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Development of an Integrated Human-Computer Interactive Model for Improved User Experience in Gesture-Controlled Smart Mirrors

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Abstract: *The advancement of smart technologies has led to the development of innovative home automation devices, with smart mirrors emerging as a modern convenience tool. This paper focuses on the design and implementation of a gesture-controlled smart mirror, incorporating a two-way mirror, monitor, raspberry pi, gesture-enabled camera, power adaptor and a swipeable interface to enhance user interaction. The objectives of the paper include designing a comprehensive smart mirror using CAD, integrating gesture control technology through Python's OpenCV package, constructing a functional prototype utilizing the Magic Mirror software, and conducting extensive testing. Key tests conducted include usability test to assess user interaction, functionality test to validate gesture control and mirror operations, data analysis for performance metrics, and visibility test for optimal display quality. Functionality test showed an average gesture detection accuracy of 92.5%, with the swipe left and swipe right gestures achieving the highest accuracy. In the usability test, the average response time across all gestures was 0.75 seconds, which is within the acceptable range for real-time interaction. Other performance indicators like error rate, average user satisfaction, device uptime and gesture latency were tested. These results demonstrated the effectiveness of the gesture-controlled interface, with the prototype showing high accuracy in gesture recognition and overall positive user feedback in terms of usability and reliability. The findings of this work suggest that the developed smart mirror could serve as a valuable addition to smart home environments, offering a seamless and interactive experience for users.*

Keywords: *Gesture Recognition, Human-Computer Interaction, MagicMirror, Raspberry Pi, Swipeable Pages*

1. INTRODUCTION

The integration of technology into daily life has led to advancements like smart mirrors, which combine functionality and aesthetics to enhance user experiences. Gesture-controlled smart mirrors represent a novel development in human-computer interaction, offering intuitive, non-contact interfaces for improved user interaction. Existing smart mirrors, as described by [1] and [2], use hardware and software such as the Raspberry Pi and Magic Mirror Module to provide features like calendars, weather updates, and music apps. Modern designs incorporate real-time data, media content, and facial recognition for personalization [3][4].

Traditional mirrors are limited to self-reflection and grooming, while current smart mirrors, though feature-rich, often lack intuitive interfaces and efficient navigation. Gesture recognition technology, a key innovation in human-computer interaction, offers natural, touch-free solutions for tasks in smart homes, healthcare, and more [5][6]. It reduces reliance on traditional input devices, addressing associated health concerns and enabling applications like sign language recognition and security [7].

Gesture recognition, supported by advancements in edge computing and computer vision, enhances the interactivity of smart mirrors, making them versatile tools for smart homes, medical care, and sports training [1]. Recent developments include features like controlling home appliances, displaying notifications, and playing music or videos through swipe gestures [8][9]. The swipeable interfaces, inspired by mobile device usability, simplify user interactions and extend functionality, creating a more immersive and personalized experience [10].

This paper supports Sustainable Development Goal 9 by promoting industry, innovation, and infrastructure and aims to develop a gesture-controlled smart mirror with swipeable pages, transforming traditional mirrors into interactive hubs that align with smart home ecosystems by leveraging gesture-based controls and robust recognition algorithms.

The remainder of this paper is organized into four sections. Section II, Related Works, explores prior research on smart mirrors, gesture recognition systems, and human-computer interaction, highlighting significant advancements, existing limitations, and potential improvements. Section III, Gesture-Controlled Smart Mirror Design and Architecture, provides an in-depth explanation of the system architecture, hardware and software components, gesture recognition methodologies, and the integration of artificial intelligence for an interactive user experience.

Section IV, Results, presents the performance evaluation of the smart mirror, including usability testing, accuracy of gesture recognition, and real-world applications. Finally, Section V, Conclusion, summarizes the findings, evaluates the system's effectiveness, and outlines future enhancements, such as IoT integration. Smart mirrors have evolved significantly, integrating advanced human-computer interaction (HCI) techniques to enhance user experience. Recent advancements in gesture recognition, artificial intelligence (AI), and Internet of Things (IoT) technologies have shown great potential in improving the functionality, responsiveness, and adaptability of smart mirrors for various applications.

1.1 Smart Mirror Architecture and Components

Various studies have explored the hardware and operational framework of smart mirrors. These systems typically incorporate a Raspberry Pi microcontroller, an LCD/LED display, and an acrylic two-way mirror to provide an interactive user experience. The Raspberry Pi enables internet connectivity, allowing the smart mirror to display personalized information such as weather updates, calendar events, and real-time news [3][8]. Some implementations also integrate microphones for voice commands, enhancing user interaction. The smart mirror also has a built-in camera and sensor to detect intruders [8]. It has a sleek design that can fit in any modern home or office. The smart mirror offers a unique and innovative way to stay connected and informed while getting ready in the morning or throughout the day. Smart mirrors also incorporate facial recognition technology to recognize users and tailor content to their preferences [11]. Some challenges in the construction and software side of smart mirrors include the reflectivity of the glass and the reliability of gesture recognition, which can be addressed through further development and testing [3].

1.2 Gesture and Voice-Activated Interfaces in Smart Mirrors

The evolution of human-computer interaction in smart mirrors has led to the integration of gesture control and voice commands. These interfaces allow users to access notifications, daily tasks, and smart home controls without physical contact [12]. The Raspberry Pi acts as the host controller, managing the display content and enabling touch or voice-based smart home automation [13]. Some smart mirrors also use face and speech recognition for security and personalized information delivery [14].

1.3 Smart Mirrors for Home Automation and Security

Beyond displaying information, smart mirrors have been integrated into home automation systems. They support features such as curtain and light control, wake-up assistance, and intrusion detection using embedded cameras and sensors [14]. These systems enhance smart home communication, providing users with an intuitive way to manage household appliances through voice recognition and biometric authentication.

1.4 Health Monitoring and IoT-Enabled Smart Mirrors

Recent advancements in smart mirror technology have expanded their application in health and wellness tracking. Some smart mirrors use biomedical sensors and IoT technology to monitor physiological parameters like heart rate, oxygen levels, and body temperature [15][16]. These health-related data can be transmitted remotely to healthcare providers for real-time patient monitoring. Additionally, smart mirrors can integrate with wearable devices, providing users with personalized health recommendations, medication reminders, and fitness tracking [17][18].

2. MATERIALS AND METHOD

2.1 Materials

2.1.1 Hardware and software selection for system design

The foundation of a gesture-controlled smart mirror lies in its hardware and software components, which must be carefully selected to ensure optimal functionality. The key elements include a two-way glass mirror, which allows light to pass through from behind while reflecting ambient light, enabling the display of digital content. A monitor serves as the primary output for visual information. Raspberry Pi 4 acts as the processing unit, managing gesture recognition, data processing, and display control. To enable gesture interaction, a gesture-enabled camera was incorporated to detect hand movements accurately, enhancing the human-computer interaction (HCI) experience. The physical design is also crucial, as the mirror must maintain a sleek, modern aesthetic while housing all necessary components compactly and efficiently.

The software components implemented include: python software, Raspbian OS, OpenCV, and MagicMirror². The hardware and software components with the respective specifications utilized are summarized in Table 1(a)-(b).

The preliminary design of the gesture-controlled smart mirror was done using computer-aided design (CAD), as shown in Figure 1(a)-(b).

2.2 Method

The process of developing a gesture-controlled smart mirror involves several interrelated steps, each designed to ensure the accuracy, reliability, functionality and usability of the system. These steps include hardware and software selection for system design, gesture recognition system development, smart mirror interface and display configuration, integration of human-computer interaction features, testing and performance evaluation, and deployment of the smart mirror prototype as shown in Figure 2. Figure 3 is a sample image of recognized finger gestures captured during gesture recognition development.

Table 1 Component for the development of gesture-controlled smart mirror

(a) Hardware components and their specification

Hardware Components	Specification
Processor	Raspberry Pi 4 Model B, Quad-core ARM Cortex-A72, 1.5 GHz
Display	22-inch Full HD LCD Monitor
Two-way Mirror	Acrylic or Glass Two-Way Mirror Sheet
Camera	Digital Web Camera
Storage	32 GB MicroSD Card (Class 10)

(b) Software components and their specification

Software Components	Specification
Operating system	Raspbian OS (Debian-based)
Programming Language	Python 3
Gesture Recognition	OpenCV
Smart Mirror Platform	Magic Mirror2
Development Tools	Thonny IDE

(a) (b)

Figure 1: CAD model for the gesture-controlled smart mirror showing (a) back view (b) front view

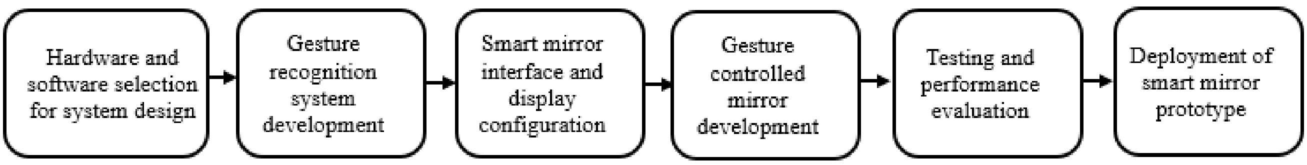

Figure 2: Design framework for a gesture-controlled smart mirror

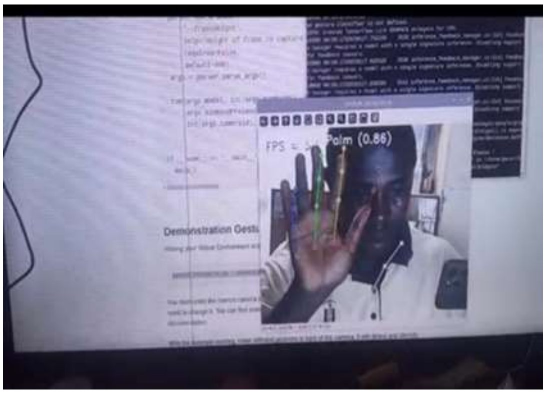

Figure 3: Sample image of recognized finger gestures captured during gesture recognition development

2.2.1 Smart mirror interface and display configuration

The user interface (UI) and display configuration are integral to the overall functionality of the smart mirror. The UI was made to be minimalistic, intuitive, and visually appealing, ensuring that users can easily access relevant information. The framework used for the installation of the smart mirror is MagicMirror² as shown in Figure 4, which allows the integration of various modules such as weather updates, time, news, calendar events, health monitoring, and notifications. Custom-built interfaces were further developed using Python software to create more personalized and interactive experiences. The UI layout was designed to adapt dynamically based on user preferences and interaction modes. During the installation of MagicMirror², the interface was configured to have several swipeable pages and one of the page interfaces is shown in Figure 5.

Figure 4: Installation of MagicMirror² software

Figure 5: MagicMirror² user interface

2.2.2 Gesture-controlled mirror development

In this phase, all components were put together to form the final prototype of the system. The procedures involve the cutting of medium-density fibreboard (MDF) wood for the rigid construction of the mirror frame, properly sized with the employed monitor. The frame was well assembled using certain adhesives and then, sanding and painting were done to create an even surface and enhance the look of the wood. The two-way glass mirror was then carefully inserted into the wood frame and other essential components like the monitor, Raspberry Pi 4, gesture-enabled camera, high high-definition multimedia interface (HDMI) cable were carefully secured in position.

The operation of the two-way glass mirror is simply based on the 'principle of light intensity'. If the light intensity is the same on both sides of the glass, the mirror will act like a normal piece of glass but when the mirror is placed on a black sheet, the light is bright on one side and much darker on the other, then the glass will look like a mirror to the people on the brighter side. This is why the smart mirror possesses a reflection-interaction feature and hence, beyond aesthetics, it further enhances human-computer interaction.

The operation of the two-way glass mirror is well described in Figure 6.

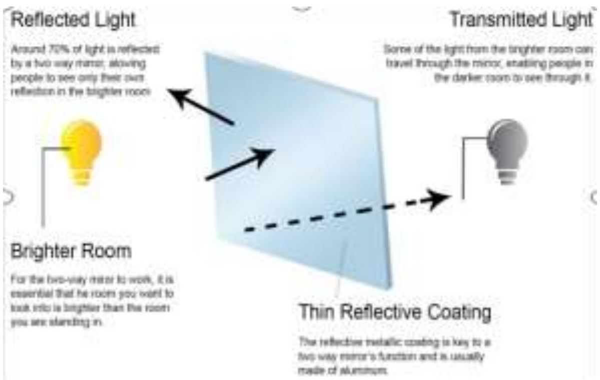

Figure 6: Reflective and transmission properties of a two-way mirror

The underlining equations employed in the development of the smart mirror include Equations (1-5)

i. Euclidean distance (for Finger Position Detection): Used to calculate distances between key landmarks (e.g., wrist to fingertip) to detect finger positions and gestures.

$$d = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{1}$$

dd: distance between two points

$(x_1, y_1), (x_2, y_2)$: coordinates of the two landmarks like fingertip and palm center.

ii. Angle between vectors (to Identify Finger Bends): Used to calculate the bending of fingers by measuring angles between bones. This helps identify whether fingers are straight (open palm) or bent (fist).

$$\theta = \cos^{-1}\left(\frac{\vec{A}\cdot\vec{B}}{\|\vec{A}\|\|\vec{B}\|}\right) \tag{2}$$

$\vec{A} \cdot \vec{B}$: vectors representing finger segments
θ: angle between the segments (in radians or degrees)

iii. Centroid Calculation (for Hand Region): Used to find the center of mass of the hand contour.

$$C_x = \frac{1}{A}\sum_{i=1}^{n} x_i \, , C_y = \frac{1}{A}\sum_{i=1}^{n} y_i \tag{3}$$

A: number of pixels in the hand region
(x_i, y_i): pixel coordinates within the hand contour
(C_x, C_y): centroid (used to track hand motion or gestures like swiping)

iv. Convex Hull and Convexity Defects: Used to detect fingers by analyzing the contour of the hand and identifying points that "dip in" from the convex outline. Convex Hull is a set of points that form the outer boundary:

$$Convex\ Hull(P) = \min\{Conv(P_i)\} \tag{4}$$

Convexity Defect is: $Defect\ Depth = Distance\ between\ hull\ point\ and\ farthest\ defect\ point\backslash$
This is handled in OpenCV using `cv2.convexHull()` and `cv2.convexityDefects()`.

v. Hand Movement Vector (for Gesture like Swipe): Used to detect movement direction and speed.

$$\vec{v} = \frac{\Delta x}{\Delta t}, or\ \vec{v} = \frac{(x_{t_2} - x_{t_1}, y_{t_2} - y_{t_1})}{t_2 - t_1} \tag{5}$$

$\vec{v}$: velocity vector
x, y: hand centroid positions at times t_1, t_2
Useful for gestures like swipe left/right or up/down.

2.2.3Testing and performance evaluation

Ensuring high accuracy and reliability in gesture recognition and system performance is critical hence, several tests including visibility test, usability test, functionality test, and data analysis test were carried out. The visibility test was done to assess the integrity of the bonding between the two-way mirror and the wooden frame. The usability test evaluates whether the gesture recognition system responds correctly to different hand movements and user inputs. The functionality test assesses system responsiveness and identifies latency issues. The data analysis test was done to derive insights from data collected during usability test and surveys.

Furthermore, tests were conducted under various lighting conditions to determine the robustness of the computer vision (OpenCV) algorithms. Performance indicators such as gesture detection speed, accuracy rate, gesture latency, error rate, device uptime and computational efficiency are measured to optimize the system. User feedback was also collected to refine the interface and interaction mechanisms, ensuring an intuitive and seamless experience.

Accuracy measures the overall correctness of the system's performance. The average accuracy of the system is calculated thus;

$$A_V = \frac{\sum_{i=1} A_i}{TP} \tag{6}$$

Where A_V is the average accuracy, A_i is the accuracy of gestures performed by each participant, and TP is the total number of participants.

2.2.4 Deployment of smart mirror prototype

After several successful tests done on the smart mirror, it is now ready to be deployed in real-world environments such as homes, offices, or healthcare facilities. However, Continuous user feedback helps improve the system by refining gesture recognition accuracy and expanding interactive features. Future enhancements may include AI-powered predictive analytics, allowing the smart mirror to learn user behavior and provide proactive suggestions. Augmented reality (AR) integration could further enhance the interface, offering virtual overlays for makeup trials, outfit suggestions, or interactive workouts.

Furthermore, expanding the IoT ecosystem by integrating with smart home devices, wearable fitness trackers, and healthcare monitoring systems can transform the smart mirror into a multi-functional intelligent assistant. Some of the features displayed by the gesture-controlled mirror include: date, time, current weather, weather forecast, news feed, compliments, traffic updates, and quotes.

3. DISCUSSION OF RESULTS

This section provides a comprehensive analysis of the outcomes of the testing procedures done on the gesture-controlled smart mirror. The results are divided into various sections.

3.1 Visibility Test Result

This test confirmed that the smart mirror was well designed; the wooden frame was properly glued and the two-way glass mirror maintained clear visibility under most lighting conditions.

3.2 Usability Test Result

The usability test revealed a high level of user satisfaction, with an average rating of 4.7 out of 5 as shown in Table 2. Most users found the system intuitive and easy to use. However, there were suggestions for improving the feedback mechanism when a gesture is not recognized.

3.3 Functionality Test Result

As indicated in Table 3, this test showed an average gesture detection accuracy of 92.5%, with the swipe left and swipe right gestures achieving the highest accuracy. The average response time across all gestures was 0.75 seconds, which is within the acceptable range for real-time interaction.

3.4 Data Analysis Test Result

The result of the data collected to determine the gesture recognition accuracy across six participants is presented in Table 2 and Table 3 shows some of the performance indicators derived from Table 2.

Table 2: Gesture recognition accuracy across six participants

Participants	Number of gestures performed	Correctly recognized gestures	Accuracy (%)	Satisfaction scores (5.0)
1	20	19	95	4.5
2	20	18	90	4.8
3	20	17	85	4.7
4	20	20	100	4.9
5	20	18	90	4.6
6	20	19	95	4.7

Table 3: Some performance indicators for the gesture-controlled smart mirror

Performance Indicators	Results
Average Accuracy	92.5%
Average Response Time per gestures	0.75 second/gesture
Error Rate	7.5%
Average User Satisfaction	4.7/5
System Stability	No crashes or delays
Device Uptime	99.8%
Gesture Latency	0.5 second

3.5 Lighting Conditions Test Result

The smart mirror was tested in environments with varying lighting conditions, such as low light, bright light, and backlight, to determine its robustness in different visibility settings and the result indicated a decline in recognition accuracy by 10% under dim lighting condition. This illustrates that for optimal performance, the gesture-controlled smart mirror should be placed and used in a well-lit environment with balanced lighting; neither too dim nor excessively bright, as consistent and uniform illumination enhances gesture visibility and recognition accuracy. However, implementing adaptive algorithms that account for varying lighting conditions can further improve system robustness.

4. CONCLUSION

This paper successfully developed a gesture-controlled smart mirror, achieving all the key objectives set out. The integration of gesture control technology, a swipeable interface, and a user-friendly design has resulted in a smart mirror that enhances the user experience significantly. Through rigorous testing, the smart mirror demonstrated high usability, consistent performance, and reliability across various conditions.

This paper not only meets the current demands for smarter, more interactive home devices but also opens the door for future advancements in smart home technology. However, a hybrid power system can be incorporated into the smart mirror to ensure continuous operation, allowing the mirror to be powered by both AC mains and a backup battery. This would enhance the mirror's reliability, especially in environments with unstable power supply. For effective gesture recognition, advanced algorithms, such as machine learning models, are recommended to improve accuracy and response time, with the option to use simpler algorithms for basic functionality. Optimizing energy efficiency through features like automatic screen dimming and using energy-efficient components is also recommended.

Furthermore, a mobile app can be integrated for remote control, allowing users to customize display settings, access information, and control connected smart home devices via Wi-Fi or Bluetooth. The app could also provide real-time notifications, usage statistics, and system diagnostics for better analysis and improvement of the mirror and gesture technology. Future works will focus on expanding the testing of the mirror sensitivity in other diverse conditions.

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