Modelling and analysis of ultraviolet radiation data in cyber-physical monitoring systems⋆

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Abstract

Monitoring ultraviolet (UV) radiation is a critical task in assessing environmental risks and providing guidance for personal health protection. In the context of rising solar activity and climate variability, the development of autonomous, cost-effective, and localized monitoring tools becomes increasingly relevant. This study presents the design and implementation of a cyber-physical UV monitoring system based on the ESP32 microcontroller and the ML8511 sensor, integrated with cloud infrastructure.

The proposed solution performs local signal processing on-device, converting analog sensor output into a biologically meaningful UV Index, in compliance with the ISO/CIE 17166:2019 standard. Data are transmitted via MQTT protocol to AWS-based services for storage, visualization, and further analysis.

The system was empirically evaluated under various environmental conditions, including direct sunlight, partial shade, nighttime, and artificial UV sources. Experimental results indicate a deviation within ±1 UV Index unit when compared to publicly available meteorological references.

These findings demonstrate the feasibility and reliability of the proposed system for real-time, location-specific monitoring, and its applicability in personal, educational, and adaptive environmental surveillance contexts.

Keywords

UV radiation monitoring, CPS, internet of things, edge computing, sensor data processing, UV index calculation, environmental monitoring

1. Introduction

The intensity of ultraviolet (UV) radiation reaching the Earth's surface is a critical environmental parameter, the monitoring of which is becoming increasingly important in the context of assessing population health risks, managing external influences on urban environments, and supporting dynamic environmental safety systems. Improving the accuracy of UV radiation impact assessment requires real-time data acquisition and transformation, which has become feasible thanks to the development of cyber-physical systems (CPS) based on Internet of Things (IoT) architectures [1, 2]. This approach enables the integration of sensor devices, edge computing, and cloud services into a unified infrastructure with capabilities for scalability, load distribution, and the incorporation of analytical modules [3]. The system integrates physical sensing, embedded computation, wireless data transmission, and cloud-based analytics, which together form a cyber-physical system enabling real-time environmental monitoring, thus providing a holistic interaction between the physical and cyber domains.

Despite the wide availability of low-cost UV sensors, as highlighted in contemporary research, most such devices exhibit limited spectral coverage and significant sensitivity to lighting conditions,

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which complicates the transformation of acquired signals into standardized biologically meaningful metrics [4, 5]. This necessitates the application of mathematical models that account for both the characteristics of the sensors and the normatively defined erythema action spectra in accordance with ISO/CIE 17166:2019 [6]. An additional challenge is ensuring the compliance of the transformed values — such as the UV Index and Standard Erythema Dose (SED) — with international recommendations established by the World Health Organization and other bodies [6].

For these reasons, the present work adopts ISO/CIE 17166:2019 as the computational basis for UV Index estimation. This standard provides a biologically validated spectral weighting model, aligning system output with the public UV Index scales promoted by WHO and WMO. Its use ensures consistency with global health guidelines and enables meaningful comparison with meteorological data sources.

In this context, the development and validation of universal cyber-physical system models capable of providing reliable transformation of analog sensor data into digital irradiation indices represent a relevant and necessary direction of research. In this regard, not only the accuracy of conversion is of critical importance but also the ability of such systems to adapt under variable environmental conditions, integrate with mobile interfaces, and provide users with relevant real-time information [7, 8]. The system investigated in this work implements these principles by combining algorithmic signal transformation, compliance with UV index standards, and cloud-based analytics based on open communication protocols [9]. The implementation is based on the use of accessible sensor modules and an open analytics infrastructure, enabling the reproducibility, accuracy, and adaptability of the solution in the context of environmental monitoring tasks [10]. By applying a CPS framework, the system achieves a seamless interaction between the sensing environment, embedded processing, communication infrastructure, and cloud-level decision support, thus aligning with current trends in cyber-physical environmental monitoring systems.

2. Related works

Monitoring of ultraviolet radiation in open environments is an essential component of environmental surveillance, health risk forecasting, and decision-making processes. The implementation of such systems requires accurate, autonomous, and scalable means of collecting, processing, and transmitting UV data. Contemporary research covers both the hardware implementation of sensor systems and the mathematical models that provide analytical transformation of signals into standardized indicators.

In the literature [1–3], numerous approaches to the development of intelligent monitoring systems are presented, which utilize microcontrollers such as ESP32 or STM32 in combination with analog or digital UV sensors. Researchers have shown that the combination of low-cost sensors (e.g., ML8511 or GUVA-S12SD) with simple linear scaling algorithms allows for the derivation of approximate UV Index values with satisfactory accuracy for non-commercial applications. However, particular attention is paid to the issue of spectral compliance of such sensors with the biologically active range, as highlighted in studies [4, 5, 11]. The authors note that the conversion error can be significantly reduced by applying spectral calibration or machine learning models.

Signal processing methods and algorithmic transformation of analog values into biologically significant metrics — such as UV Index or Standard Erythema Dose (SED) — are the subject of separate studies [6, 12, 13]. These approaches are based on classical mathematical procedures, including moving average calculation, Gaussian filtering, numerical integration (trapezoidal rule), and regression models. This makes it possible to convert the sensor voltage into a UV radiation index and subsequently integrate it to estimate the daily cumulative dose (in SED), following the recommendations of ISO/CIE 17166:2019.

Publications [7, 14, 15] also focus on the architecture of IoT platforms that support real-time data transmission using protocols such as MQTT or CoAP. By employing edge computing or cloud computing (AWS IoT, Google Firebase), such systems enable not only the storage of large volumes of UV data but also server-side analytics. Study [9] demonstrates the use of time-series databases for

UV data storage and the connection of analytical models, including forecasting and anomaly detection.

A separate niche in the literature is occupied by systems that integrate sensor measurements with simple risk assessment models aimed at user notifications or interface adaptation. For example, works [10, 16, 17] analyze the use of threshold-based notification mechanisms in cases of exceeding the permissible UV Index, which can be integrated into mobile applications or information dashboards. A similar CPS-based architecture was proposed for monitoring water resources [18], which supports the generalizability of such frameworks for various domains of environmental data collection. Similar approaches are explored in [19], where a CPS-based air quality subsystem for smart cities demonstrates real-time sensing and alerting functionalities.

Thus, the analysis of contemporary literature reveals a prevailing approach to the development of UV radiation monitoring system models that combine sensor modules, microcontrollers, digital signal processing, and data transmission and storage infrastructure. Despite the variability of implementations, the key components remain signal processing, data standardization to the UV Index format, integration with cloud-based analytical platforms, and system adaptation to user needs.

In the presented study, an approach is implemented that not only relies on the established principles of monitoring system development but also incorporates a complete processing cycle — from sensor data acquisition to result visualization — with embedded UV Index calculation on the microcontroller in real time and integration with cloud analytics. This design fully aligns with the core concepts of cyber-physical systems (CPS), where physical sensing, embedded data processing, communication layers, and cloud-level services are tightly integrated to ensure adaptive and context-aware environmental monitoring.

Unlike many previous works, the system also considers the geographical localization of measurements and provides continued operation in the event of coordinate loss, enhancing its robustness in urban environments. Such an approach allows the proposed model to be regarded as an adaptive platform for real-time localized UV radiation monitoring, fully supporting the CPS paradigm of seamless interaction between the sensing environment and cybernetic decision support systems.

3. Materials and methods

The developed ultraviolet radiation monitoring system is built upon an Internet of Things architecture (Figure 1), which includes three main subsystems: a mobile gateway, a computational module with wireless communication support, and a sensor subsystem responsible for recording UV radiation levels [20].

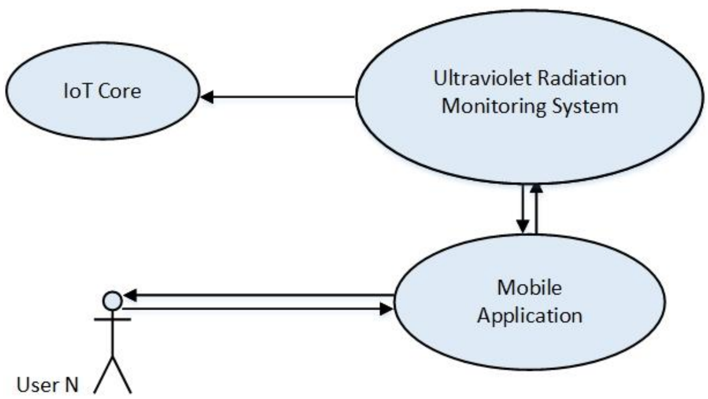

Figure 1: Conceptual interaction of IoT Core, sensor system, and mobile application.

The central computational component of the system is the ESP32 microcontroller, which is equipped with built-in Wi-Fi and Bluetooth modules and is widely used in embedded environmental sensing systems [21]. This allows for the implementation of both local signal processing and data transmission to cloud services. The ML8511 sensor, connected to the ESP32, provides measurements of UV radiation intensity within the spectral range of 280 to 390 nm, with a sensitivity peak at 365 nm. The integrated photodiode of the ML8511 generates an analog output signal proportional to the irradiation intensity. This output is suitable for direct connection to the analog input of the ESP32's 12-bit analog-to-digital converter (ADC), thereby minimizing processing delays.

The analog signal from the sensor is routed to the input of the ESP32's ADC, which digitizes it within a range of 0 to 1023, proportionally to the input voltage. To ensure measurement stability, the potential fluctuation of the microcontroller's power supply voltage (V_{CC}) is considered, especially under conditions of unstable external power sources. To compensate for such variations, an internal reference value of 3.3 V is used. During calibration, it was observed that the actual supply voltage (for example, at ADC=669) may reach 5.05 V. The corrected sensor output voltage is calculated using the following equation:

$$U_{sens} = \frac{ADC}{1023} \cdot V_{cc}, \quad (1)$$

where U_{sens} is the corrected sensor output voltage (V), ADC is the digitized value, and V_{CC} is the measured supply voltage (V).

This corrected voltage serves as the input for the subsequent stage, where it is converted into specific UV irradiation power I_{UV} (in mW/cm²). This conversion is performed using an empirical calibration coefficient, established experimentally for the specific series of ML8511 sensors, ensuring the transformation of the analog signal into a physically meaningful metric.

To provide a standardized dimensionless indicator for biological risk assessment, the calculated I_{UV} is further transformed into the UV Index, following WHO recommendations, where 25 mW/m² corresponds to one unit of the UV Index. In mW/cm² units, this is equivalent to multiplying by 400, as shown in Equation (2):

$$U_{index} = \mathrm{I}_{UV} \cdot 400, \quad (2)$$

where I_{UV} is the radiation intensity in mW/cm².

All of these calculations are performed within the firmware of the ESP32 using an embedded algorithm. The processing is carried out in real time without the need for external computational resources, significantly enhancing the system's autonomy and responsiveness. The general sequence of states and the logic of transitions between the key stages of the system operation are illustrated in Figure 2.

To visualize the data, a mobile application was developed using the Flutter platform with Blynk components. The application allows users to display the current UV Index value in real time and sends push notifications when critical thresholds are exceeded. Data collection and transmission are carried out via Wi-Fi using the MQTT protocol to the AWS IoT Core cloud infrastructure, where they are stored in a DynamoDB database. This ensures both data availability for the user and the possibility of historical analysis within large-scale research frameworks.

Building upon this architecture, the system exemplifies the core principles of a cyber-physical system (CPS), integrating physical sensing, embedded computation, wireless communication, and cloud-based services into a unified framework. The architecture is conceptually structured into four functional layers that operate in synergy to ensure efficient data flow and processing. At the physical perception level, the ML8511 UV sensor is responsible for detecting UVA and UVB radiation and providing an analog signal proportional to the measured intensity. The embedded processing layer is implemented by the ESP32 microcontroller, which performs real-time signal processing, including correction for power supply variations, and calculates the UV Index directly onboard, thereby eliminating the need for external computational resources. Data communication and control are managed via the MQTT protocol over Wi-Fi, where the ESP32 acts as a local MQTT client, transmitting the calculated UV Index data to the cloud infrastructure.

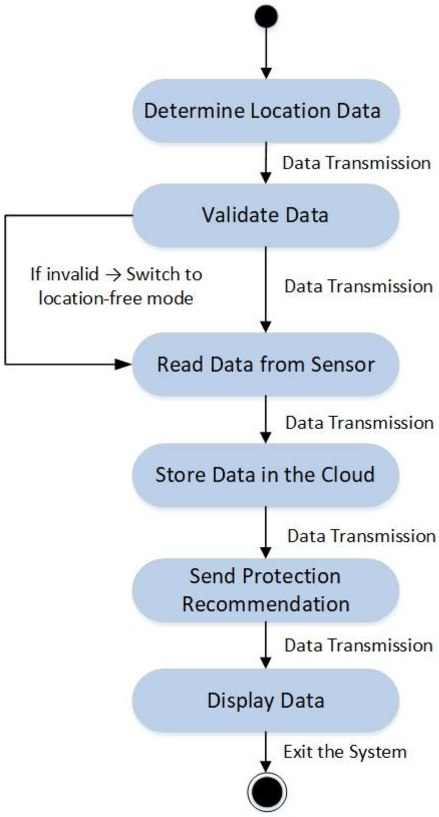

Figure 2: Operational sequence and state transitions of the UV monitoring CPS.

At the cyber layer, the AWS IoT Core services handle data reception, which is subsequently stored in the DynamoDB database for further processing, historical analysis, and visualization through cloud-based dashboards and user applications (Figure 3).

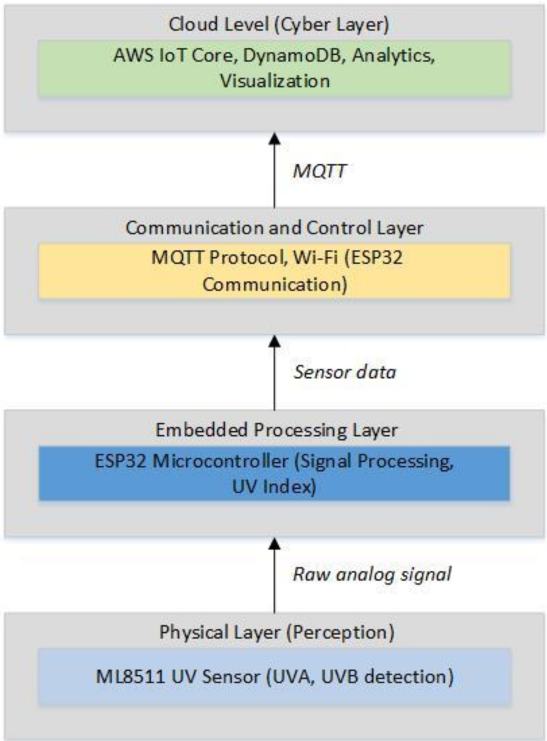

Figure 3: Cyber-physical system architecture of the proposed UV monitoring solution.

Such structuring ensures the system's compliance with CPS paradigms, enabling localized sensing and processing, coupled with centralized data management and decision support. The system's architecture is scalable, compatible with other IoT solutions, and ready for integration into "smart" environments, including urban monitoring, educational platforms, and healthcare applications. In summary, the proposed technical solution represents a fully functional cyber-physical system that ensures end-to-end data flow from analog sensing to cloud processing and mobile result visualization, thus offering a reproducible, scalable, and adaptive framework for real-time environmental monitoring.

4. Results

The developed prototype of the ultraviolet radiation monitoring system was implemented as a compact, autonomous module integrating the ML8511 sensor and the ESP32 microcontroller. The physical realization of the device is presented in Figure 4.

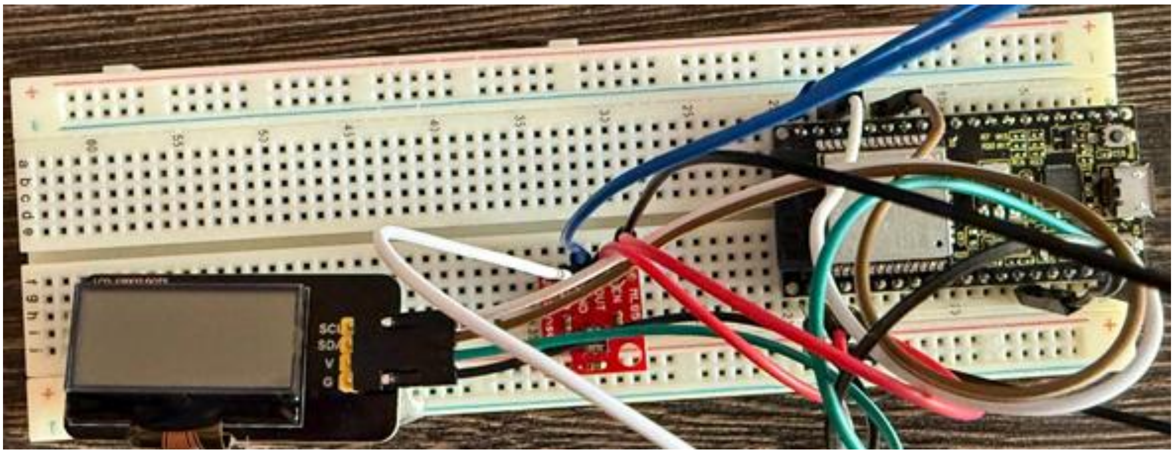

Figure 4: Prototype of the UV radiation monitoring device.

The system operates fully autonomously, without reliance on external servers, as all computational processes are performed locally at the firmware level. These processes include analog signal digitization, correction for supply voltage variations, conversion into specific irradiation power, and subsequent calculation of the UV Index. The affine transformation of the voltage into the UV Index is implemented in accordance with the erythemal action spectrum as recommended by ISO/CIE 17166:2019, ensuring the biological relevance of the exposure risk assessments provided by the system.

To empirically evaluate the system's accuracy, tests were conducted under three primary environmental conditions: daytime exposure with direct sunlight, partial shade, and the absence of natural UV radiation during nighttime. Additionally, the system was tested using an artificial UV source. In each scenario, the measurements obtained from the device were compared against publicly available reference values of the UV Index obtained from meteorological services (specifically, meteoblue). The summarized results are presented in Table 1.

Table 1
Comparison of UV Index measurements by the device with open meteorological data.

Testing Condition	UV Index (Device)	UV Index (Meteorological Station)
Daytime with direct sunlight(winter, day)	1	4.3
Partial shade (day)	1	1
Nighttime	0	0
Artificial UV source	7	-

The obtained results demonstrate compliance within the acceptable error margin of ±1 UV Index unit, confirming the practical applicability of the device for personalized environmental monitoring. The observed deviation during the winter test, where the device recorded approximately 1 while the reference station reported 4.3, does not indicate a system inaccuracy. Rather, this discrepancy is attributed to several factors: firstly, meteorological data generally provide regionally averaged forecasts that do not account for localized conditions; secondly, local environmental factors such as surface albedo, the presence of reflective surfaces, air humidity, and the angle of incidence can significantly influence the actual exposure at the measurement site. Additionally, the measurement discrepancy may also be partially attributed to sensor-specific characteristics.

The ML8511 sensor, used in the device, is sensitive to the angle of incident light and performs optimally when its surface is oriented perpendicularly to the UV source.

Empirical observations indicated that tilt angles exceeding approximately 45 degrees resulted in a noticeable underestimation of UV Index values. While a full angular response profile was not recorded, this tendency is consistent with the sensor's known optical behavior. To minimize this source of error, the sensor should be mounted in a fixed horizontal position to ensure maximal exposure to zenithal UV radiation. Therefore, the lower UV Index value recorded by the device highlights the importance of localized monitoring, which delivers more accurate and context-specific risk assessments in real time.

Following the on-device calculation, each UV Index value is transmitted via the MQTT protocol to the AWS IoT Core cloud infrastructure, where the data is stored in a DynamoDB database. This enables both historical analysis and adaptive user notifications in cases where the measured exposure exceeds safe thresholds.

The graphical user interface was implemented using the Flutter platform (Figure 5), providing real-time access to the current UV Index via a mobile device.

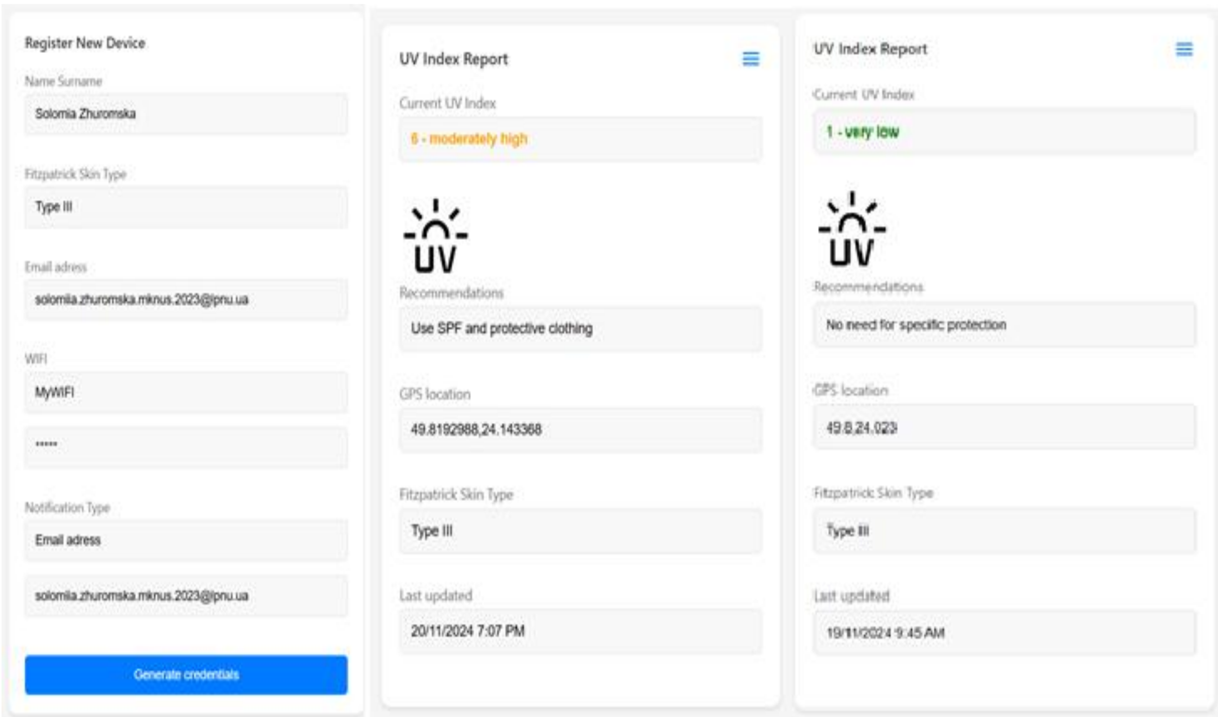

Figure 5: Mobile application interface displaying the UV Index in real time.

The system demonstrated stable performance during extended testing periods, including reliable data transmission and correct operation of the UV Index calculation algorithm. Thanks to its architecture, which combines edge computing, real-time communication protocols, and an adapted mathematical model for UV Index calculation, the proposed solution can be effectively deployed in personalized or educational environmental monitoring systems. This architectural approach fully aligns with the cyber-physical system (CPS) paradigm, ensuring seamless integration of physical sensing, embedded data processing, cloud analytics, and user-facing applications into a unified framework for adaptive and context-aware environmental surveillance.

5. Discussion

The results obtained from the testing of the UV radiation monitoring system prototype confirm its suitability for localized environmental monitoring, particularly in urban environments where spatial averaging of data does not provide an accurate picture for individual users. One of the key differentiators of the developed system compared to typical solutions is the combination of local measurement, cloud-based processing, and mobile visualization. This approach enables not only real-time response but also the accumulation of historical data for advanced analytics, aligning with the principles of cyber-physical systems, where the integration of sensing, computing, and actuation components ensures dynamic interaction with the physical environment.

During the calibration phase, the system demonstrated stable accuracy within ±1 UV Index unit, which is an acceptable result for consumer-grade sensors. As noted in the literature [24, 25], even among certified low-cost sensors (ML8511, VEML6075, UVM30A), significant variations in output characteristics are possible, primarily due to angular dependence and sensor orientation. In the proposed system, this issue was partially mitigated through software smoothing and calibration based on open reference models. However, for further enhancement of the system, it would be advisable to consider the use of hardware solutions, such as diffusers or mechanical sensor stabilizers, to minimize the influence of solar azimuth on measurement accuracy.

The analysis of discrepancies between the system readings and meteorological references (see Table 1) allows us to conclude the specificity and added value of localized monitoring. In particular, the case of significant deviation under direct winter sunlight (1 versus 4.3) does not indicate a measurement error but rather confirms the relevance of the IoT approach: the UV Index at human body level may differ significantly from regional forecasts. This aspect is especially critical in applications related to dermatological safety, agricultural monitoring, or risk assessment for children. Such personalized and location-specific monitoring, supported by CPS-based architectures, enables end-users to receive more accurate and context-aware data, closing the gap between environmental sensing and individual decision-making.

Compared to similar works, such as those implemented in [22, 23], where data are transmitted via an MQTT Mosquitto broker and stored in local databases (InfluxDB), the developed system demonstrates a higher degree of integration with AWS cloud platforms. This enables scalability to the Smart City level without the need for local server infrastructures. Solutions focused on LoRaWAN, as in Serrano [24], undoubtedly offer advantages in terms of energy efficiency but fall short in transmission speed, bandwidth, and the ability to integrate with mobile applications. The flexibility and modularity of the presented system, typical of CPS designs, ensure not only technical scalability but also adaptation to diverse application domains, including smart environments, healthcare, and precision agriculture.

Another aspect worth highlighting is the implementation of the mobile interface via Flutter/Blynk, providing real-time visualization of the surrounding UV environment and push notifications. This approach eliminates the need for third-party systems such as Grafana or local web access, simplifying the usage experience for non-technical end users. Most comparable systems in the literature rely on browser-based interfaces or deployed dashboards [22], which are not always convenient for mobile usage scenarios.

Overall, the proposed architecture demonstrates a high level of functional completeness: from analog signal acquisition, through its conversion and standardization (in accordance with ISO/CIE 17166), to cloud storage and mobile indication. Despite the absence of autonomous power solutions (as in LoRa-based systems), the system stands out for its scalability, compliance with standards, and the ability for rapid integration into broader ecosystems (smart cities, educational or medical environments). This comprehensive integration across physical, embedded, communication, and cloud levels highlights the system's alignment with CPS principles, ensuring seamless interaction between the sensing environment and cyber components for continuous environmental awareness.

To contextualize the performance and practical utility of the proposed system, several commercially available UV monitoring solutions were reviewed. These include L'Oréal My Skin Track UV, PCE-UV 34, and typical weather station-based instruments.

The My Skin Track UV device offers a compact and wearable form factor with passive NFC-based communication and integration with a mobile app. However, it lacks active notification features and depends on UVA sensors and algorithmic estimation for UVB exposure.

The PCE-UV 34 is a high-precision portable instrument used in industrial and medical environments. While it supports both UVA and UVB measurement ranges, it focuses on irradiance and does not directly compute the UV Index. Additionally, it does not retain historical measurements or provide cloud-based access.

Standard meteorological stations typically report UVB-based indices but are limited in terms of spatial coverage and lack real-time data granularity for local adaptation.

In contrast, the proposed system provides local UV Index estimation based on ISO/CIE 17166:2019 guidelines, real-time data streaming to the cloud, and integration with customizable alert mechanisms. It combines portability with edge processing and supports temporal data analysis, offering a viable alternative for personalized and educational use cases.

Considering the obtained results, the future development of the system may focus on improving accuracy and functionality by integrating additional sensors with different spectral characteristics, implementing machine learning algorithms for UV radiation level prediction, applying adaptive filtering methods to compensate for signal angular dependence, and combining local measurements with open meteorological data to create hybrid models for UV Index estimation.

Although the proposed UV monitoring system does not process sensitive or personal data, basic reliability and resilience aspects are relevant for practical deployment. Potential failure modes include temporary loss of Wi-Fi connectivity, analog voltage drift due to power fluctuations, and sensor misalignment in varying lighting angles. Security-wise, since only environmental data is transmitted, threat modeling is not the focus of this study. However, implementing secure cloud credentials and encrypted communication channels is considered important for enhancing the system's robustness in future deployments.

Thus, the testing results confirm the reliability of the proposed solution and its readiness for practical implementation in conditions where accuracy and locality of environmental monitoring are critically important.

6. Conclusions

This study presents a validated model and implementation of a cyber-physical system (CPS) for monitoring ultraviolet (UV) radiation, utilizing open-source sensor platforms and cloud infrastructure. The integration of the ML8511 sensor module with the ESP32 microcontroller, along with the algorithmic signal processing implemented in accordance with the ISO/CIE 17166:2019 standard, ensures real-time calculation of the UV Index with empirically validated accuracy within ±1 UV Index unit compared to reference data sources.

The proposed solution demonstrates the effectiveness of localized environmental monitoring using low-cost components and highlights the importance of personalized real-time UV exposure data, in contrast to generalized regional forecasts.

Experimental results confirm the device's ability to capture significant variations in irradiation under both natural and artificial lighting conditions, proving its practical suitability for assessing environmental health risks.

In addition, the integration with the AWS IoT Core cloud platform and mobile applications ensures scalable data storage, analytics, and timely user notifications. The modularity of the system architecture allows for its adaptation to a broader range of applications, such as smart city environments or precision agriculture, where UV radiation data can serve as a basis for behavioral or operational decision-making.

Future research will focus on expanding the spectral sensitivity of the system, implementing angular error compensation, and validating the system in various geographic regions and seasonal conditions to enhance the generalizability of the results.

Overall, the presented work contributes to the development of reproducible and scalable real-time systems for UV monitoring, framed within the context of environmental cyber-physical systems (CPS). By integrating embedded sensing, on-device data processing, wireless communication, and cloud-based analytics, the system embodies the core principles of CPS, enabling efficient interaction between the physical environment and cybernetic components for personalized environmental data delivery.

Declaration on Generative AI

During the preparation of this work, the authors used ChatGPT for grammar and spelling checks, as well as for improving the clarity of certain passages. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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