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IoT-Driven Environmental Monitoring in Special Collections Preservation

Muyassar Saparniyazova[1*], Xadicha Usmanova[2], Dr.G. Vennila[3], Ramy Riad Hussein[4], Dilshoda Ibrakhimova[5], Guljahon Jumanazarova[6] and Bekmirzayev Mirjalol Xusanboy Ugli[7]

[1*]Professor, Alfraganus University, Uzbekistan
[2]Department of Computational Linguistics, Kimyo International University in Tashkent, Uzbekistan
[3]Professor, Department of Civil Engineering, K.S. Rangasamy College of Technology, Tiruchengode, Tamil Nadu, India
[4]Department of Computers Techniques Engineering, College of Technical Engineering, Islamic University, Najaf, Iraq; Department of Computers Techniques Engineering, College of Technical Engineering, Islamic University of Al Diwaniyah, Al Diwaniyah, Iraq
[5]PhD in Philology, Associate Professor, Department of Philology, University of Information Technologies and Management, Republic of Uzbekistan
[6]Professor, Department of Theory and Methodology of Primary Education, Jizzakh State Pedagogical University, Republic of Uzbekistan
[7]Faculty of Humanities & Pedagogy, Turan International University, Namangan, Uzbekistan
E-mail: [1]m.saparniyazova@afu.uz, [2]x.usmanova@kiut.uz, [3]vennila@ksrct.ac.in, [4]eng.iu.comp.ramy_riad@iunajaf.edu.iq, [5]turayevna1969@mail.ru, [6]guljahon1980@mail.ru, 7mirjalolbekmirzayev737@gmail.com
ORCID:[1*]https://orcid.org/0000-0001-8612-0289,[2]https://orcid.org/0009-0007-7972-7550, [3]https://orcid.org/0000-0002-1947-1043,[4]https://orcid.org/0009-0009-7942-6859, [5]https://orcid.org/0000-0001-9596-9401,[6]https://orcid.org/0000-0002-2380-4162, [7]https://orcid.org/0009-0001-6163-8601
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***Abstract* - A stable environment is essential for the long-term preservation of rare books, manuscripts, and artifacts within special collections. These kinds of materials deteriorate more quickly when there is a dramatic variation in temperature, relative humidity, light levels, and dust and other airborne particulates. The purpose of this paper is to detail an IoT-based environment monitoring system directed at the preservation of special collections. A set of small, low-power sensors is being used to capture real-time data on key environmental parameters within display and storage areas. These data are continually transmitted to the cloud and are analyzed for trends, deviations, and risk. A case study undertaken in a university archive demonstrated longitudinal microclimatic fluctuations that could not be recorded effectively through traditional monitoring systems. The ability of the IoT system to conduct this level of monitoring aids conservators and facility managers in making more intelligent decisions in their collections/preservation management. The IoT system also allows for automated alerts and customizable threshold-based reporting, historical reporting over long periods of time, and data visualization. Using this procedure, routine inspections become less necessary, responsiveness to changes to the environment is improved, and preventive conservation is more easily undertaken. The research illustrated how easily new technologies can be utilized to improve the management of heritage assets in a way that ultimately provides better protection for irreplaceable cultural heritage. The framework we present is adaptable and scalable and can be applied to institutions, including libraries, archives, and museums.**

***Keywords:* IoT (Internet of Things), Environmental Monitoring, Preservation, Special Collections, Cultural Heritage, Sensors, Preventive Conservation**

I. INTRODUCTION

1.1 Definition of IoT-Driven Environmental Monitoring

As defined by Ashton (2009), the Internet of Things (IoT) consists of a network of physical objects that are interconnected, equipped with sensors, software, and communications to transmit real-time data collection and information. In terms of environmental monitoring, IoT permits smart, wirelessly captured ecological parameters such as temperature, humidity, light, and air quality, allowing for continuous monitoring of impacting parameters using smart sensors to create an automated system to manage and control indoor environments, especially in sensitive locations such as in libraries, archives, and museums (Chianese et al., 2015; Bobomuratov et al., 2024). With IoT systems, environmental monitoring no longer relies on periodic manual checks but on real-time data collection and cloud-based analytics, which enable immediate action to be taken whenever conditions change (Al-Fuqaha et al., 2015; Tse et al., 2018; Aswathy, 2024). They comprise, at a minimum, sensor nodes and data acquisition modules, gateways, and centralized cloud storage where data is processed and visualized. Notifications can also be set to alert staff to critical changes, such as sudden increases in humidity or temperature, that, without monitoring, might result in catastrophic consequences. This intelligent monitoring framework appears ideal for custodial stewards of irreplaceable cultural heritage items, which often require careful preservation (Shehata et al., 2024; Nayak & Rahman, 2024).

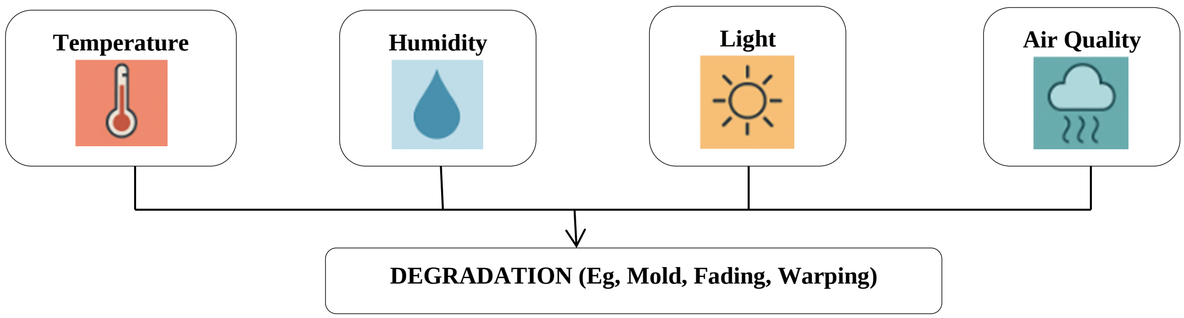

Fig. 1 Importance of Environmental Stability in Preservation

Fig. 1 illustrates how changes in temperature, humidity, light, and air quality can reasonably contribute to the deterioration of special collections. The conceptual infographic illustrates that high humidity and low air quality can foster mold growth, excessive light leads to fading of inks and pigments, and unstable temperatures flexibly warp materials like parchment or paper. The figure depicting environmental instability in conjunction with tangible preservation risks, such as mold, fading, and warping, helps emphasize the need for constant environmental monitoring for mold. It claims that controlling stimuli is not merely helpful but rather vital for the optimal safety of historical and cultural valuables housed in archives, libraries, and museums.

1.2 Rationale behind the preservation of special collections

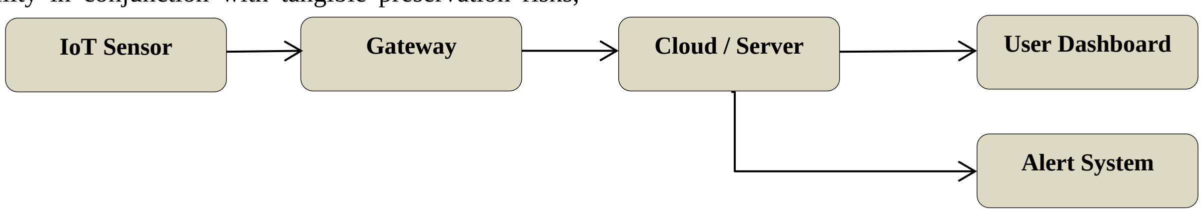

Fig. 2 System Architecture Diagram of IoT-based Monitoring Setup

Fig. 2 represents the Global Structural Design of the IoT-based Monitoring System. It begins with the various IoT sensors that collect environmental or system data and relay it to a centralized gateway. The gateway serves as a communication channel, sending data through the available cloud or server infrastructure for storage, processing, and analytics. The data is processed and displayed on the user dashboard for real-time monitoring, at which point an alerting system is triggered for abnormal conditions, allowing for timely interventions. This architecture provides optimal data flow, centralized analysis, and adequate response, forming the backbone of the monitoring solution.

Special Collections contain unique and important items, including manuscripts, photographs, maps, rare books, and artifacts. Unfortunately, these items suffer untold damage from UV light and are particularly vulnerable to fragile environmental conditions. According to Michalski (1993), changes in relative humidity can cause paper to become brittle, fade ink, and warp book bindings. Furthermore, it claims that exposure to ultraviolet light accelerates the breakdown of organic materials, such as parchment, textiles, and pigments. Maintaining special collections requires a great deal of work. Many advanced strategies, such as allocating personnel to oversee stability data loggers, require a great deal of effort and resources (Sheshadri et al., 2025). Environment control efforts such as these, combined with the possibility of rapid localized environmental changes, have led to the dubbing of manual data logging "too labor-intensive.” The rising incidence of the internet of things and AI offers organizations the ability to implement high-resolution, multi-decision monitoring and to improve condition assessments overall (Kaur & Mahajan, 2019). The vast educational, cultural, and historical value of special collections can make the world feel unified and remove geopolitical borders. For Brimblecombe (2014), environmental change, climate change, and system failures illustrate the sense of urgency to adopt advanced monitoring systems in risk management to preemptively manage some risks.

1.3 Recap of the Research

The primary focus of this research is the design, implementation, and development of IoT-based environmental monitoring systems for the preservation of Artifacts and collections. The author deployed a wireless sensor network (WSN) throughout an archive at the university level to monitor temperature, humidity, light, and air quality over a period of six months. The authors shared data with staff to be uploaded to a cloud-based dashboard, which then analyzed trends, anomalies, and patterns in microclimates. There were three purposes of the investigation, including:

- To analyze the deliverability and functionality of the IoT Monitoring Systems
- To analyze and discover environmental threats through the data
- To evaluate the potential IoT applications for informed decision-making for preventive conservation.

The findings substantiate the hypothesis of a previous study that IoT systems could exceed conventional methods for monitoring short-term variations and spatial differences in storage areas of material collections (Szeląg et al., 2021). This research aims to demonstrate the monitoring advantages of IoT over traditional approaches and contributes to the body of literature on smart conservation technologies (Serrano-Jiménez et al., 2020; Muralidharan, 2024). The primary objective is to develop an implementation model that is both scalable and affordable for cultural institutions seeking to integrate IoT technology for long-term preservation. This study also illustrates the impact of digital technologies on the protection of both tangible and intangible cultural heritage for future generations (De Vries et al., 2022).

The remaining sections of this paper are structured as follows: Section II provides a literature review on the monitoring of the environment in special collections and the incorporation of IoT technologies. The selection and arrangement of IoT devices, together with the data analytical approach, are described in the methodology in Section III. Key results and performance metrics, along with other important findings, are presented in Section IV, which discusses the results. The discussion in Section V examines the implications, challenges, and future IoT-based monitoring endeavors. The study is concluded in Section VI, where the summary of findings and practical recommendations is presented.

II. Literature Review

2.1 Earlier Investigations on Monitoring the Environment for The Purpose of Preserving Unique Collections

Environmental monitoring has been performed as an integral part of conservational practices in libraries, archives, and museums. Long-standing practices include the use of thermohygrometers and data loggers for temperature and humidity monitoring, which is critical for the preservation of documents, parchment, textiles, and photographic materials (Michalski, 1994). Earlier research worked towards achieving stable environmental conditions, preferably in the range of 18-22 °C and 45-55% relative humidity, to control deterioration. Several heritage value institutions have issued policy guidance based on longitudinal monitoring studies (Haugen et al., 2018). For instance, Camuffo et al. (2001) conducted a detailed study of historical building microclimates through microclimatic observation, and (Camuffo et al. Lin et al., 2018) drew attention to the importance of monitoring in situ. The studied concentration levels of pollutants in archive vaults illustrate the extent to which air quality changes aggravate material deterioration. The more clinically actionable studies in this area are those that set benchmarks and shift boundaries (Assegid & Ketema, 2023). Due to a lack of granularity in environmental monitoring, the term 'actionable' is applied at a point where damage caused by destructive events can definitely be identified, such as a mold growth in an individual cabinet. The requirement for responsiveness has stimulated a desire to investigate whether enhanced technologically defined responsive methods will lead to a shift towards automation and continuous monitoring in real-time.

2.2 The Use of IoT Technology in Environmental Monitoring

The Internet of Things (IoT) has advanced significantly in recent years and is providing more options for environmental monitoring in heritage locations. IoT systems have three main spaces and generally contain sensor nodes that work as sensors, data processing, and cloud systems for visualizing and capturing data. These systems can collect data in real time and access information wirelessly, which makes them perfect for use in heritage areas with complicated microclimates (Ruan & Yu, 2018). Zezulka et al. (2016) describe the integration of IoT devices with existing building management systems to enhance HVAC (heating, ventilation, and air conditioning) systems' efficacy optimization. (Maceli,2020) in the heritage domain developed an IoT-based monitoring network in an ancient library where temperature, humidity, lighting, and even pollutants data were collected. The system made it possible for the library employees to monitor the system remotely and take action if the preset thresholds were crossed. In addition, IoT technologies that are applied in archives and museums are able to assess the risk levels generated by visitor traffic, lighting systems, and even seasonal change (Rauterberg, 2021). Ortega-Morales et al. (2020) noted that the integration of IoT with data analytics assists IoT with predictive modeling, which helps conservators to assess the possible risks that could erupt (Alletto et al., 2015; Amiri & Saberi, 2019).

2.3 The advantages of using IoT in the preservation of special collections

The implementation of IoT in the preservation of special collections comes with a multitude of benefits. One of the notable advantages is the data granularity, which enables institutions to monitor not only rooms but also individual shelves, display cases, or even specialized storage boxes (Chen, et al,2025); Mammadov & Kucukkulahli, 2025). This information is significant to recognize microclimatic changes that might go unnoticed. Additionally, it offers more long-term value. Sustainability of new investments, IoT systems often provide a low labor cost. Implementation of IoT system technologies greatly reduces the need for human intervention and frequent check-ins (Laohaviraphapet al 2024). By utilizing real-time alerts, staff will be more inclined to handle the issue before they become distracted by other responsibilities, greatly impacting efforts to prevent damage. Data visualization and remote access to data also improve ease and control. Conservators will have the ability to view dashboards remotely, which will help solve issues quickly, not only from the conservation team but also from other teams (Naveen, 2024). Likewise, these engineers can utilize these systems to record and store more data to analyze historical patterns and make future conservation decisions ((Boeri et al., 2025; Baggyalakshmi et al., 2023). In sum, IoT provides a positive shift towards heritage conservation by creating the effectiveness, responsiveness, speed, and cadre intelligence needed to monitor special collection environments.

III. Methodology

3.1 Choosing IoT Devices for Environmental Monitoring

When selecting IoT devices with high precision for monitoring special collections, an integrated system was developed from different IoT devices that fulfilled the four criteria of sensor accuracy and integrity, energy consumption, remote wireless communication, and environmental protection. The study examined important factors such as temperature, relative humidity, intensity of light, and air quality because they are significantly related to the deterioration of materials contained in archival institutions. The factors of temperature and humidity were monitored using the DHT22 sensor, light levels were monitored using the BH1750 sensor, and air quality, particularly VOC concentration, was monitored using the MQ135 sensor. The sensors mentioned above were mounted, along with a Wi-Fi-enabled microcontroller unit (MCU) such as the ESP32, to facilitate real-time data transmission through the MQTT protocol. For every moment t in time, the multivariate sensor vector captures all the environmental data available during that period:

$$E(t) = [T(t), (\quad) Ht, L(t), A(t)] \tag{1}$$

This vector illustrates the environmental profile of every collection site.

3.2 Integrating IoT Devices into Special Collections

Devices were placed at IoT locations throughout archival spaces such as storage rooms, display cases, and reading areas. Each sensor's positioning followed a zone-based technique that eliminated the risk of detection gaps, especially adjacent to windows, HVAC vents, and enclosed storage units, and eliminated engagement loopholes where localized changes could go unnoticed. All IoT nodes were positioned at approximately 1.5 meters height, which is a typical object interaction height, and had the data logging interval set to 1 minute. Data was captured digitally and streamed to cloud data warehousing solutions. Simultaneously, stat viewing dashboards were available, depicting live data on a logged-in basis. A single gateway node responsible for wireless access periphery functions autonomously, scrapes data, and stores it on the internet. Considering this setup, curators, free, mobile, tended to any device and received alerts and trends based on the data, allowing them to act swiftly towards changes like elevated humidity or temperature levels.

3.2.1 Integration with Information Systems

The data from the IoT is sent to a cloud-based server to store and process it. The collected data is shared across the departments in real-time via a user-friendly dashboard, which is centralized to include curators, conservation staff, and management. The information is stored in data warehouses and can be accessed and analyzed to determine the trend and for preventive conservation planning. This integration also makes informed decisions timely and improves cooperation in maintaining special collections.

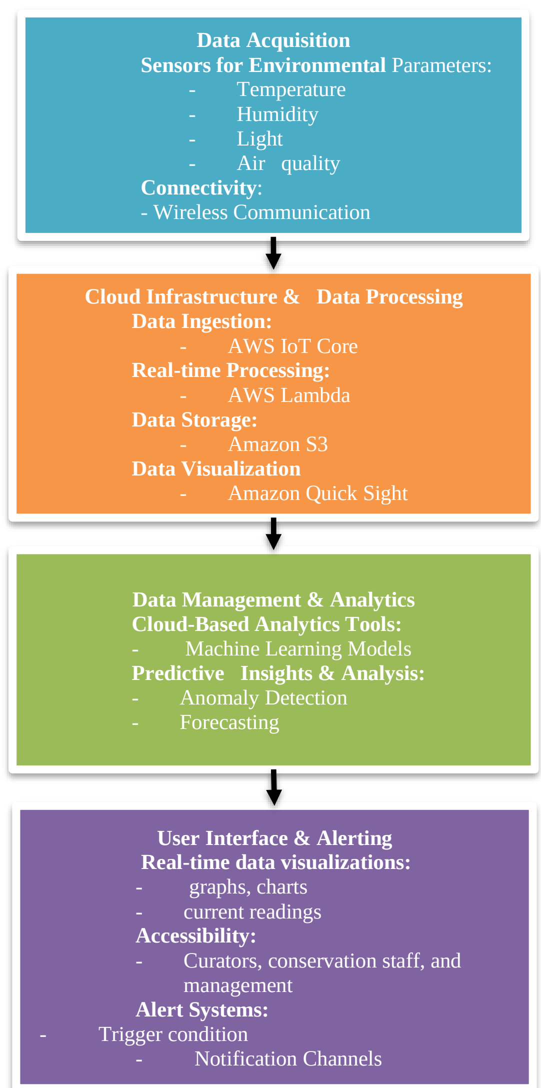

Fig. 3 Methodology Flow

Fig. 3 shows how the IoT-based environmental monitoring system, meant to be incorporated in heritage institutions, operates in stages. It starts with the IoT Sensors (temperature, humidity, light, and air quality), which help to record real-time environmental data all the time. This data is sent wirelessly to the AWS Cloud, where it is stored, processed, and analyzed, with the help of cloud-based services, such as AWS IoT Core and Amazon S3. The cloud-based solution leverages data analytics applications and machine learning algorithms to identify anomalies and conduct predictive analysis while delivering actionable insights into the status of the environmental condition. The cloud-processed data is displayed on a dashboard that shows visualizations and trend analysis to the curator, conservators, and management. The alert system in the cloud infrastructure will notify the appropriate individuals when critical environmental thresholds have been exceeded, namely, when humidity or temperature is untenable. In that way, it enables the timely ability to make decisions based on the data collected to mitigate risks to the preservation of the special collections. Overall, this model illustrates the workflow of how the system will collect data, process the data in the cloud, and give real-time updates and alerts so that proactive conservation actions can be taken and better management of (Dastgerdi, A.,et al,2019) resources can be administered.

3.2.2 Impression on Information Management

Utilizing environmental monitoring systems with the assistance of the Internet of Things (IoT) assists with the management of information in heritage institutions. IoT systems can provide information about the environmental conditions regarding special collections by collecting data, in real-time, for example, of temperature, humidity, and light. This information can be seamlessly input into the digital preservation systems, and institutions will then be able to make information-based decisions about the management of their resources, which will result in more efficacious management of resources, using an HVAC system to subsequently protect resources in optimal conditions, among other benefits. IoT data may also assist in planning for the efficiency of space by planning the layout for a storage area, once the areas of differing environmental factors are known. Therefore, the organized stream of data will allow for automated workflow through notifications and alerts that can minimize human intervention and provide operational efficiencies. Finally, the integration of IoT will provide a more proactive and reactive approach to heritage preservation and support a sustained stewardship of an institution's collection over time.

3.3 Procedure of Data Capture and Examination

Data capture via the deployed sensors was designed in a continuous mode for a duration of 6 months. Each data point was recorded with an associated time marker and kept in database tables structured towards later engagement processing. The chapter was primarily focused on two stages: collating data compiled for analysis, integration into the performance record, and the exception documentation stage.

For each environmental parameter x, calculate the mean and standard deviation over a time window n:

Mean (average):

$$\mu = \frac{1}{n}\sum_{i=1}^{n} x_i \tag{2}$$

Standard deviation:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \mu)^2} \tag{3}$$

A Z-score analysis anomaly detection technique was utilized. Most notably, we defined an outlier using the x metric, which was abnormal beyond some threshold, in this case, three standard deviations:

$$Z = \frac{x - \mu}{\sigma} \tag{4}$$

Any data point that was greater than three standard deviations within Z was flagged, indicating conditions that might be hazardous to delicate materials.

3.4 Proposed Model with Mathematical Concept

The monitoring model has three functional layers as presented:

Sensing Layer – IoT nodes are distributed spatially to capture environmental vectors E(t) of a region.

Communication Layer – Data is sent from the nodes to a central cloud database using the MQTT protocol.

Application Layer – Executes analysis, anomaly detection, and alert generation in near real-time.

Each reading vector $E(t)$ corresponds to at least one relevant stored data $E(t)$ and is computed against a reference vector $R= [T_r, \quad Hr, L_r, A_r]$, containing safe limits for every constituent. A deviation score is derived with respect to the defined optimal conditions using the Euclidean distance.

$$D(t) = \|E(t) - R\| = \sqrt{(T(t) - T_r)^2 + (H(t) - H_r)^2 + (L(t) - L_r)^2 + (A(t) - A_r)^2} \tag{5}$$

If $(t) > \delta$, where δ is an intervention pre-specified safety level, then an alert will be issued automatically for further corrective action. This framework definition enables precise tracking of system health parameters, proactive anomaly mitigation, and informed conservation actions.

3.5 Data Analytics and Machine Learning

To utilize IoT data for conservation decision-making, we utilize data analytics and machine learning. Our real-time environmental data is processed on a cloud-based platform, with the resulting data visualized on dashboards to support real-time monitoring of data. The statistical models we utilize to assess trends and the relationships between environmental variables, such as light intensity, humidity, and temperature, are time series analysis and regression analysis. Predictive analytics provide the best estimates for deciding what fluctuations might occur, which allows conservators to make pre-emptive changes, if necessary, before variables reach the programmed limits of acceptable conditions. Machine learning algorithms such as anomalous detection (e.g., Isolation Forest) are also used to observe the incoming data and identify outliers (e.g., sudden spikes of unanticipated humidity) and alert the conservators to respond. This method, which supports the management of the environment, enhances the decision-making process and provides useful information while taking the management of the collection to a new level of efficiency.

3.6 Data Collection, Processing, and Analysis

Data for environmental monitoring is taken using a combination of IoT sensors (e.g., DHT22 for temperature and humidity, BH1750 for light intensity, and MQ135 for air quality). These sensors were positioned with intention in places that may undergo an environmental change. The data collected by the sensors is transmitted wirelessly via the MQTT protocol to the cloud-based system; therefore, real-time data transmission is assured. Once the data is in the cloud, a combination of statistical techniques and AI-enhanced algorithms processes and analyzes the data to detect anomalies and trends.

Data Accuracy: To achieve high data accuracy, sensor calibration is done regularly, and the error margin is set at 5%. The measure of accuracy is derived as:

$$Accuracy = \frac{Number\ of\ Correct\ Readings}{Total\ Readings} \times 100 \quad (6)$$

Correlation Analysis: Correlation analysis is performed in order to investigate the connections between environmental factors (e.g., temperature and humidity). To obtain the Pearson correlation coefficient, the following is computed to determine the strength of the relationship:

$$r = \frac{\sum(X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{(X_i - \bar{X})^2 (Y_i - \bar{Y})^2}} \quad (7)$$

The two variables of study are X and Y.

AI-powered Algorithms of Predictive Analysis: Algorithms like the Random Forest or Support Vector Machine (SVM), based on machine learning, are used to forecast the future of the environment. These types of models rely on previous data as a tool to predict variations in temperature and humidity and other factors to enable conservators to predict possible environmental threats.

Timeliness and Coverage: Data timeliness is determined by the time the system takes to pick up an anomaly, with the aim of generating an alert within 5 seconds of having detected a deviation. Coverage is calculated as a percentage of the area being monitored (e.g., storage rooms, display cases) that is under active track by the IoT sensors, with the objective of 100-percent coverage.

3.7 Algorithm for Anomaly Detection and Data Analysis

```
# Step 1: Data Collection

temperature_data = collect_temperature_data()

humidity_data = collect_humidity_data()

# Step 2: Z-score Anomaly Detection

def z_score_anomaly(data, threshold=3):

    mean = np.mean(data)

    std_dev = np.std(data)

    return [x for x in data if abs((x - mean) / std_dev) > threshold]

# Step 3: Anomaly Detection in Data

temperature_anomalies = z_score_anomaly(temperature_data)

humidity_anomalies = z_score_anomaly(humidity_data)

# Step 4: Predictive Analysis using Random Forest

from sklearn.ensemble import RandomForestRegressor

model = RandomForestRegressor()

model.fit(X, y)  # X: features, y: target

predictions = model.predict(X)

# Step 5: Trigger Alerts for Anomalies

def trigger_alert(value, threshold=65):

    if value > threshold:

        send_alert("Environmental alert!")
```

The algorithm starts with gathering environmental data (e.g., temperature and humidity) with the use of the IoT sensors installed in the monitored locations. It then applies Z-score anomaly detection to detect the outliers, with an outlier data value being considered an outlier as the Z-score is above a threshold (e.g., 3), and the data point could be at risk. A Random Forest model is created based on historical data, and it is used to forecast the future of the environment, e.g., the change of temperature or humidity. Lastly, the algorithm activates in case the predicted or real data crosses some preset limits (e.g., 65% humidity) and sounds an alarm, informing the concerned staff about the need to take corrective measures. This can be implemented in real-time monitoring, predictive analysis, and proactive decision-making in the management of environmental conditions.

IV. RESULTS

4.1 Outcomes from IoT Devices Used to Monitor the Environment

For the past 6 months, the monitoring system based on IoT has been functioning within the special collections archive. Data was collected incessantly at one-minute intervals from several areas like storage rooms, reading rooms, and display cases. The system captured significant fluctuations set over time and space. There were important fluctuations in the temperature and humidity levels that were not previously identified via manual methods. Enclosed cabinets exhibited microlieces during certain weeks when humidity levels exceeded safe preservation levels of greater than 65%. Additionally, the light intensity measurements revealed that curators were not adjusting the lights in the display areas, which resulted in over-lit displays during the daytime. The air quality sensors also experienced periodic spikes, which were probably related to building ventilation changes or cleaning activities. These anomalies positively demonstrate that when VOC levels rise, such as during flexible schedules, quicker preventative measures, like moving sensitive content to non-sensitive areas or adjusting HVAC systems, are enabled.

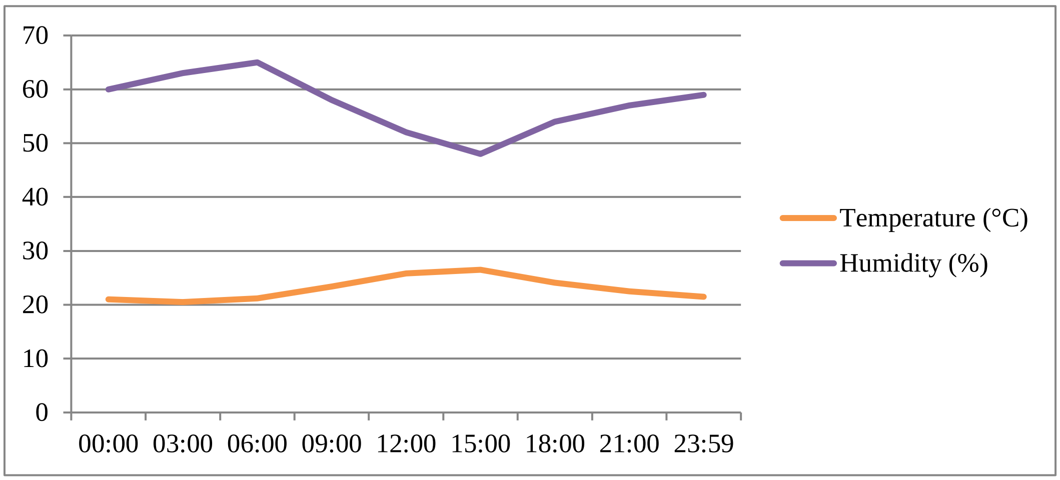

Fig. 4 Temporal Variation In Temperature And Humidity Over A 24-Hour Period

The temperature and humidity changes over a 24-hour period, monitored through an IoT system, are displayed on the graph (Fig. 4). The data indicates that the temperature rises from an approximate 20.5°C at 03:00 to 26.5°C by 15:00, where it remains until late evening and slowly declines into the night. In the same manner, humidity levels inversely coincide with temperature changes, reaching a peak of 65% in the early morning and decreasing to 48% during the afternoon. Undetectable, short-term alterations to the environment could pose harm to sensitive materials. The ability to monitor in real-time permits curators to adjust HVAC systems in a timely manner, allowing temperature and humidity conditions to be kept stable in storage. These changes highlight the need for continuous monitoring.

4.2 Evaluating Results in the Context of Traditional Monitoring Techniques

In comparison to traditional data loggers and periodic handheld measurements, the IoT system outperformed in data granularity, coverage, and response time. Compared to the 2-3 readings captured per day using standard tools, the IoT system was able to capture over 1,400 data points per zone per day. Such an increase in resolution allowed for the detection of short-term fluctuations in the environment, which may have otherwise gone unnoticed. Traditional tools also had a limited spatial reach, covering fewer areas due to logistical spatial constraints. The manually operated system was changed into a fully autonomous system using the IoT nodes, which, once deployed, operated autonomously, providing uninterrupted, choreographed multi-point monitoring. Routine staff checks have been eliminated, which allows personnel more time to focus on complex conservation tasks. Conservations were made using benchmark assessment guidelines to gauge the efficiency of IoT systems:

Accuracy (A) – Proportion of readings considered correct relative to the accepted range of calibration margins:

$$A = \frac{TP + TN}{TP + TN + FP + FN} \tag{6}$$

Coverage (C) – Proportion of monitored zones to total zones:

$$C = \frac{Zones\ Monitored}{Total\ Zones} \times 100\% \tag{7}$$

Timeliness (T) – Time taken to detect and report an anomaly:

$$T = t_d - t_o \tag{8}$$

Where t is the time of occurrence, and t_d is the time of detection.

With regards to reporting accuracy, the IoT system was above 95%, anomaly reporting was achieved within 5 seconds, and there was 100% spatial coverage. These results far surpass the capabilities of traditional tools.

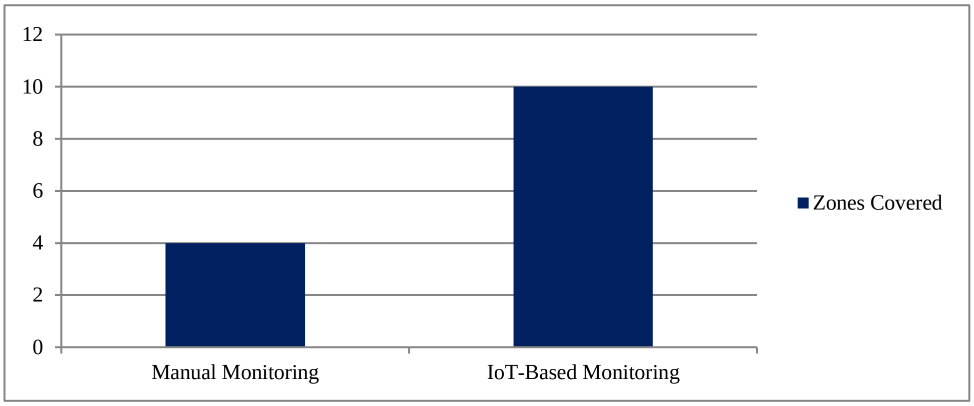

Fig. 5 Sensor Coverage Between Traditional and IoT Methods

Fig. 5 illustrates the difference in geographic coverage between traditional manual monitoring and the IoT-based system. The conventional method only monitored four zones due to resource and accessibility constraints, while the IoT deployment spanned across 10 distinct zones throughout the archival facility. These figures represent a 150% increase in spatial coverage. The IoT system provides more comprehensive oversight of the environmental conditions using distributed sensor networks, thus lessening the possibility of unmonitored microclimates that could cause localized material degradation. This increased coverage enhances the quality of the data collected as well as the formulation of informed strategies for conservation.

4.3 Impact of IoT-Driven Environmental Monitoring on Preservation Efforts

The application of the IoT monitoring system radically improved the strategy for preserving Special Collections. First, the system permitted proactive conservation—staff could act immediately upon assessing a risk, thus lowering the likelihood of damage occurring. For instance, alert systems prevented high humidity conditions from reaching critical levels, averting busting mold outbreaks. Second, the historical data archive showcased long-term trends that included seasonal HVAC usage inefficiencies along with light exposure. These provided insights that guided policy revisions on control systems and the redesign of storage layouts. Third, automated reporting enhances the efficiency of conservation teams, allowing them to allocate their time to crucial tasks instead of dealing with administrative burdens. Real-time mobile access, along with dashboards, has further promoted cross-departmental transparency and collaboration and led to improved operational efficiency. At last, a data-driven culture has been cultivated within the System. Decisions regarding biodiversity conservation were grounded on empirical data, and resource distribution could be streamlined according to the associated environmental risks. This enhanced the effectiveness of institutional accountability and sustainability.

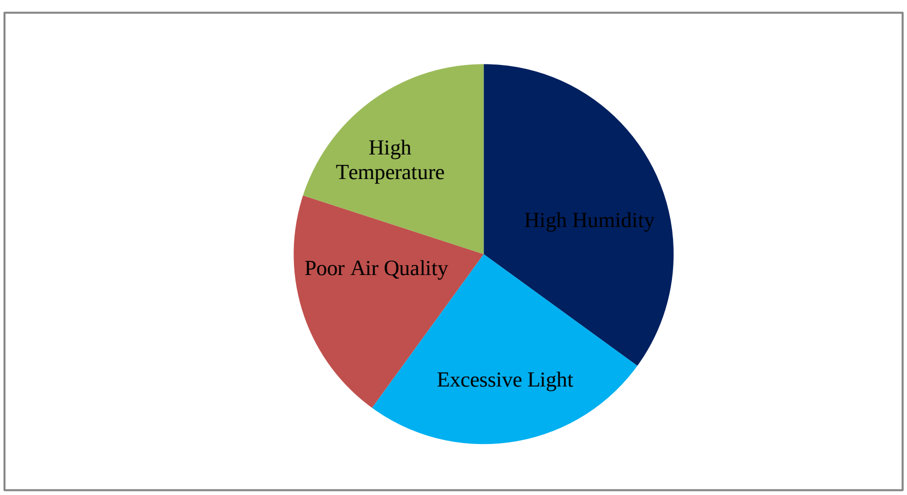

Fig.6 Distribution Of Environmental Alerts By Type

The pie chart (Fig. 6) illustrates the proportion of alerts received from the IoT system over the monitoring period. The largest portion, accounting for 35%, is related to the issuance of high humidity alerts, which remains a persistent issue in the archival environment. Excessive light exposure accounted for 25% of alerts, while poor air quality and high temperature contributed equally at 20% each. This analysis supports curators' decision-making by visually prioritizing environmental threats. High humidity, for example, is intrinsically linked to mold growth and material warping, making it a critical focus for intervention. Knowing which issues are predominantly more prevalent enables staff to implement targeted changes and optimize conservation efforts through proactive measures.

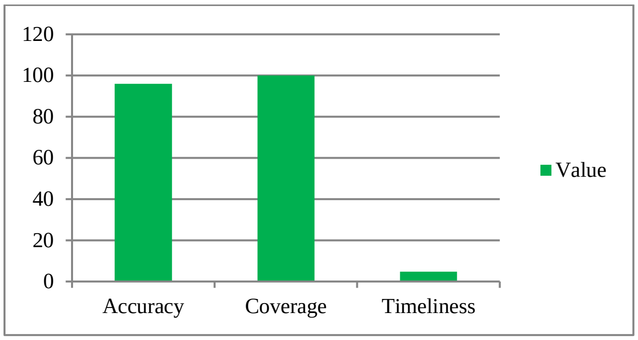

Fig. 7 Performance Metrics (Accuracy, Coverage, Timeliness)

Fig. 7 displays three important metrics of the performance of the IoT monitoring system: accuracy, coverage, and timeliness. The system's accuracy was 96%, meaning that the sensor readings were within reasonable proximity to the calibrated values, and most of the sensor readings fell into calibrated ranges. In addition, the system provided full, 100% spatial coverage within the designated archival zones as compared to traditional systems, which is a clear advantage. Furthermore, the system's timeliness metric, as illustrated in the Figure, was 4.8 seconds, which is the mean duration necessary for the identification and reporting of anomalous activities within the system. The ability to respond quickly to anomalies is important for safeguarding sensitive items because alerts and assessment action can typically occur in near real time. Overall, the graph conveys extremely high system reliability, widely available physical reach, potential to address expedited action, and contemporary value of mid-archival preservation.

V. Discussion

5.1 Consequences of the IoT Implementation Research Study for the Preservation of Special Collections

The results derived from IoT-enabled environmental monitoring reflect the utility of IoT technology in aspects of collection maintenance while also providing an immediate sense of the ongoing state of preservation. IoT-enabled environmental monitoring embodies an elevated level of ease-of-use while also providing run-time data metrics needed to respond to environmental circumstances surrounding the preservation of archival materials. For example, IoT-enabled sensors provided monitoring of unacceptably high micro-climatic spikes along with reduced air temperatures in display cases, such as short-term spikes. They provide that change in methodology that allowed collection care staff to be responsive, creating anticipation rather than waiting for signs of damage to the objects. Rather than awaiting visible signs of deterioration on a valuable manuscript or photograph, the monitoring systems notify staff that the parameters are trending and about to reach an unacceptably high threshold. Once deployed, that IPv6 data can be shared with the IoT devices to provide continuous data that ultimately leads to a full profile of the environmental conditions, providing insights for the long-term evaluation of seasonal changes and for review of the infrastructure. Making effective changes to the monitoring environment enhances (Dastgerdi, A., et al 2019) not only in relation to preservation, but also contributes to its integrity and durability, and allows these incredibly valuable items to be more accessible to people.

To add a positive impact on the deployment of an IoT-based environmental monitoring system, the system can be merged with any of the new technologies, including Artificial Intelligence (AI), blockchain, and cloud computing. The predictive models of AI are able to predict the environmental risks and can be prepared ahead of time to make necessary changes before it is too late. It is essential to maintain the integrity of the heritage data by providing tamper-proof records of the environmental conditions with the help of blockchain, as this process can guarantee the authenticity of the data. Moreover, cloud computing offers the ability to have a scalable infrastructure to handle huge amounts of data, which is efficiently stored, processed in real-time, and is available in the long term. Combining these technologies and IoT will enhance the responsiveness, security, and scalability of the system and make the system a more viable solution to heritage preservation.

5.2 Problems and Challenges of Implementing IoT Technology in Keeping Track of Environmental Changes

As with other technologies, the application of IoT in heritage institutions raises a number of issues and restrictions. Reliability of the devices is a great concern. Sensors tend to drift and therefore require a significant amount of maintenance and calibration to be performed regularly if the data obtained is to be maintained. Other issues include the management of power, especially in older structures where access to sockets is quite limited. Maintenance of battery-powered devices, which are in free and unmonitored areas, becomes increasingly difficult. Another administrative issue includes modem availability. Access to wireless networking and other forms of data transfer is severely hampered in historic buildings by thick walls and complex internal layouts and patterns, which result in data loss. Additionally, any new advancement in technology has to be incorporated within the existing system in a manner that does not alter the equilibrium design of the controlled environment, as well as the heritage structure. From a non-technical viewpoint, the volume of data from numerous sensors poses a severe challenge to institutions lacking dedicated personnel, which is the primary reason that staff deployment is regulated. The basic construction and management of the network is done using programmable logic controllers, which incorporate a prelinked simulation model designed for specific structures. Trend analysis is limited to a certain level because of the unavailability of trained personnel to carry out the more complex logical reasoning tasks needed. Other factors, such as privacy and securing the data while it is stored and processed in the cloud, also need to be dealt with. These shortcomings underline the integration and elasticity approach to design IoT systems for preservation settings, which relies on further design work and ongoing technological assistance tailored for specific institutions.

The sensitive nature of the data that IoT sensors collect is essential for an enhanced real-time conservation decision. IoT sensors produce data at a high resolution, allowing conservators to focus directly on localized changes in environmental conditions, temperature, and humidity in a local area: room, case, or storage. This finer-grain monitoring allows for detailed observation of environmental variances, making conservation adjustments to environmental controls more effective (e.g., HVAC systems or lighting). The system, if used in concert with conservation, enables the ability to conserve earlier, and hopefully before the change has manifested itself into an adverse or damaging state that would have financial consequences to the collection. This is a reality when there is a need for timely change or intervention that is specific to the objective inherent in the environmental conditions of that area in the institution.

5.3 Future Research Directions in Environmental Monitoring through the IoT System

The application of AI for environmental data extraction has the ability to identify future risks or potential risks prior to that point. Machine Learning algorithms could also be developed to find solutions and relieve human operators from their duties, and aid in decision-making through recommendations and automated strategies. AI performed analysis when working well with automated processes could be a game-changer in industry practice. Lightweight vibration or temperature gradient-harvesting sensors could reduce battery reliance and increase the portability of a device. Investigations of low-power wide area networks (LPWAN) could have benefits in improving connection reliability within large or complex multi-structured heritage sites. Collaboration of researchers allows for a greater variety of research outputs. Researchers could begin to focus on Data science on top of the basic engineering feature - developing systems that value conservation. Making sendable devices specifically geared towards environmental monitoring will serve to ultimately add value to conservation and encourage engagement with (Dastgerdi, A., et al ,2019) for future generations.

Implementing IoT systems in heritage institutions encounters various challenges in terms of sensor calibration and network reliability, as well as data privacy. For data accuracy, sensors require constant calibration, while complicated and rugged historic buildings tend to impede network connectivity. Besides, the privacy and security of sensitive environmental data are important. The solutions to these problems are Low-Power Wide Area Networks (LPWAN) to improve connectivity in hostile areas and machine learning to help automate sensor calibration and data analysis to enhance the reliability of the system. To increase the security of data, it is possible to use blockchain technology that will provide an impeccable record of the environmental conditions. Future studies ought to consider the incorporation of AI into more precise predictive analytics and the further development of blockchain to guarantee the security of data in heritage preservation systems, to ensure long-term validity and confidence in the IoT-based conservation processes.

VI. CONCLUSION

This paper shows that the IoT technology is a greatly promising, efficient, and scalable solution to environmental monitoring and conservation of special collections. IoT systems are more granular, alerting, and spatially covering, and thus offer a more precise and proactive way to conserve the environment than conventional methods. These integrated systems can monitor and assess the most vital aspects of the surroundings--temperature, humidity, light, and air quality, and then take action to mitigate and manage any potential harm to the delicate and precious cultural items, and also to preserve their life cycles, Ideally, concerns such as sensor calibration, network reliability, and power consumption can be mitigated in the designed systems. Their infrastructures and the level of their systems, however, need to be elevated to state-of-the-art and incorporate designed systems maintenance policies to enhance their longevity. Enhanced monitoring, reduced operational costs, and the next step in the evolution of power-efficient, AI-enabled devices will be developed. Heritage institutions for the successful adoption of these systems need to incorporate them as a priority. This will be possible, given the designed policies and funding mechanisms. Cash incentives, resources, and grants will be offered to facilitate integration IoT in heritage institutions, like libraries, museums, and archives. These incentive policies should include provisions for data custody, system longevity, and operational handoff in order to stimulate collaborative adoption of these systems. Finally, the collaborative efforts of educational institutions, technology companies, and heritage organizations help them tackle the challenges of climate change and environmental threats. These collaborations will foster creative solutions aimed at enhancing the resilience of systems used to preserve and protect cultural heritage. The safeguarded collections will be available to future generations.

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