UrbanHeatSense.IoT: A Low-Cost, Open-Source LoRaWAN Sensor for Real-Time Crowdsourced Environmental Data

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Abstract— UrbanHeatSense.IoT is a low-cost, open-source LoRaWAN-based air temperature and humidity sensor system designed to enable real-time, crowdsourced environmental monitoring in urban areas. The system has been developed through three design iterations since 2022 as part of an action-based PhD research project at UCL. The first (pilot) and second (solar-powered) versions used commercial development boards and off-the-shelf components. A total of 43 sensors from these two versions have been deployed across London in collaboration with UCL IEDE, the Greater London Authority, and the LLDC SHIFT team in the Queen Elizabeth Olympic Park. These deployments validated both the sensor's ability to capture fine-scale temperature variations and the use of a spatial sensor network for studying urban heat island effects and microclimate differences. The third iteration introduces a fully custom PCB, onboard sensing, and a 3D-printed Stevenson screen enclosure. This version combines low-cost hardware with real-time data collection, open-source accessibility, and deployment insights, offering a scalable path for citizen science participation. 24 boards has been fabricated at UCL Electrical and Electronic Engineering, with the first 12 distributed to UCL colleagues for feedback and the remainder now being rolled out to citizen scientists. UrbanHeatSense.IoT lowers barriers to environmental sensing and supports the creation of distributed urban climate networks, aiming to fill in sensor deserts and data gaps in the availability of accurate, high-resolution air temperature measurements for understanding microclimates, heatwaves, and urban heat island effects.

I. Introduction / Background

Rapid urbanisation has increased the frequency of extreme weather events and the urban heat island (UHI) effect, in which urban areas exhibit higher temperatures than their rural surroundings [1]. Understanding how cities shape their own microclimates is crucial for effective monitoring, mitigation, and management of UHI and heatwaves. Air temperature is a key indicator of human heat exposure and is frequently used to study heat-related morbidity and mortality [2]. Currently, the challenge for local authorities and urban planners is capturing high-resolution, time-series air temperature data to make otherwise invisible health risks (such as clinical syndromes of heat stroke, heat exhaustion, heat syncope, and heat cramps [3]), as well as associated social, economic, and environmental impacts of heat stress, detectable and quantifiable.

Urban Meteorological Networks (UMN) have the ability to continuously monitor air temperature and humidity, two major parameters for studying UHI, and provide an invaluable tool for environmental research and urban management [4]. Dense networks of weather stations are increasingly employed to monitor urban climates, yet this approach remains costly. These expenses stem not only from the initial installation but also from the continuous maintenance required, which can present significant challenges over extended monitoring periods [5]. Recent advancements on the Internet of Things (IoT) and wireless sensor networks offer new possibilities for addressing this challenge. LoRaWAN (Long Range Wide Area Network) technology enables the deployment of low-power, long-range environmental sensors capable of providing real-time, high-resolution climate data at low cost. This paper presents an open-source, citizen science sensor system designed to support a distributed microclimate network in London. The latest version contributes to a public-facing live temperature map and provides data for UHI research and climate mitigation policy through crowdsourced environmental monitoring. The paper introduces the iterative design process of the sensors, covering the software, hardware, and 3D-printed enclosure. It also presents lab-based power consumption measurements, a one-month garden deployment comparing data accuracy against a commercial weather station, and insights from real-world deployments, including challenges and lessons learned, which highlights the potential for cost-effective expansion of urban climate monitoring networks while addressing existing sensor deserts and data gaps in London and other cities.

II. Related Work

In Indonesia, Fauzandi et al. [6] developed a $ 21.32 IoT sensor system that transmits temperature and humidity data via MQTT to the cloud every hour, reducing reliance on manual data retrieval. Hari [7] designed and deployed a set of low-cost sensors for temperature monitoring via LoRaWAN, minimizing maintenance efforts compared to older systems requiring on-site data extraction. Besides, citizen scientist involvement can further reduce operational costs and manpower, facilitating large-scale deployments. For example, The Birmingham Urban Climate Laboratory [8] introduced a high-density UMN involving citizen scientists, consisting of a total of 250 low-cost Wi-Fi sensors and 30 weather stations, leveraging existing infrastructure and community participation to achieve near–real-time data collection across the city.

Building on these approaches, this section presents three sensor iterations developed over three years, each refining cost, durability, and ease of deployment. All three sensor iterations (Fig.1, from left to right: Version 1, Version 2 and Version 3) operate on the same software stack, network architecture, and data transmission process, designed to enable real-time monitoring. On-site sensors send real-time temperature and humidity readings to a LoRa gateway, which forwards these messages through The Things Network—a community-driven LoRaWAN platform. The data are then routed to an MQTT (Message Queuing Telemetry Transport) broker, enabling efficient, lightweight communication. Telegraf continuously captures these data and stores them in a time-series database (InfluxDB), while end users can visualize and interact with the information through a Grafana dashboard that provides real-time temperature trends and downloadable datasets for deeper analysis. This approach minimizes software setup complexity. All sensors operate on a uniform 5-minute duty cycle, entering deep sleep between transmissions to conserve power. The consistency of all measurement intervals enables the final dataset to be inherently time-aligned, eliminating the need for post-processing steps such as aggregation or shifting. The differences between the three iterations consist of the hardware components and enclosure designs (Table I):

TABLE I. THE KEY FEATURES OF THREE SENSOR ITERATIONS

Feature	Pilot Version	Solar-Powered Version	Citizen Scientists Version
Development Board	Arduino MKR WAN 1310	Arduino MKR WAN 1310	Custom PCB Board
MCU	SAMD21	SAMD21	ATmega328p
Radio module	CMWX1ZZABZ	CMWX1ZZABZ	RN2483
Sensor	HDC1080 on I2C port	HDC1080 on I2C port	On board HDC1080
Enclosure	Commercial Stevenson Screen (TFA Dostmann GmbH)	IP67 box for the circuit, a laser cut acrylic solar panel holder and a 3D-printed Stevenson Screen	3D-printed Stevenson Screen
Cost (per unit)	£66	£80	£30
Power Source	LiPo Battery	Solar Power + Rechargeable Ni-MH batteries	AA Lithium Batteries
Use Case	Cost-effective, small-scale deployments (GLA project in schools)	Long-term, low-maintenance outdoor deployments (QEOP project with LLDC)	Large-scale, community-driven deployments (Citizen Scientist network)

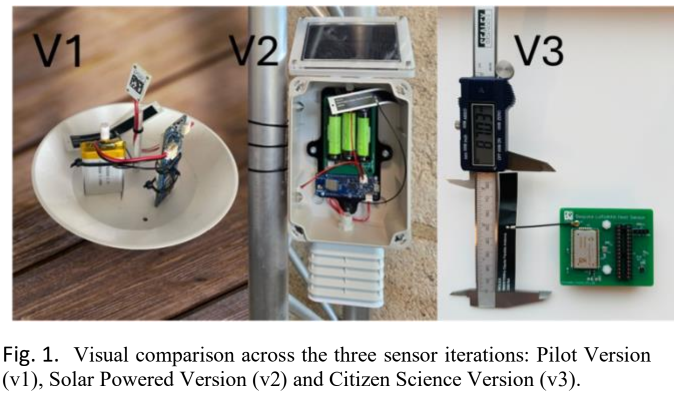

Fig. 1. Visual comparison across the three sensor iterations: Pilot Version (v1), Solar Powered Version (v2) and Citizen Science Version (v3).

III. Imagined or existing prototype sketches/drawings/photos

Although the Solar-Powered Version (v2) enabled continuous monitoring outdoors, its larger size and additional weatherproof enclosure increased manufacturing complexity and the manual assembly time required for each device, thus making fast, large-scale deployments less feasible. To address these challenges, the Citizen Scientists Version (v3) was developed with a focus on scalability and ease of deployment. This design simplifies assembly, reduces overall size and weight, and employs standard Lithium AA batteries instead of LiPo batteries—improving safety and eliminating specialized charging requirements. To promote accessibility, the Gerber files for PCB fabrication and STL files for the enclosure are freely available for downloading on our project website. The tutorial and a detailed assembly video are also provided, guiding users through the manufacturing and setup process. This open-source strategy empowers community members to build and deploy their own sensors at home. Recognising that technical complexity could present barriers, we also provided prepared kits to simplify the assembly and installation process, thus facilitating broader participation in large-scale, citizen-driven environmental monitoring.

A. Hardware and Power Consumption

A custom PCB (Fig. 2) serves as the core of this low-cost LoRaWAN heat sensor, creating a minimum circuit for temperature monitoring by integrating key components onto a single board: (1) *ATmega328P: A low-cost microcontroller chosen for its simplicity, wide community support, and compatibility with the Arduino ecosystem. (2) RN2483: A LoRaWAN transceiver module that enables long-range, low-power wireless communication. (3) Onboard HDC1080: The same temperature and humidity sensor with previous versions to keep measurement consistency, the on-board layout simplifies assembly by eliminating the need for an external sensing module. (4) Power Regulator Zetex AP2112K-3.3TRG: Regulates the voltage from the 3 x AA batteries, ensuring stable power delivery and safeguarding the circuit. (5) Abracon 16MHz Crystal Unit: used as the oscillator for the microcontroller. It provides a stable and accurate clock signal that ensures precise timing for the microcontroller's operations.* A battery holder for 3 AA lithium batteries is mounted on the back of the PCB to minimize the overall footprint, resulting in a more compact design. By consolidating the microcontroller, transceiver, sensor, and power management components onto one board, this approach reduces wiring, minimizes potential failure points, and lowers the total cost to around £30 per unit. Additionally, four pin headers remain on the PCB, allowing users to further develop or modify functionality by using an FTDI board for USB to serial communication, simplifing transmission setup and debugging. Power consumption was measured in a laboratory setting using an Otii Arc Pro model and OTII 3 software, powered by a 3.7V bench supply. The sensor's duty cycle was recorded over a 10-minute period while transmitting at 2-minute intervals (due to limitations imposed by the OTII software) . The results (Fig. 3) indicate that the device's sleep mode consumption is 58.2 microamperes (μA), which is lower than the specified 110 μA sleep consumption of the Arduino MKR WAN 1310 used in the first two versions. Transmission power consumption varies depending on the spreading facto. In the lab, active sensing and transmission averaged 10.2 mA over 9 seconds, with a peak current draw of 61.3 mA was measured at spreading factor 7. To assess real-world performance, field tests were conducted: one deployment in a lab setting with a 15-minute duty cycle lasted 121 days, however another deployment in a garden with a 5-minute duty cycle only lasted 42 days. However, subsequently an issue with the RN2483 firmware was discovered that may have caused the device to hang prematurely. This has been addressed in later deployments and further lifetime tests are ongoing.

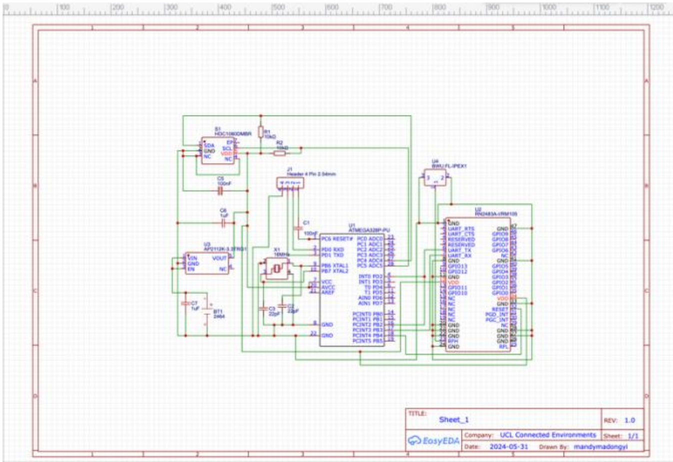

Fig. 2. Compact integrated PCB of the Citizen Science Version (v3).

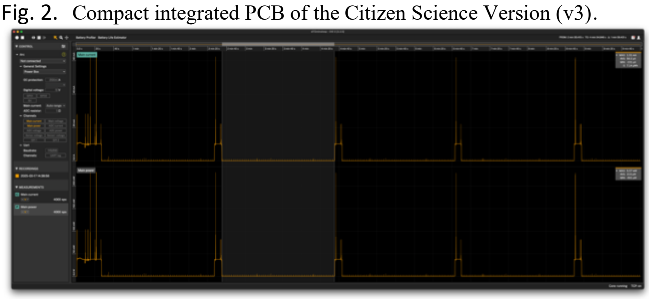

Fig. 3. Measured current consumption) using OTII Analyzer, showing active/sleep phases for a typical 10-minute duty cycle.

B. Redesigned Enclosure

A custom Stevenson screen was developed in Fusion 360 for the v3 boards to consolidate the entire system into a single, standalone housing. Where the v2 enclosure is printed as a single layer, the v3 design consists of nine layers: a top layer, seven middle layers, and a base layer. The top layer features a built-in holder for mounting the screen to posts using cable ties. The design has been optimized to minimize support materials during 3D printing, simplifying both the printing and post-processing steps for citizen scientists Inside the enclosure, both the PCB and the antenna are oriented vertically, with only the battery holder making contact with the internal platform—thereby minimizing direct heat transfer to the board, and ensuring the best angle for dipole antenna radiation. Four footers on the platform secure the PCB at the center of the screen along the X and Z axes. The HDC1080 sensor is positioned near the bottom, leveraging airflow openings in the base layer to circulate air from below. Additionally, ten-centimeter spacers are integrated between layers to further enhance ventilation and ensure accurate temperature measurements. This layered, open design accommodates natural convection, allowing hot air to rise away from the sensor while cooler air enters from below, thereby improving overall measurement reliability.

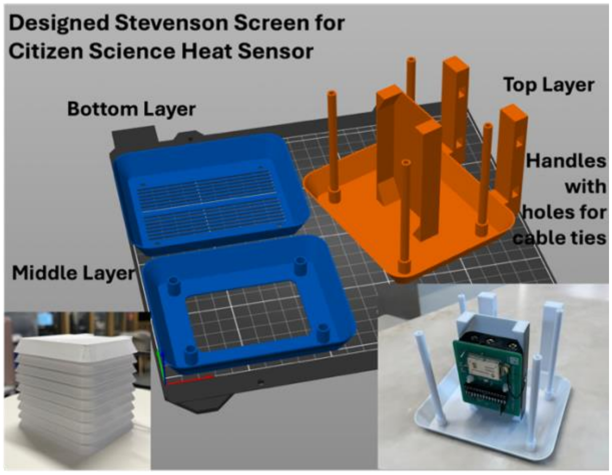

Fig. 4. Designed Stevenson Screen of the Citizen Science Version (v3). Total printing time: approximately 3.8 hours, printed using off-white PETG filament for its UV-resistant properties.

C. Data Accuracy vs Weather Station

To evaluate the measurement accuracy of the designed sensor systems, we co-deployed one sensor from each of the three iterations on a single tripod, positioned adjacent to a reference weather station (Fig.5). The reference station is the commercial model Davis Vantage Pro 2 (priced at ~£2000) and was mounted independently on a separate tripod at the same site. It measures temperature, humidity etc. and features fan-assisted ventilation to ensure accurate air temperature readings. From December 20, 2024, at 00:00 to January 24, 2025, at 23:59, the raw data collected indicated that in 97.5% of cases, the designed sensors recorded temperatures within ±0.5 °C of the weather station measurements. After removing outliers using the 1.5×IQR method [9], the results show a strong correlation (r = 0.999) between sensor readings and weather station data, with an inter-sensor standard deviation of 0.20°C, demonstrating high consistency across deployments. The performance metrics of the cleaned dataset are summarized in Table 2.

Fig. 5. Experimental setup for sensor accuracy benchmarking.

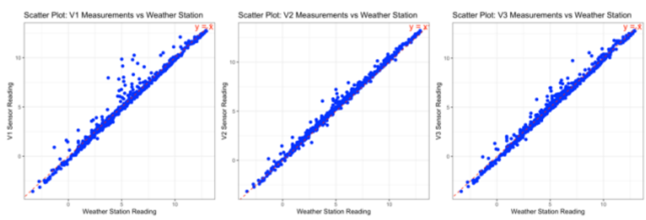

Fig. 6. Scatter plot of sensor temperatures versus weather station data highlighting metadata measurement deviations across versions (raw data).

TABLE II. THE KEY FEATURES OF THREE SENSOR ITERATIONS

Sensor	MAE	MB	RMSE	Pearsonr	SD	Cov
V1-day	0.120	-0.085	0.155	0.999	0.130	12.642
V2-day	0.305	0.301	0.328	0.999	0.129	12.675
V3-day	0.134	-0.035	0.159	0.999	0.156	12.690
V1-night	0.206	-0.201	0.231	0.999	0.113	11.183
V2-night	0.216	0.209	0.238	0.999	0.113	11.193
V3-night	0.221	-0.219	0.240	1.000	0.099	11.197

IV. RESPONSIBLE INNOVATION

UrbanHeatSense.IoT was developed for distributed IoT network using bespoke LoRaWAN heat sensors, focusing on practical, accessible, and cost-effective methods for collecting high-resolution air temperature data. However, real-world deployment presents significant challenges. Installing sensors in public spaces often requires lengthy permission processes and liability considerations. Our deployment in London's Olympic Park, for example, took over six months to gain approval from the relevant authorities. As many public spaces are privately owned, these logistical hurdles can limit scalability. To address these challenges, UrbanHeatSense Version 3 adopts an open-source, citizen science model. Individuals and communities can download the fabrication files, assemble the sensor at home, and deploy it independently. The sensor is fully wireless, powered by AA lithium batteries, and transmits data via LoRaWAN using Over-the-Air Activation (OTAA). No Wi-Fi or local configuration is required, which eliminates privacy concerns and simplifies deployment, making it easier for non-experts to contribute data. All hardware schematics, firmware, and enclosure designs are open source and publicly available, enabling others to replicate, adapt, or build upon the system.However, deploying devices to the general public, a key component of crowdsourcing and citizen science also requires substantial background work to ensure data privacy and compliance with national regulations. It also takes time to connect with relevant networks and community groups. Broader citizen science participation is often constrained by limited resources, lack of technical confidence, and the need for simplified, durable sensor kits. Public awareness and engagement remain low, which may limit adoption even when tools are freely available. These challenges are a focus of the next phase of the project, which involves collaboration with schools in Newham and the Eastbank Summer School to raise awareness of environmental science and climate resilience through education.

Fig. 7. UrbanHeatSense.IoT collaborates with the Greater London Authority, the London Legacy Development Corporation, and Newham Council on real-time urban climate monitoring initiatives. In recognition of the work in environmental sensing, UrbanHeatSense system was invited by UCL to present the to Her Royal Highness The Princess Royal as part of a showcase of cutting-edge research. These activities reflect the project's commitment to responsible innovation, linking research, education, and community action.

V. AUTHOR BIO(S) / EXPERIENCES

Dongyi Ma received her B.Sc. (Hons.) degree and M.Sc. degree in telecommunications engineering from the University of Wollongong, Wollongong, NSW, Australia, in 2015, and the University of Melbourne, Melbourne, VIC, Australia, in 2016, respectively. She then worked as a Research and Design Engineer at the Big Data Center, Beijing Unicom, Beijing, China. She received a second M.Sc. degree in connected environments from University College London (UCL), London, U.K., in 2022 and is currently a Ph.D. student at the Centre for Advanced Spatial Analysis, UCL. Her research focuses on developing IoT sensor systems to measure and communicate urban heat islands and urban microclimates. She has led the full development lifecycle of UrbanHeatSense.IoT, including hardware prototyping, firmware development, LoRaWAN network configuration, field deployment, data processing, and public engagement. She has also worked on communication design, outreach activities, and website development to support citizen science participation. More information about her project and sensor designs can be found at: https://mandymadongyi.github.io/UrbanHeatSense.IoT/getinvolved.html

VI. ACKNOWLEDGEMENTS

Thanks to my supervisors Professor Andy Hudson-Smith and Dr Martin De Jode for their constant guidance and support.

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