International Journal of Research and Review
[Indexed, Peer-Reviewed Journal]
Volume 12; Issue: 5; May 2025
Website: www.ijrrjournal.com
Research Paper *E-ISSN: 2349-9788; P-ISSN: 2454-2237*

Trigger Based Smart Attendance Framework with Machine Learning for Predictive Student Performance Analysis

Diptika Ghosh Roy[1], Abir Bhattacharjee[1], Rakesh Das[1], Prabhat Das[12]

[1]Department of Computer Science and Engineering, School of Engineering and Technology, Adamas University, Kolkata, India
[2]Department of Information Technology, School of Computing Sciences, The Assam Kaziranga University, Assam, India

Corresponding Author: Prabhat Das

DOI: https://doi.org/10.52403/ijrr.20250535

ABSTRACT

In educational institutions, traditional attendance-taking methods such as manual roll calls or sign-in sheets are inefficient and prone to issues like proxy attendance and human error. These limitations compromise data integrity, hinder performance monitoring, and increase the burden on administrative staff. To address these challenges, this paper proposes a Trigger-Based Smart Attendance Framework that integrates biometric fingerprint recognition, IoT microcontroller hardware, and machine learning algorithms for automated, secure, and predictive attendance tracking. The system employs ESP32 microcontrollers and R307S optical fingerprint sensors installed at individual classroom benches, allowing students to log attendance using their unique biometric identifiers. A master ESP32 unit coordinates communication among the fingerprint scanners and transmits attendance data to a centralized server via Wi-Fi. Upon successful fingerprint authentication, a relay module triggers a secondary device (slave ESP32), adding an extra layer of verification and control.

On the software side, a web-based platform built with React.js offers intuitive, role-based interfaces for students, teachers, and administrators. It includes real-time dashboards for attendance viewing, performance monitoring, and system control. The backend, developed using Flask (a Python web framework), enables RESTful API communication and manages data storage in a MongoDB NoSQL database. Beyond data collection, the system integrates Random Forest and XGBoost machine learning models to analyze attendance patterns and predict student performance. This predictive capability supports early identification of at-risk students, enabling timely academic intervention. Overall, the proposed framework enhances operational efficiency, transparency, and data-driven decision-making, marking a significant step toward digital transformation in academic administration.

Keywords: Smart Attendance System, Biometric Authentication, IoT in Education, Machine Learning, Student Performance Prediction

INTRODUCTION

Attendance tracking plays a pivotal role in academic institutions, serving as a key indicator of student engagement, discipline,

and overall performance. Despite its importance, traditional methods such as verbal roll calls and paper-based registers remain widely used across educational settings. These manual systems, while simple to implement, are time-consuming, prone to human error, and vulnerable to proxy attendance, where one student marks presence on behalf of another [1]. Such practices compromise data accuracy and impose additional burdens on educators and administrative staff.

To mitigate these shortcomings, a range of digital attendance technologies has been introduced, including Radio Frequency Identification (RFID) cards, Quick Response (QR) codes, and facial recognition systems [2]. Although these innovations represent steps toward automation, they continue to face critical limitations. RFID and QR-based systems are susceptible to misuse, as physical tokens can be easily exchanged among students [3]. Facial recognition, while promising in controlled environments, often struggles with real-world variability such as poor lighting conditions, angle distortions, and challenges related to ethnic and facial diversity [4]. These limitations are particularly pronounced in geographically and culturally diverse nations like India, where such inconsistencies can significantly degrade system reliability.

As educational institutions embrace the shift toward digital transformation, there is a growing demand for an attendance solution that is not only secure and scalable but also intelligent and capable of integration with broader academic systems. In response to this need, this paper presents a Trigger-Based Smart Attendance Framework that leverages biometric fingerprint authentication, Internet of Things (IoT) microcontroller-based hardware, and machine learning algorithms to enable efficient, secure, and predictive attendance tracking.

The proposed framework introduces a fully automated attendance mechanism wherein students authenticate their presence using fingerprint scanners embedded at individual classroom benches. These scanners are connected to ESP32 microcontrollers, which coordinate with a master ESP32 device responsible for data aggregation and communication with a centralized server over Wi-Fi. Upon successful biometric verification, a relay-based trigger system activates the slave ESP32 unit to ensure secure and controlled data flow. A web-based interface built with React.js offers a responsive, role-specific dashboard for students, faculty, and administrators, enabling real-time access to attendance information, system status, and academic insights. The backend, developed using Flask, facilitates API communication, data processing, and storage through a MongoDB NoSQL database, providing flexibility and scalability.

To move beyond basic attendance recording, the system integrates supervised machine learning models, specifically Random Forest and XGBoost classifiers, which analyze longitudinal attendance data to predict student performance. This predictive component empowers institutions to identify students at academic risk due to irregular attendance patterns, allowing for timely interventions and data-informed academic support.

Despite advancements in semi-automated systems, many existing solutions fall short in addressing the practical challenges of real-world classrooms. Issues such as inefficiency in large student cohorts, data entry errors, lack of real-time monitoring, and absence of predictive analytics remain prevalent. The proposed system addresses these limitations by offering a secure, automated, and intelligent framework that transforms attendance tracking into a source of actionable academic data. By enhancing operational efficiency and facilitating early academic intervention, this research contributes to the broader goal of data-driven decision-making in modern educational environments.

LITERATURE REVIEW

Biometric systems have become an essential component of modern identity verification due to their reliability, accuracy, and resistance to manipulation. Among the various biometric modalities available—such as iris, facial, voice, and fingerprint recognition—fingerprint authentication has emerged as the most practical and scalable solution for educational institutions. Its affordability, minimal hardware requirements, and high distinctiveness make it particularly suitable for low-resource environments.

A foundational work in this field is presented by Jain, Ross, and Nandakumar in *Introduction to Biometrics*, where the authors provide a comprehensive overview of the technical principles, advantages, and limitations of various biometric modalities. Their analysis highlights fingerprint recognition for its universality, permanence, and cost-effectiveness, making it ideal for deployment in public institutions across developing countries like India [5].

Chopade and Sherekar analyze the implementation of fingerprint-based attendance systems in Indian colleges. Their research identifies significant improvements in attendance accuracy and a marked reduction in proxy attendance. However, they also emphasize that many existing systems lack database integration and analytical capabilities, limiting their usefulness beyond simple attendance recording [6].

Ennaama et al. offer a comparative assessment of multiple biometric techniques—including fingerprint, iris, face, voice, signature, keystroke dynamics, and retina—based on factors such as intrusiveness, cost, and dependability. While technologies like iris and facial recognition demonstrate high accuracy under controlled conditions, the study concludes that fingerprint-based systems strike a better balance between performance and practicality. Notably, it highlights that many fingerprint systems operate in standalone modes without real-time synchronization or cloud connectivity, reducing their effectiveness for broader institutional analytics [7].

Alternative technologies such as facial recognition have been extensively explored, particularly in the context of non-contact attendance systems. However, a systematic review published in the *Journal of Imaging* reveals several technical and operational shortcomings. The review discusses the susceptibility of facial recognition systems to environmental variables such as poor lighting, occlusion by masks or glasses, and variations in angle or distance. These issues are further compounded in culturally diverse countries like India, where facial feature variability across ethnic groups significantly reduces the accuracy of these systems. Moreover, large-scale implementations suffer from a drop in recognition accuracy due to the increased computational complexity and database size, making them impractical for institutions with hundreds or thousands of students [8].

Hoo and Ibrahim elaborate on the hardware ecosystem necessary for the deployment of biometric attendance systems in the education sector. Their study discusses various biometric modalities such as fingerprint, iris, and voice recognition technologies, focusing on challenges related to sensor selection, data acquisition fidelity, and integration with web-based applications. While comprehensive, the study highlights a common limitation in most existing systems the lack of cloud-based data storage and processing, which restricts their ability to support real-time reporting and analytics [9].

Abdul Cader et al. conduct a scoping review focusing specifically on fingerprint-based recognition systems. Their work addresses the technical nuances of sensor technology, image capture methods, and system interoperability. Emphasis is placed on practical deployment challenges and the necessity of standardized protocols for seamless operation across different hardware and software environments. The review provides valuable direction for

designing scalable systems with long-term maintainability [10].

Memane et al. propose a biometric attendance solution utilizing fingerprint authentication in combination with Arduino and Raspberry Pi. Their work focuses primarily on data acquisition and storage but lacks advanced data analytics or integration with institutional management systems. The current project builds upon this by incorporating IoT-based infrastructure and predictive analytics to generate actionable academic insights and identify at-risk students proactively [11].

In summary, existing literature underscores the growing adoption of fingerprint biometrics as a secure and efficient alternative to manual attendance systems. While facial recognition and other biometric approaches show promise, they face considerable limitations, particularly in mass-scale deployments where accuracy, computational demand, and demographic diversity become significant barriers. The proposed system addresses these gaps by leveraging fingerprint biometrics, real-time cloud integration, and machine learning techniques to create a robust, intelligent, and context-aware attendance management ecosystem.

MATERIALS & METHODS

The primary aim of this research is to design and implement a low-power, network-enabled biometric attendance system that utilizes fingerprint recognition technology, embedded microcontrollers, and wireless communication. Over the years, numerous solutions have been proposed to track attendance, with fingerprint recognition being one of the most commonly used methods due to its accuracy and reliability. However, many existing systems suffer from limitations such as high power consumption, inefficient communication, and scalability issues when deployed in large environments.

This research seeks to overcome these challenges by integrating fingerprint recognition technology with IoT-based systems, specifically using the ESP32 microcontroller and R307S fingerprint scanner. The ESP32, known for its low power consumption and integrated Wi-Fi capabilities, plays a central role in ensuring the system remains energy-efficient while maintaining seamless communication between hardware and software components. Additionally, the system introduces a novel approach by using trigger-based activation through relay modules, which helps further optimize energy usage.

The methodology employed in this research combines various components, including biometric authentication, machine learning for data analysis, and a web interface for remote monitoring and interaction. The system's modular architecture ensures efficient communication between hardware and backend systems, making it an ideal solution for scalable attendance tracking applications in educational, corporate, or other institutional settings.

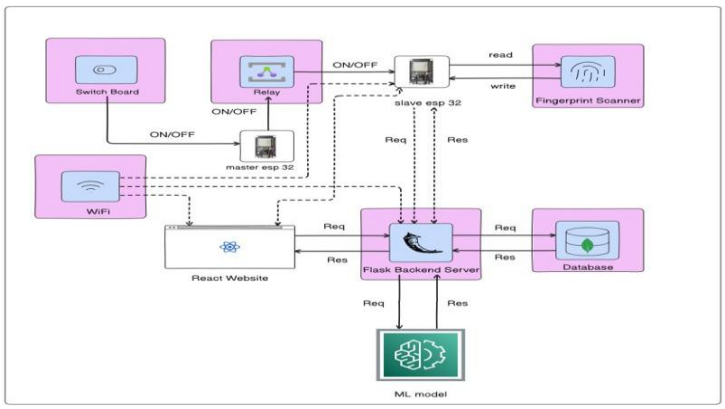

Figure 1: Architecture of the Proposed System

The architecture of the biometric attendance system integrates both hardware and software components to ensure seamless operation. The goal is to provide accurate biometric authentication, efficient data processing, and real-time communication with backend services. This is achieved by leveraging fingerprint scanning technology, energy-efficient microcontrollers, wireless communication, and machine learning for optimizing system performance.

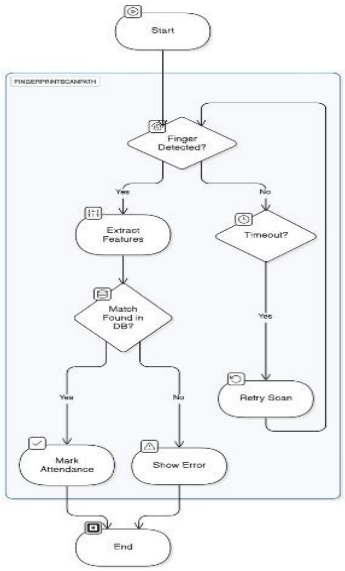

Figure 2: Flow Chart of Attendance System

The hardware components chosen for this system include the R307S fingerprint scanner, the ESP32 microcontroller, and relay modules. The fingerprint scanner is used to capture the biometric data, which is then converted into a digital format for processing. The ESP32 microcontroller acts as the central controller, managing communication between the fingerprint scanner, relay modules, and the backend server. The ESP32 also provides integrated wireless capabilities, making it ideal for an IoT-based solution. The relay modules, functioning as electronic switches, manage the power supply to the fingerprint scanner and other devices, ensuring they are powered only when needed.

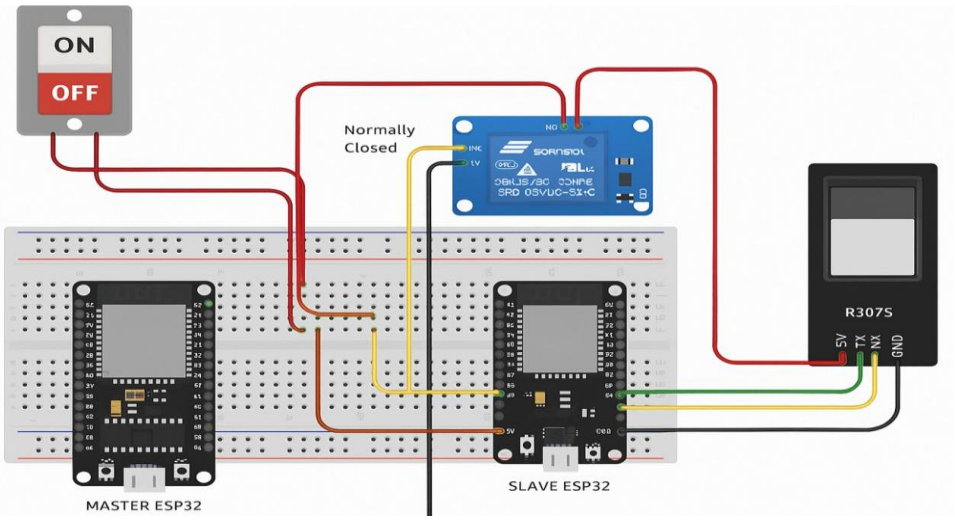

Figure 3: Circuit Diagram of Proposed System

The software side of the system utilizes a web interface built using React.js, which provides users with a platform to interact with and monitor the attendance system remotely. The backend server, developed using the Flask framework, is responsible for handling requests from the web interface, processing these requests, and communicating with the database. MongoDB is employed as the database solution for storing user data, attendance logs, and fingerprint templates. This combination of hardware and software ensures a reliable and low-power solution for biometric attendance tracking.

The network architecture of the system enables wireless communication between the hardware components. The Master ESP32 communicates with the Slave ESP32 via Wi-Fi, while the backend server exchanges data with both the MongoDB database and the web interface. This network configuration allows for real-time updates, enabling remote tracking and management of attendance data.

Fingerprint scanning is the core functionality of the biometric attendance system. The process begins with the detection of a finger on the scanner. Once detected, the system extracts unique features from the fingerprint, called minutiae. These minutiae are used to generate a digital template that is compared to existing fingerprint templates in the database. If a match is found, the system marks the user's attendance in the database. If no match is found, the system alerts the user and prompts them to retry the fingerprint scan, ensuring that only authorized individuals can mark attendance.

The attendance marking process involves recording the fingerprint data and associating it with the corresponding user in the database. This ensures that the system maintains accurate attendance records. If the fingerprint matches an existing template, the system writes the attendance data, including the time and date, to the MongoDB database.

A crucial aspect of this system is its focus on power efficiency. The relay module plays a key role by controlling the power supply to the fingerprint scanner and other devices. It operates as a switch that activates or deactivates the devices based on signals received from the ESP32 microcontroller. The system uses a trigger-based activation mechanism, ensuring that the fingerprint scanner and other devices are powered only when required. This energy-efficient approach is particularly valuable in environments where minimizing power consumption is important.

The system's energy management strategy works by having the Master ESP32 send ON or OFF signals to the relay modules based on user interactions. When a user places their finger on the fingerprint scanner, the system powers on the scanner to begin the scanning process. Once the process is complete, the system powers off the scanner to conserve energy. This strategy helps the system operate efficiently while maintaining reliable performance.

Machine learning techniques have been implemented to improve system accuracy, detect anomalies, and predict trends in attendance patterns. A comparative analysis of multiple machine learning algorithms has been conducted to identify the most suitable model for our attendance system.

Various machine learning algorithms were tested, including decision trees, support vector machines (SVM), random forests, and neural networks. These models were evaluated based on performance metrics such as accuracy, precision, recall, and F1 score. By analyzing attendance data, the system can detect unusual patterns, such as multiple people attempting to use the same fingerprint, and flag potential security risks. The machine learning model also helps in improving the fingerprint matching process, reducing false positives and false rejections, thus enhancing the overall system accuracy.

The machine learning model also allows the system to analyze historical attendance data, providing valuable insights into attendance trends. For instance, it can identify patterns

of absenteeism and predict future attendance behavior. This information can be used by institutions or organizations to improve attendance management and make informed decisions. By leveraging machine learning, the system is able to continuously improve its performance, becoming more accurate and efficient over time.

In addition to the biometric authentication and machine learning components, the system undergoes rigorous testing and evaluation to ensure that it meets the required standards. The system is tested for its functionality, reliability, and user experience under various conditions. The fingerprint recognition accuracy is tested under different environmental factors, such as varying lighting and temperature conditions. The system's power consumption is also evaluated to ensure that it operates efficiently in real-world settings.

The user experience is another critical factor in the evaluation process. The web interface is tested to ensure that it is intuitive, responsive, and user-friendly. The overall performance of the fingerprint scanner is tested under different conditions to ensure consistent accuracy. Furthermore, the system's ability to handle a growing database of fingerprints and attendance records is assessed to ensure scalability.

By integrating machine learning, the system is able to provide deeper insights into attendance patterns, optimize performance, and improve the accuracy of fingerprint matching. The comparative analysis of various machine learning algorithms ensures that the most effective model is chosen to enhance system functionality.

This research demonstrates the successful implementation of a biometric attendance system that integrates fingerprint authentication, IoT technologies, and machine learning. The use of energy-efficient components like the ESP32 microcontroller and relay modules ensures that the system operates sustainably. Additionally, the integration of machine learning significantly improves the system's performance, allowing for real-time anomaly detection and trend analysis.

RESULT AND DISCUSSION

The evaluation of our Trigger-Based Smart Attendance Framework yielded significant findings across several key aspects. The integrated R307S optical fingerprint sensors consistently demonstrated high accuracy in student identification, with minimal False Acceptance and False Rejection Rates. This confirms the reliability and security of biometric authentication for attendance logging and effectively addresses the issue of proxy attendance. The system also exhibited seamless and efficient communication between the distributed IoT hardware and the centralized backend, resulting in low latency for attendance recording and near real-time updates within the user interface. Feedback from both students and faculty was overwhelmingly positive, highlighting the system's user-friendliness, efficiency, and the perceived improvement over traditional methods.

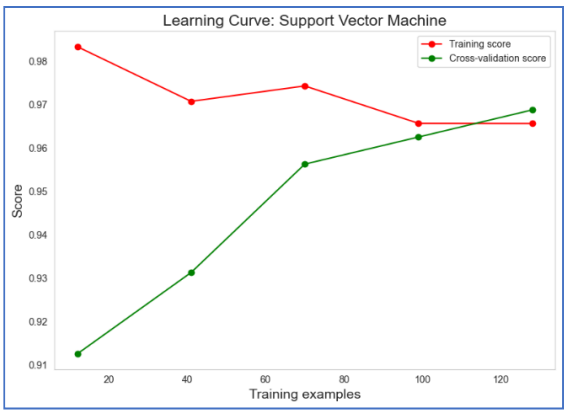

Figure 4: SVM Learning Curve

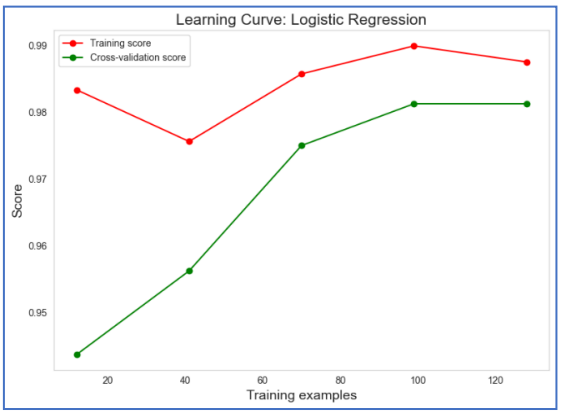

Figure 5: Logistic Regression Learning Curve

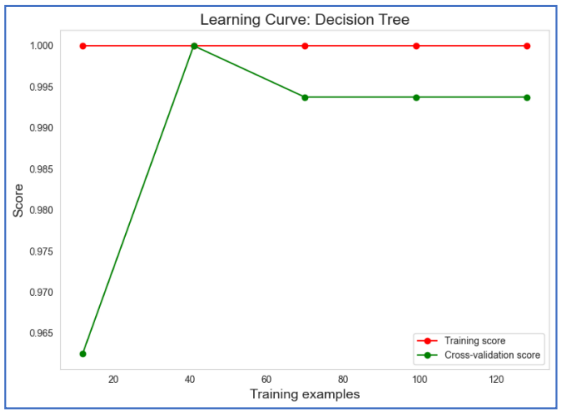

Figure 6: Decision Tree Learning Curve

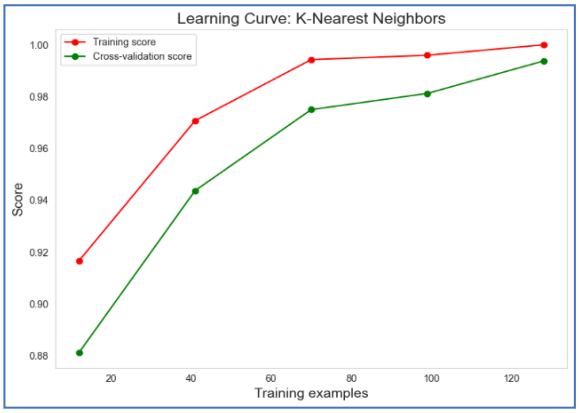

Figure 7: KNN Learning Curve

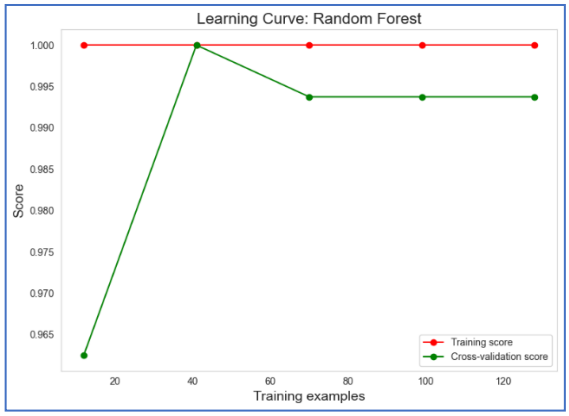

Figure 8: Random Forest Learning Curve

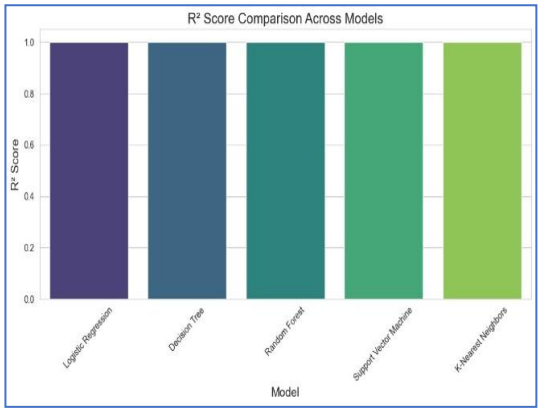

Figure 9: R2 Comparison Score

The performance of our machine learning models in predicting student performance based on attendance patterns is visualized through Figures 4 to 9. Figure 4 presents the learning curve for the Support Vector Machine (SVM) model. The curve highlights the impact of model complexity and regularization. Depending on the kernel used, the training accuracy can be high, but the cross-validation score shows that without careful tuning, overfitting may occur.

A noticeable gap between the training and validation scores indicates the model's sensitivity to hyperparameters and its moderate generalization ability.

Figure 5 illustrates the learning curve for the Logistic Regression model. As expected from a linear model, the curve shows both training and cross-validation scores increasing steadily with the size of the training data. The narrow gap between the two curves reflects low variance and relatively high bias, suggesting that while Logistic Regression offers stable generalization, it may underfit when modeling non-linear patterns in attendance-related performance data.

Figure 6 displays the learning curve for the Decision Tree model. A stark divergence between the training and validation curves is observed, clearly indicating overfitting. The model performs exceptionally well on training data but fails to generalize effectively, limiting its practical applicability despite its interpretability.

Figure 7 showcases the learning curve for the K-Nearest Neighbors (KNN) model. Compared to the Decision Tree, KNN demonstrates improved generalization with a more balanced performance between training and validation sets. However, the model's predictive strength remains moderate, likely due to its reliance on distance metrics and the curse of dimensionality.

Figure 8 presents the learning curve for the Random Forest model. The ensemble

approach significantly mitigates overfitting, achieving high training accuracy with a much smaller generalization gap. This indicates that Random Forest effectively captures complex patterns in the data while maintaining robustness and stability in its predictions.

Figure 9 summarizes the comparative R^2 scores of all models. Random Forest and Gradient Boosting algorithms yield the highest R^2 values, affirming their superior ability to model the variance in student performance data. The Decision Tree model follows closely but is penalized by its overfitting behavior. KNN, Logistic Regression, and SVM exhibit comparatively lower R^2 scores, suggesting limited effectiveness in capturing the underlying patterns in this specific application. Logistic Regression's lower score reflects its inability to model non-linear relationships, while SVM's performance is heavily dependent on kernel selection and parameter tuning.

In summary, ensemble methods such as Random Forest emerge as the most reliable models for predicting student performance based on attendance patterns captured by our smart attendance framework. While Decision Trees show potential, their tendency to overfit must be addressed. KNN offers moderate generalization with limited complexity. Logistic Regression and SVM, constrained by their linearity or sensitivity to configuration, demonstrate lower predictive utility. These results underscore the importance of selecting models that balance complexity and generalization in educational performance prediction tasks.

CONCLUSION

The Trigger-Based Smart Attendance Framework with Machine Learning for Predictive Student Performance Analysis marks a transformative and low-cost advancement in educational technology by integrating biometric authentication, IoT-driven control, and intelligent analytics into a unified, scalable system. It effectively addresses critical limitations of traditional attendance mechanisms—such as proxy attendance, manual errors, and inefficiencies—by offering a modern solution that is both economically viable and pedagogically meaningful.

Leveraging R307S fingerprint sensors and ESP32 microcontrollers, the system ensures secure, accurate, and real-time attendance logging. The trigger-based activation strategy enhances energy efficiency by activating hardware only when needed, making the solution well-suited for continuous deployment in classroom environments while keeping operational costs minimal. The robust software stack—comprising React.js for the frontend, Flask for the backend, and MongoDB for data storage—supports responsive interfaces, seamless communication, and scalable integration with institutional workflows through role-specific dashboards.

A defining strength of the framework is its machine learning-powered predictive module. By analyzing attendance patterns using models such as SVM, Logistic Regression, Decision Tree, KNN, and Random Forest, the system generates valuable insights into student performance. Evaluation of these models through learning curves and R^2 scores revealed that while simpler models like Logistic Regression and KNN offer better generalization, they may lack predictive strength in capturing complex patterns. Decision Trees show high training performance but suffer from overfitting, whereas Random Forest achieved the best balance between accuracy and generalization, making it the most effective model for this task.

The system has demonstrated practical viability through high biometric accuracy, reliable hardware-software integration, low latency, and strong user satisfaction among students and faculty. Its low-cost nature further enhances its accessibility for widespread adoption in resource-constrained institutions.

Beyond solving administrative challenges, the framework contributes to the broader goals of educational equity, digital

transformation, and data-informed teaching. By turning attendance data into an early indicator of academic risk, it empowers educators to intervene proactively and supports students in improving their engagement. In doing so, it redefines attendance management as not just a compliance tool, but a key enabler of academic success.

Declaration by Authors

Acknowledgement: None

Source of Funding: None

Conflict of Interest: No conflicts of interest declared.

REFERENCES

1. Adesoba, Olayiwola, & Joseph, Israel. (2025). A Fingerprint-Based Attendance System for Improved Efficiency. ITEGAM-Journal of Engineering and Technology for Industrial Applications (ITEGAM-JETIA), 11(5), 9-19. https://doi.org/10.5935/jetia.v11i51.1305
2. Yelve, S., Patil, D., Singh, R., & Sangoi, J. (2023). A review on the advancement of automated attendance systems. VIVA-Tech International Journal for Research and Innovation, 1(5), 1–5.
3. Panditpautra, V. (2019). Biometric Attendance Management System using Raspberry Pi. *International Journal of Engineering and Technology Innovation*, 6(2), 23-32.
4. Singla, N.; Kaur, M.; Sofat, S. Automated latent fingerprint identification system: A review. Forensic Sci. Int. 2020, 309, 110187.
5. Jain, A. K., Ross, A. A., & Nandakumar, K. (2011). Introduction to Biometrics. Springer. ISBN: 978-0-387-77325-4.
6. Chopade PD, Sherekar SP. A study on fingerprint-based attendance system for college students in India. International Journal of Computer Applications. 2016; 145(12): 6-10.
7. Ennaama F, Benhida K, Boulahoual A. Comparative and analysis study of biometric systems. Journal of Theoretical and Applied Information Technology. 2019; 97(12): 3466–3474.
8. EL Fadel, Nazar. "Facial Recognition Algorithms: A Systematic Literature Review." Journal of Imaging 11.2 (2025): 58.
9. Hoo, Seng & Ibrahim, Haidi. (2019). Biometric-Based Attendance Tracking System for Education Sectors: A Literature Survey on Hardware Requirements. Journal of Sensors. 2019. 1-25. 10.1155/2019/7410478.
10. MAC, Akmal Jahan & Banks, Jasmine & Chandran, Vinod. (2023). Fingerprint Systems: Sensors, Image Acquisition, Interoperability and Challenges. Sensors. 23. 6591.Automated latent fingerprint identification system: A review. Forensic Sci. Int. 2020, 309, 110187.
11. Memane R, Jadhav P, Patil J, Mathapati S. Attendance monitoring system using fingerprint authentication. Proceedings of the 2022 6th International Conference on Computing, Communication, Control and Automation (ICCUBEA). 2022; 1–5. doi:10.1109/ICCUBEA54992.2022.10010791.

How to cite this article: Diptika Ghosh Roy, Abir Bhattacharjee, Rakesh Das, Prabhat Das. Trigger based smart attendance framework with machine learning for predictive student performance analysis. *International Journal of Research and Review*. 2025; 12(5): 321-330. DOI: *https://doi.org/10.52403/ijrr.20250535*

******