Dynamic Light-field Sensing for Distributed Light Pollution Monitoring

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***Abstract*— Light pollution stems from excessive, misdirected, or indiscriminate use of artificial lights at night; it has profound impacts on human health, nocturnal animals, and coastal ecosystems. The existing systems for light pollution monitoring (LPM) rely on error-prone manual surveys or use low-resolution satellite data for basic analysis. In this work, we present the design, development, and early field experimental analyses of a portable, scalable, and low-power solution for multimodal light-field sensing in vulnerable coastal communities of Florida, US. The intelligent data acquisition and reporting capabilities of the proposed system enable automatic and dynamic light-field sensing for long-term LPM.**

I. Introduction & Related Work

With the rapid growth of urban communities and coastal cities, alarming levels of light pollution are causing long-term consequences on humans and other animals [1]. Numerous research works over the past two decades have shown that light pollution compromises human well-being by disrupting natural sleep cycles, causing chronic sleep deprivation that increases risks for high blood pressure, exhaustion, and depression [2]. Despite the importance, the existing technology still relies on manual single-point light surveys that are tedious, labor-intensive, and error-prone.

Specifically, artificial light pollution is measured by satellite imagery and distributed light surveys [2], [3] that capture geospatial radiance data from sensors such as TSL2591 [4] or SQMs (Sky Quality Meters) [5]. On the other hand, standard satellite imaging and standalone radiance measurements [3] help identify vulnerable areas of light pollution. However, such low-resolution maps are not informative for effective Light Pollution Monitoring (**LPM**) and sustainable policy implementations in local communities.

To this end, contemporary researchers utilize ground terrestrial robots to measure light pollution, offering dynamic measurements due to their autonomous mobility [6], [7]. A comprehensive research effort is conducted in the Gulf of Aqaba with 19 stations to monitor surface-level measurements of coastal light pollution [8]. Beyond satellite imagery and space-borne sensors, DSLR cameras with wide-angle lenses or fisheye lenses are utilized to evaluate sky radiance for LPM [9]. However, these approaches still collect sparse measurements with a single node, hence not scalable to large-scale distributed LPM networks.

We attempt to address the issues of limited spatial resolution and manual sampling processes of existing manual *light surveying* practices by developing a compact light-field sensor module. As shown in Fig. 1, our module enables standalone single-point operation as well as dynamic field operation by an ASV (autonomous surface vehicle). Our low-power design enables standalone long-term operations without manual human intervention. The overarching goal here is to deploy multiple such autonomous modules as a distributed sensor network for LPM in Florida coastlines.

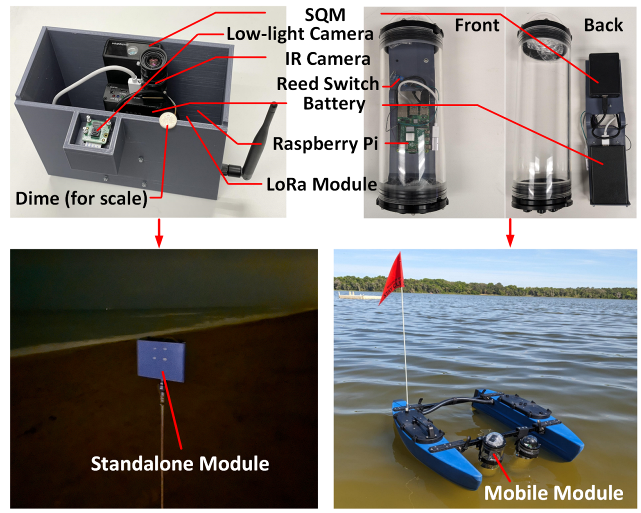

Fig. 1. Our portable light-field sensing module is being used in the field: (a) Standalone operation for overnight data collection in Jenson Beach, FL; (b) GPS-guided mobile operation with a BlueBoat in Lake Wauburg, FL.

II. System: Sensor Suite & Mobile Platform

Standalone Sensor Module. Our light-field sensor module includes an SQM for light intensity measurements (in $mag/arcsec^2$) as well as a low-light camera and an IR camera to capture scene radiance (single-channel images). The collected data is then processed using a Raspberry PI-4B with 8 GB of RAM and subsequently transmitted to a base station via a LoRa RFM95 module (915MHz) and UHF/VHF antenna. The system is powered by a 10 Ah rechargeable battery that ensures independent and prolonged operation. The portable standalone module is shown in Fig. 1.

ASV Integration for Field Operation. Mobile robots such as ASVs are suitable platforms to integrate our sensor module for dynamic light-field sensing on water surfaces. As shown in Fig. 1, we assemble the components of the standalone module into a watertight enclosure with a transparent dome on top to provide a window to SQM. A magnetic reed switch is added to allow the module to be powered on with a magnetic key for contactless triggering in field operation.

Multi-node Distributed Sensor Network. The mobile module can be integrated into a network of ASVs following predefined waypoints to allow for scalable and dense LPM along large coastal areas. This complements the land-based

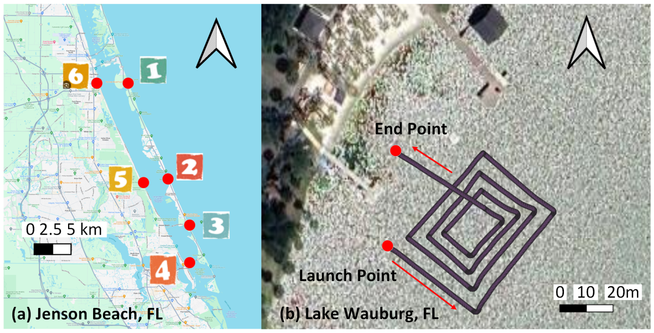

Fig. 2. Illustrations of our light-field sensing modules being are deployed for distributed LPM in: (a) Jensen Beach, FL; and (b) Lake Wauburg, FL.

standalone module and provides a significantly broader space where light-field data can be recorded.

III. Preliminary Deployment & Results

Initial assessments of the LPM system are conducted in both beachfront communities and closed-water (lake) environments. The standalone module is first deployed at Jensen Beach, FL. As shown in Fig. 2a, six observation locations are selected uniformly surrounding a beachfront waterbody. The exact GPS coordinates are marked and the nodes continuously capture timestamped light intensity data for 30-minute intervals; a sample result is shown in Fig. 3a.

On the other hand, lake experiments are carried out with the BlueBoat ASV. Pre-planned GPS-guided missions are planned at Lake Wauburg, FL with multiple respective waypoints. The ASV follows these waypoints at a constant cruising speed while the LPM module captures light-intensity data. A sample trajectory is visualized in Fig. 2b that shows a surveyed area of $40 \times 40\ m^2$, demonstrating viability of using an ASV for dynamic light-field estimation in the field.

The experiments reveal some important observations and challenges of our current LPM system. First, multiple standalone and mobile sensor units are necessary for comprehensive coastal area monitoring, which requires a stable wireless sensor network to interconnect the sensor nodes seamlessly. Second, strong waves cause ASVs to sway significantly at times. This disrupts the SQM's vertical orientation, resulting in inaccurate light-field measurements. Hence, it is essential to design a stabilized platform to ensure that the LPM module can maintain its orientation toward the sky. Third, we find that even when two nodes are close to each other (less than 50 m), they capture slightly different light-field data, thus implying that our system can record complex geospatial LPM patterns in high resolution.

IV. Ongoing Work

Distributed Sensor Network Deployment. To facilitate inter-node communication among static and mobile nodes, we are exploring various wireless sensor network topologies. The goal here is to utilize the onboard LoRa module to routinely share the locally processed data in real-time for holistic light-field map visualization at the base station or by the end users. We are working with the local Florida authorities to annotate suitable locations for such deployments.

Sparse-to-Dense Light-field Estimation. We are currently working on developing intelligent geo-spatial interpolation methods for sparse-to-dense light-field estimation. The goal here is to register our distributed sensory measurements with space-borne satellite data to construct an incrementally denser map from the sparse measurements.

Mechanical Design Improvement. To stabilize the mobile module on the ASV, we are developing a 2-axis active stabilizer. It will use high-response and robust control algorithms to ensure the stability of the LPM module in strong current and turbulent water conditions in the field.

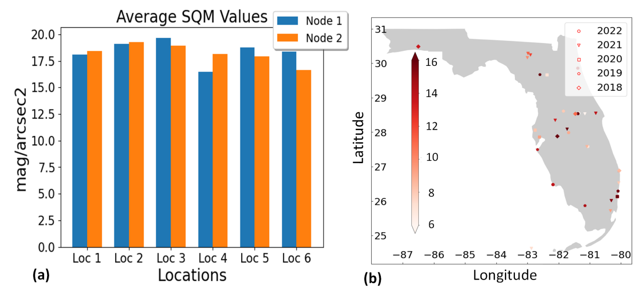

Fig. 3. Two sets of sample results are shown: (a) Aggregated data from our beachfront experiments in Jensen Beach, Florida; (b) Historic SQM values in the State of FL for the last five years (Globe at Night Campaigns data).

V. Conclusion

We present a novel light-field sensing module for autonomous LPM in the vulnerable coastal communities of US. It facilitates high-resolution light pollution map generation (in standalone mode) and dense light sensing in a given area (by mobile robots). Compared to traditional single-point measurements with manual surveys, these maps are more accurate, dense, and reliable – enabling long-term LPM. We are currently working on deploying a computational framework to exploit the light-field maps to find community-specific preventive and reactive measures for coastal conservation.

References

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