. The hybrid sensor setup enables both intensity-based direction (via LDRs) and faster response to sharp directional changes (via photo diodes), improving the robustness of

the alignment algorithm. In addition, a liquid crystal (LC) shutter is included in the optical chain to enable light modulation for communication purposes.

- Subsystem Integration:
  The sensors feed directional error signals to the microcontroller, which runs a PID control algorithm to calculate stepper movement commands. These are output to the motor drivers using digital step and directional signals. A 12V rail powers the motors, while a 3.3V regulator is used to supply the MCU and sensor array. All components share a common ground to ensure signal integrity and safe operation.

This architecture supports real-time control, low power operation, and modular scaling to multiple nodes. Each node can operate independently while maintaining directional accuracy with the Sun, enabling system-to-system excommunication without central coordination.

3 Control Logic and Path Modelling

The sun-tracking subsystem uses a feedback-based control system to align with the Sun's position consistently throughout the day. The system reads light intensities from directional sensors and computes the angular misalignment between the current orientation and the Sun's incident direction. This misalignment is corrected by issuing precise motor control signals to reorient the tracking head in both the azimuth and elevation planes.

3.1 Sun Path Modelling

The Sun's apparent position in the sky varies based on:

- Time of day
- Date (seasonal tilt)
- Geographic location (latitude and longitude)

Two angles define its position:

- Solar Azimuth Angle: the Sun's direction along the horizontal plane, relative to true north
- Solar Elevation Angle: the Sun's angle above the horizon

Sun-path plots were studied using simulation tools to anticipate expected sun positions. At mid-latitude locations such as Auckland, New Zealand, the azimuth angle can vary from approximately 60°(sunrise) to 300°(sunset) over a single day. The elevation angle peaks around 60-70°and 330- 40°in winter at solar noon, per the 2024 model. These ranges define the necessary sweep angles for the tracker:

- Azimuth Range: 180-240°
- Elevation Range: 0-90°

These estimates inform both the mechanical design and the motor resolution requirements.

3.2 Sensor-Based Error Detection

The light's position is sensed using a 2x2 sensor array of LDRs and photo diodes. All sensors receive equal illumination when the light is centred over the array. Any angular deviation produces an imbalance, which is used to compute the error signal:

$$e_{azimuth} = (S_1 + S_4) - (S_2 + S_3)$$
$$e_{elevation} = (S_1 + S_2) - (S_3 + S_4)$$

Where S_1 through S_4 are the sensor readings in the top-left, top-right, bottom-left, and bottom-right quadrants, respectively.

3.3 PID Control Strategy

A proportional-integrating-derivative (PID) controller is planned to regulate the motor commands based on these error signals. The control law for each axis is:

$$u(t) = K_p e(t) + K_i \int e(t)dt + K_d \frac{de(t)}{dt}$$

Where:

- K_p defines the proportional gain (response speed)
- K_i mitigates steady-sate error
- K_d reduces overshoot and dampens oscillations.

Initial tuning will be done using the Ziegler-Nichols heuristic method with additional anti-windup limits and derivative filtering introduced for system stability.

The control outputs will determine the number and direction of steps sent to each stepper motor via the A4988 driver (azimuth) or ULN2003 (elevation). Micro-stepping will enable sub-degree precision, enhance smoothness and reduce mechanical jitter.

4 Mechanical Design and Mounting

The sun tracker uses a dual-axis pan-tilt platform to cover the necessary range of motion for solar alignment. The current mechanical design is conceptualised and supported by system mock-ups and early CAD sketches.

4.1 Mount Configuration

The tracking head consists of a base-mounted azimuth motor (NEMA 17), which rotates the entire upper assembly, and an elevation motor (28BYJ-48) that tilts the sensor and optical assembly up/down. This approach allows independent control over each axis. Each axis is designed to sweep at least 180°in azimuth, cover 0-90°in elevation, and uses gear reduction or micro-stepping to achieve at least 1°angular resolution.

A 3D printed mount is planned for the initial build, with modular slots to support the sensor, shutter, and optical elements. A bearing or bushing will be utilised to minimise friction and backlash on the gear rotation, as an added amount of quality control, where these elements all allow for easy design calibration.

5 Interface and Power Planning

The sun-tracking subsystem integrates various components operating at different voltage levels and interface protocols. To ensure reliable performance, the system is organised with a well-isolated power supply structure and clearly defined signal routing to the micro-controller, sensors, and actuators.

5.1 Power Architecture

The system uses a primary 12V DC input to supply the stepper motor directly and another 3.3V rail for the micro-controller and sensors. This approach minimises losses and simplifies regulation for low-power devices.

Component	Supply Voltage	Source
NEMA 17 Stepper motor	12V	Main Rail
28BYJ-48 Servo Motor	5V	Second Rail
A4988 Driver	12V logic + VM	Main Rail
ULN2003 Driver	5V	Second Rail
MSP430FR2433 MCU	3.3V	Step Down
LDR + Photodiode Sensors	3.3V	Step Down
LC shutter (modulation)	TBD	Second Rail

Figur 1: Power Architecture Table

A common ground is shared across all subsystems to avoid grounding loops and enable consistent ADC and logic level referencing.

Decoupling capacitors are used near the MCU and motor drivers to stabilise transient current, and ferrite beads are used to ensure the EMI from the stepper switching events poses no electronic harm.

5.2 Micro-controller Interfaces

The MSP430-FR2433 provides sufficient GPIO, ADC, and serial interfaces to manage the sun-tracking subsystem efficiently. The key I/O mappings are as follows:

Function	Interface Type	MCU Connection
Azimuth Motor Control (A4988)	Digital GPIO	Step / Dir pins
Elevation Motor Control (ULN2003)	Digital GPIO	Sequence control
LDR / Photodiode Inputs	Analog (ADC)	4x ADC channels
LC Shutter Control	Digital GPIO / PWM	TBD
Debug / Data Logging	UART	Serial TX/RX
Optional Limit Switches	Digital Input	Interrupt pins

Figur 2: Key I/O mapping Table

6 Implementation Plan and Future Work

With the architectural design and system modelling completed, the project's next phase involves physical implementation, testing, and refinement of the sun-tracking subsystem.

The initial phase will involve assembling the prototype circuitry on a breadboard, consisting of the sensor array, motor drivers, and the MSP430-FR2433 micro-controller. Electrical verification will ensure proper voltage regulation on both the 12V and 3.3V rails, as well as basic functionality for micro-stepping operation to achieve fine-gain positioning on the NEMA 17 motor. At the same time, the ULN2003 driver will be used to interface with the 28BYJ-48 stepper as a secondary actuator.

Subsequently, sensor calibration will be carried out to characterise the response curves of both the LDRs and photodiodes used in the directional light sensing array. Each sensor's output will be recorded in the directional light sensing array under varying angular illumination. Each sensor's output will be recorded under varying angular illumination, and these measurements will be used to generate lookup tables or model-based error functions that map differential light intensity to angular deviation from the Sun's position. This calibration is essential for developing accurate input to the control system, especially under non-uniform lighting conditions or partial occlusion.

Once the sensor subsystem is calibrated, the closed-loop control logic will be implemented. The control strategy will rely on PID feedback for each axis to minimise tracking error. The error signal will be derived from the sensor array using quadrant-differential methods, and the PID controller will output the corresponding step and direction signals to the motors. The controller will be tuned empirically using step response testing, adjusting parameters to balance responsiveness and stability.

In parallel, the mechanical assembly of the dual-axis mount will be completed, where the proposed design employs a pan-tilt mount assembled to support both axes of motion, including mounting fixtures for the sensors, motors, and the optical payload. The mount will be tested for a range of motions, mechanical backlash, and structural rigidity to ensure consistent and precise actuation.

The system can be tested under proper artificial/simulated conditions upon successful validation. To test the tracker's accuracy under illuminance across different levels of lighting. This data will be collected on angular error, motor duty cycles, and system response latency, providing the basis for evaluating the real-world viability of the design.

Finally, the sun-tracking subsystem will be integrated with the VLC communication module to assess its impact on data transmission reliability. The alignment performance will be compared against static baseline configurations to quantify signal strength, range, or bit error improvements under dynamic lighting conditions.