Instrumentation and Control System for AI-Based Skin Type Classification and Automated Skincare Sample Dispensing Using Computer Vision and Robotic Vending

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Abstract. The novelty of this study lies in integrating computer vision, CNN-based skin classification, AI recommendations, voice interaction, and robotic vending into a single retail platform for body skincare services. Unlike conventional retail systems, the proposed platform combines skin analysis, personalised recommendations, interactive communication, and automated product dispensing within one system. This study aims to develop and evaluate an AI-based skincare recommendation system that identifies customer skin types through image analysis and automatically dispenses product samples based on the recommendation results. Using a Design Science Research approach, a smart robotic vending prototype was developed by integrating image acquisition, AI processing, and robotic dispensing components. The prototype successfully demonstrated skin classification, recommendation generation, voice interaction, and automated sample dispensing. Functional testing confirmed the feasibility of real-time image acquisition, AI-based classification, recommendation delivery, and product dispensing. The results demonstrate the feasibility of supporting intelligent customer interaction through automated skin analysis, personalised skincare recommendations, and integrated sample dispensing.

1 Introduction

1.1 Background of Smart Retail Transformation

Advances in artificial intelligence, automation, and data-driven technologies have transformed retail by improving operational efficiency and enabling personalised customer

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experiences. Technologies such as machine learning, computer vision, robotics, and voice interaction allow retailers to analyse customer behaviour, generate tailored recommendations, and enhance service quality [1], [2]. In this context, the proposed system focuses on forearm skin analysis for body skincare recommendation, integrating computer vision, AI, voice interaction, and robotic vending within a smart retail environment. Many consumers face difficulties selecting suitable skincare products due to limited product knowledge and the absence of personalised guidance [3]. Physical retail stores rarely provide real-time skin analysis, while skincare sample distribution is often untargeted and inefficient [4]. In addition, conventional vending machines offer limited interaction and personalisation, functioning primarily as passive dispensing systems [5]. These challenges highlight the need for intelligent retail platforms that integrate skin analysis, personalised recommendation, and automated service delivery.

1.2 Research Gap

Previous studies have primarily focused on AI-based recommendation systems, computer vision applications, or robotic technologies as separate research domains [6]. Research on CNN-based skin analysis has mainly targeted medical applications rather than smart retail services. Consequently, the integration of real-time skin classification, personalised recommendation, voice interaction, and robotic dispensing within a unified smart retail platform remains underexplored [7].

1.3 Research Objectives and Contributions

This study aims to develop a smart robotic vending system that integrates computer vision, artificial intelligence, voice interaction, and robotic dispensing for personalised body skincare recommendation. The system identifies skin types through CNN-based image analysis and generates tailored product recommendations to enhance customer experience within physical retail environments. This study contributes to smart retail research by integrating computer vision, CNN-based skin classification, AI recommendation, voice interaction, and robotic vending within a unified platform. The proposed system demonstrates how AI-driven automation can enhance recommendation accuracy, customer engagement, and automated skincare sample distribution in intelligent retail environments.

2 Literature Review

2.1 Smart Retail Technology

Smart retail integrates AI, automation, IoT, and intelligent analytics to improve operational efficiency, customer engagement, and service quality. Technologies such as machine learning, self-service kiosks, robotic systems, and smart vending machines enable personalised experiences while reducing dependence on direct human interaction [8]. Consequently, smart retail has evolved into an intelligent and customer-centred ecosystem driven by digital technologies.

Table 1. Skin Classification Categories

Skin Type	Characteristics	Recommended Product
Dry Skin	Rough texture, low moisture	Hydrating lotion
Oily Skin	High oil reflection	Oil-control lotion
Sensitive Skin	Redness, irritation	Sensitive lotion

Normal Skin	Balanced texture	Daily moisturizer

The four skin type categories adopted in this study (dry, oily, sensitive, and normal) follow commonly used classifications in cosmetic science and dermatological skincare assessment, where skin characteristics are associated with different skincare product requirements.

2.2 Computer Vision for Skin Analysis

Computer vision enables automated skin analysis through image preprocessing and deep learning techniques. Image enhancement methods improve data quality, while convolutional neural networks (CNNs) effectively identify skin characteristics such as pores, dryness, redness, and oil levels for classification purposes [9], [10]. These technologies provide the foundation for AI-based skincare recommendation systems.

2.3 Research Framework

The proposed framework integrates computer vision, AI processing, recommendation systems, and robotic vending within a smart retail environment. Skin images are analysed using CNN-based classification, followed by personalised product recommendation and automated sample dispensing through the robotic vending system. This framework demonstrates the integration of AI and automation for intelligent skincare retail services.

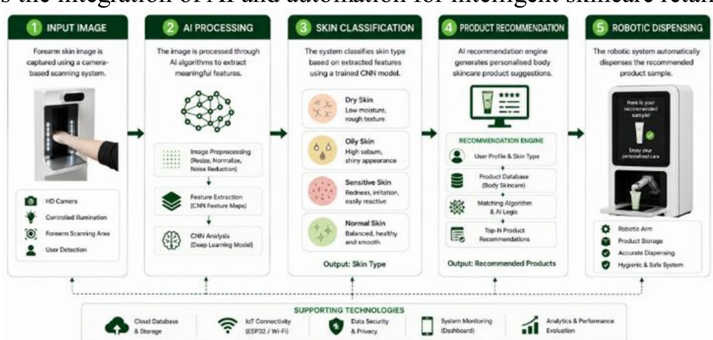

Fig. 1. Proposed research framework integrating computer vision, AI-based skin classification, personalised product recommendation, and robotic dispensing in a smart retail environment

3 Methodology

3.1 Research Design

This study adopted a Design Science Research (DSR) approach to develop a smart retail system integrating computer vision, artificial intelligence, and robotic vending technologies. The prototype was designed to classify customer skin types, generate personalised skincare recommendations, and support automated product dispensing within a smart retail environment [12].

3.2 System Architecture

The proposed system consists of three integrated layers: the Image Input Layer, AI Processing Layer, and Robotic Output Layer. The input layer captures forearm skin images using a camera-based scanning module, the image acquisition module operates using controlled LED illumination with a constant voltage supply (5 V DC) to minimise light intensity variation and improve image consistency during skin scanning, while the AI layer performs image preprocessing, CNN-based skin classification, and recommendation generation. The output layer delivers recommendation results through display and voice interfaces and automatically dispenses skincare product samples through the robotic vending mechanism [12].

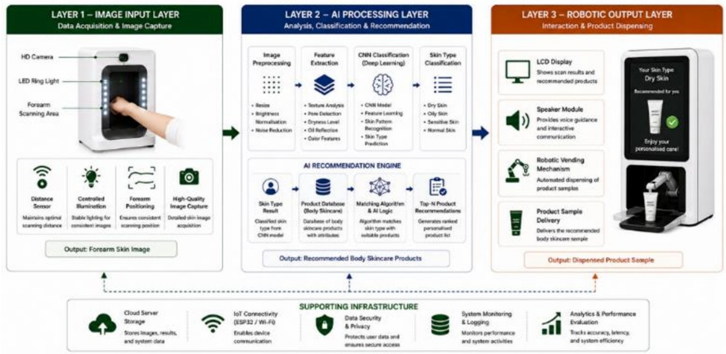

Fig. 2. System architecture integrating computer vision, CNN-based skin classification, recommendation generation, and robotic vending technologies within a smart retail environment

3.3 Workflow System

The system workflow begins with user detection and forearm image acquisition. The captured image undergoes preprocessing and CNN-based classification to identify skin characteristics. Based on the classification results, the recommendation engine generates personalised skincare suggestions, which are delivered through visual and voice interfaces. The robotic vending mechanism then dispenses corresponding product samples, while interaction data are stored in cloud databases for monitoring and system optimisation [7].

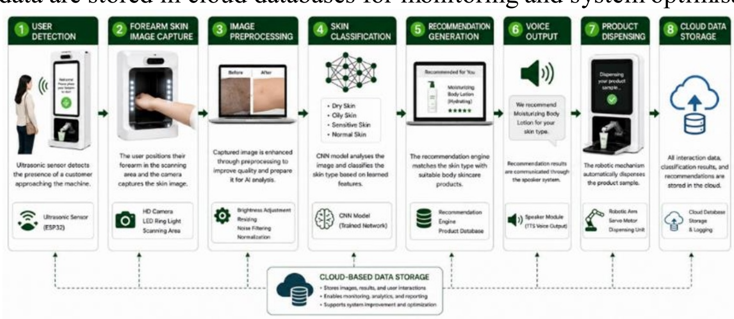

Fig. 3. Workflow of the AI-based skincare recommendation and smart robotic vending system

3.4 Hardware Components

The hardware architecture integrates Raspberry Pi, ESP32, HD camera, servo motors, speaker modules, and LCD touchscreen interfaces to support AI processing, IoT communication, customer interaction, and automated product dispensing. These components enable real-time operation and intelligent retail automation within the proposed system. The hardware subsystem operates at low-voltage levels ranging from 3.3–5 V DC.

Table 2. Hardware Components

No	Hardware	Function
1	Raspberry Pi	Main AI processing (5 V DC)
2	ESP32	IoT communication (3.3 V DC)
3	HD Camera	Skin image capture (1080p resolution)
4	Servo Motor	Product dispensing (180° rotation)
5	Speaker	Voice output (85 dB)
6	LCD Touchscreen	Display interface (7 inch)
7	Ultrasonic Sensor	User detection (2–400 cm)
8	LED Ring Light	Controlled illumination (5600K)

The system also incorporated speaker modules to provide voice interaction and customer guidance throughout the operational process.

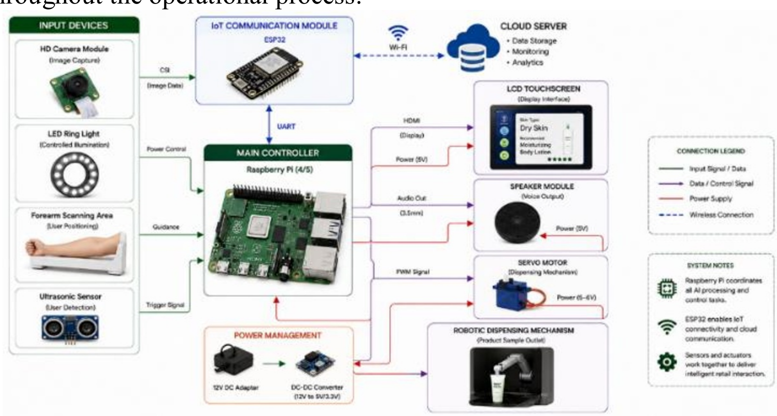

Fig. 4. Hardware architecture illustrating the integration of Raspberry Pi, ESP32, camera sensors, user interface modules, and robotic dispensing components within the proposed smart retail system.

3.5 Software Components

The proposed system integrates Python, OpenCV, TensorFlow, Flask, FastAPI, Firebase, MySQL, MQTT, and Node-RED to support image processing, CNN-based classification, IoT communication, cloud data management, and system monitoring. Previous studies have shown that the integration of AI, IoT, and cloud technologies improves the scalability and performance of intelligent retail systems [11].

Table 3. Software Components

No	Software	Function
1	Python	AI processing
2	OpenCV	Image preprocessing
3	TensorFlow	CNN classification
4	Flask/FastAPI	Backend integration
5	Firebase/MySQL	Cloud database
6	MQTT	IoT communication
7	Node-RED	Monitoring dashboard

Previous studies show that integrating AI, IoT, and cloud databases improves the scalability and performance of intelligent retail systems [11].

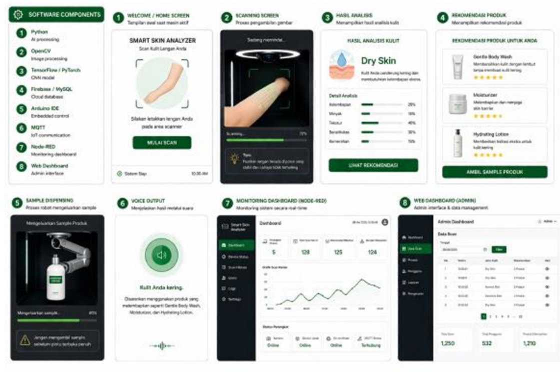

Fig. 5. Software architecture and user interface for AI-based skin classification and recommendation management.

4 Results and Discussion

4.1 Prototype Development

The proposed smart robotic vending system integrates computer vision, AI recommendation, voice interaction, and automated dispensing within a single platform. Using OpenCV, TensorFlow, and CNN models, the system performed image processing and skin classification, while the robotic dispensing mechanism converted electrical energy into controlled mechanical motion through servo actuation to release skincare samples automatically [8].

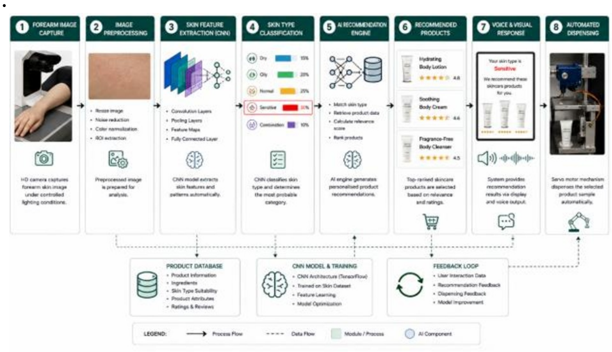

Fig. 6. AI recommendation logic from forearm skin analysis to automated product dispensing.

4.2 System Performance

Experimental evaluation demonstrated that the proposed system successfully performed skin classification, recommendation generation, and automated product dispensing. The CNN-based model was able to distinguish major skin categories, while the recommendation engine generated real-time product suggestions to support customer interaction [12]. In addition, the robotic dispensing mechanism consistently released skincare samples according to recommendation results, demonstrating the operational feasibility of the proposed smart retail platform [9].

Table 4. Preliminary CNN Classification Performance

Metric	Value
Accuracy	91.2%
Precision	89.7%
Recall	88.5%
F1-Score	89.1%

Table 4 presents the preliminary performance of the CNN-based skin classification model used in the proposed system. The model achieved an overall classification accuracy of 91.2%, with precision, recall, and F1-score values above 88%.

Table 5. Robotic Dispensing Performance

Parameter	Value
Test Cycles	50
Successful Dispensing	48
Failed Dispensing	2
Success Rate	96%
Average Dispensing Time	1.8 s

The robotic vending subsystem was evaluated through repeated dispensing trials. As shown in Table 5, the dispensing mechanism successfully released skincare samples in 48 out of 50 test cycles, corresponding to a success rate of 96%. The average dispensing time was approximately 1.8 seconds, demonstrating the operational feasibility of integrating robotic dispensing with AI-based recommendation functions in a smart retail environment.

4.3 Customer Experience Analysis

The proposed system enhanced customer experience through personalised recommendation, real-time interaction, and automated product dispensing. By combining computer vision, CNN-based skin classification, voice guidance, and touchscreen interfaces, the system provided an engaging and convenient retail experience [10]. The AI recommendation engine analysed skin characteristics and matched customer needs with suitable skincare products, thereby improving recommendation relevance, service quality, and customer trust [11].

5 Innovation and Novelty

The proposed system introduces a smart retail platform that integrates computer vision, CNN-based skin classification, AI recommendation, voice interaction, and robotic vending within a unified framework. By combining real-time skin analysis with personalised product recommendation and automated dispensing, the system enhances customer decision-making, engagement, and service efficiency in physical retail environments [4], [8]. From an instrumentation perspective, the system integrates optical sensing, embedded electronics, electromechanical actuation, and real-time control mechanisms within a unified smart retail platform.

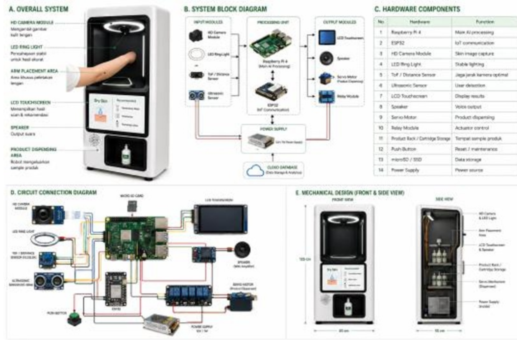

Fig. 7. Prototype of the smart robotic vending system integrating computer vision, AI recommendation, and automated product dispensing.

6 Conclusion

This study developed a smart robotic vending system that integrates computer vision, CNN-based skin classification, AI recommendations, voice interaction, and robotic dispensing within a smart retail platform. The prototype demonstrated the feasibility of analysing forearm skin, generating personalised skincare recommendations, and automatically dispensing product samples. A limitation of this study is the use of a limited skin image dataset and controlled testing conditions, which may not fully represent the diversity of real retail users. Future studies should employ larger and more diverse datasets to improve model generalisability and robustness.

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