

AI Enabled Teaching & Child Monitoring Robot

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Abstract

With rapid urbanization and the rise of dual-income households, continuous child supervision within homes has become increasingly challenging. Parents must balance professional responsibilities with child safety and early education, creating a need for intelligent home-based solutions. Most existing smart home monitoring systems rely on cloud-based architectures for video processing and behavior analysis, leading to issues such as network-dependent latency, privacy risks, and system failure during internet outages. The HomeLumos project addresses these challenges by proposing a centralized-intelligence autonomous home monitoring and child-teaching robot that operates entirely within a local home network. All artificial intelligence tasks, including child detection, anomaly detection, and teaching interaction, are performed locally, ensuring that sensitive data remains within the household. The system integrates a Raspberry Pi Zero 2 W for multimedia acquisition and communication with an Arduino Uno for reliable autonomous navigation. A browser-based parental dashboard enables live monitoring and alert notifications. By eliminating cloud dependency, HomeLumos enhances privacy, reduces response latency, and ensures reliable operation, as validated through successful prototype testing in domestic environments.

Keywords

Autonomous Robot, Home Monitoring, Child Safety, Local Intelligence, Edge AI, Parental Dashboard, Raspberry Pi, Arduino, Privacy-Preserving Systems.

1. INTRODUCTION

Smart home technologies have become increasingly common, with cameras, sensors, and automated devices being deployed for surveillance and convenience [7]. Most commercial smart monitoring systems rely on cloud-based infrastructure for data processing and analytics, which often introduces network dependency and latency [7], [10]. While these systems offer advanced features, they suffer from several limitations such as delayed response times due to network congestion, continuous internet dependency, subscription costs, and serious privacy concerns related to storing sensitive household data on external servers [7], [10].

In child monitoring applications, these limitations are particularly critical. Children require constant supervision and immediate intervention during unsafe situations, and any delay in detecting abnormal events may result in serious consequences [8], [9]. To overcome these challenges, HomeLumos is proposed as a fully local-intelligence autonomous robot. The system processes all sensory data locally using a laptop, ensuring that no private information leaves the home network [7]. The robot autonomously navigates indoor environments using established mobile robotics principles [1], [8], monitors child activity in real time, detects abnormal events, and supports basic teaching interactions based on parental instructions. A centralized parental dashboard ensures that parents retain full control and visibility at all times. This approach improves privacy, reliability, and responsiveness while combining safety monitoring and educational assistance in a single integrated system [10], [18].

2. RELATED WORK

Research in home monitoring and child safety systems has evolved significantly over the past decade, driven by advancements in computer vision, wireless communication, and embedded systems [2], [3], [7]. Early child monitoring solutions primarily relied on static CCTV camera networks, which provided basic video surveillance but lacked intelligence, mobility, and real-time analysis [7]. These systems required continuous human observation and were limited by fixed viewing angles, making them insufficient for dynamic indoor environments where children move frequently.

With the growth of artificial intelligence, several studies introduced cloud-based vision systems capable of activity recognition, motion tracking, and anomaly detection [2], [3]. Such systems utilize deep learning models hosted on remote servers to analyze video feeds in real time. While they offer higher accuracy and advanced analytics, they suffer from critical drawbacks such as increased latency, dependence on uninterrupted internet connectivity, and serious privacy concerns due to the transmission and storage of sensitive child data on external servers [7], [10]. Wearable child-tracking devices have also been explored using GPS, accelerometers, and heart-rate sensors [11], [12]. Although effective in outdoor environments, these devices are often uncomfortable for children, require frequent charging, and do not provide contextual visual information about the surrounding environment. Mobile service robots have been researched extensively in domestic applications such as cleaning, elderly assistance, and social companionship [8], [14]. These robots focus mainly on navigation and interaction but rarely integrate continuous child monitoring, parental supervision, and educational assistance into a single platform. Recent edge-computing-based solutions attempt to reduce cloud dependency; however, many still rely on remote servers for either model training or inference [7], [10]. HomeLumos differentiates itself from existing work by combining autonomous mobility, local AI-based perception, continuous parental supervision, and child-teaching functionality within a strictly local intelligence framework [1], [8], [18]. In addition, the proposed system emphasizes real-time responsiveness and modular system design, allowing easier scalability and future enhancements. By avoiding cloud dependence, HomeLumos provides a more reliable and privacy-focused solution suitable for everyday domestic environments.

Aspect	HomeLumos (Proposed System)	IROBI (Educational Robot)	Cloud-Based Home Monitoring
Main Focus	Child safety, monitoring & teaching	Educational learning support	Remote surveillance
Intelligence	Local intelligence (no cloud)	Network-based	Cloud-dependent
Privacy	High (local data processing)	Medium	Low
Hardware	Raspberry Pi, Arduino	Commercial robot	Cameras & servers
AI Processing	Local AI	Predefined interaction	Cloud AI
Monitoring	Real-time alerts	Limited	Network dependent
Teaching	Basic parental teaching	Structured content	Not supported
Autonomy	Autonomous + manual	Limited	No mobility
Cost	Low-cost	High-cost	Medium-high
Reliability	Works without internet	Partial dependency	Internet dependent

Table I: Comparison Table: Project vs Reference Journal

3. System Overview

The HomeLumos system follows a layered architecture consisting of sensing, control, intelligence, and user interaction components. Figure 1.1 illustrates the overall workflow of the proposed system.

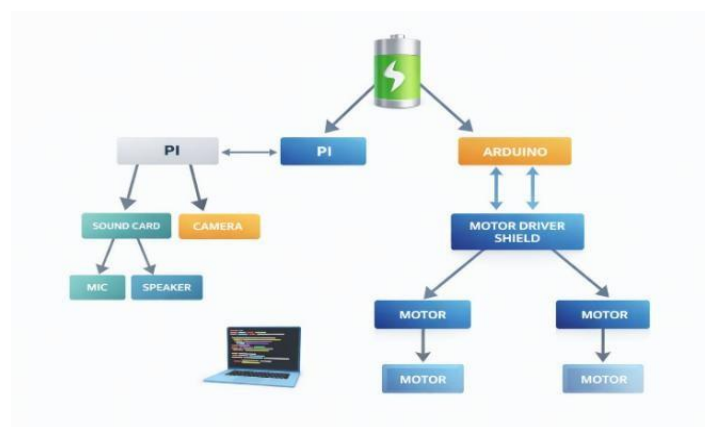


Fig. 1.1 Flow of HomeLumos

Fig. 1.1 shows the overall operational flow of HomeLumos from sensing to parental interaction. At a high level, sensory data captured by the robot are streamed to a local laptop, where AI models perform perception and decision-making. Control commands and alerts are then routed back to the robot and the parental dashboard.

User Interface Layer

The User Interface Layer consists of a web-based parental dashboard accessible through a laptop or mobile browser. This dashboard provides live video streaming, alert notifications, autonomous/manual mode switching, and teaching control options. All user commands originate from this interface, ensuring centralized and secure control.

Centralized Intelligence Layer

The Centralized Intelligence Layer runs on a local laptop, which acts as the brain of the system. It performs all AI-related tasks, including child detection, anomaly detection, decision-making, and teaching logic. Processing data locally ensures fast response times, predictable performance, and complete data privacy.

Communication Layer

Communication between system components is achieved using Wi-Fi for high-bandwidth data such as video and audio streams, and Bluetooth for manual movement override. This dual communication mechanism improves system robustness and reliability.

Robot Control and Sensing Layer

The robot control layer includes both the Raspberry Pi Zero 2 W and Arduino Uno. The Raspberry Pi handles video capture, audio interaction, and wireless communication, while the Arduino Uno manages low-level motor control and obstacle avoidance independently. This separation ensures continuous mobility even if high-level processing experiences delays.

Sensors and Actuators

The robot is equipped with ultrasonic sensors for obstacle detection, DC motors for movement, a motor driver for actuation, a camera for visual monitoring, and a microphone and speaker for audio interaction. These components allow the robot to perceive and interact with its environment effectively.

4. Hardware Architecture

The hardware design emphasizes modularity and reliability. Table I summarizes the major hardware components.

Component	Purpose
Raspberry Pi Zero 2 W	Video/audio capture, Wi-Fi communication
USB Camera	Real-time visual sensing
Microphone & Speaker	Audio interaction
Arduino Uno	Autonomous movement and motor control
Ultrasonic Sensors	Obstacle detection
L293D Motor Driver	DC motor actuation
DC Motors & Chassis	Mobile platform

Table II: Hardware Components Used in HomeLumos

The hardware architecture of HomeLumos is designed with a strong emphasis on modularity, reliability, and real-time performance.

Raspberry Pi Zero 2 W

The Raspberry Pi Zero 2 W serves as the primary multimedia and communication controller of the robot. It interfaces with the USB camera to capture live video and processes audio input from the microphone. The Raspberry Pi is also responsible for wireless communication with the local laptop through Wi-Fi, enabling real-time video streaming and command exchange.

Arduino Uno

The Arduino Uno acts as the low-level autonomous control unit. It handles motor control, obstacle avoidance, and navigation logic independently of high-level AI processing. By separating motion control from perception tasks, the system ensures that the robot continues to move safely even if communication delays or processing bottlenecks occur at the intelligence layer.

Ultrasonic Sensors

Ultrasonic sensors are mounted on the robot to detect obstacles in its path. These sensors continuously measure the distance between the robot and surrounding objects, enabling real-time obstacle avoidance. The sensor data is processed by the Arduino to make immediate navigation decisions.

Motor Driver and DC Motors

The motor driver acts as an interface between the Arduino and the DC motors, providing sufficient current to drive the motors. The DC motors, mounted on a mobile chassis, enable forward, backward, and turning movements. This configuration allows smooth and controlled navigation across indoor surfaces.

Camera, Microphone, and Speaker

The camera provides visual input for child detection and monitoring. The microphone and speaker enable basic audio interaction, allowing the robot to deliver instructions or respond to parental commands. Together, these components support multimodal interaction between the robot and its environment.

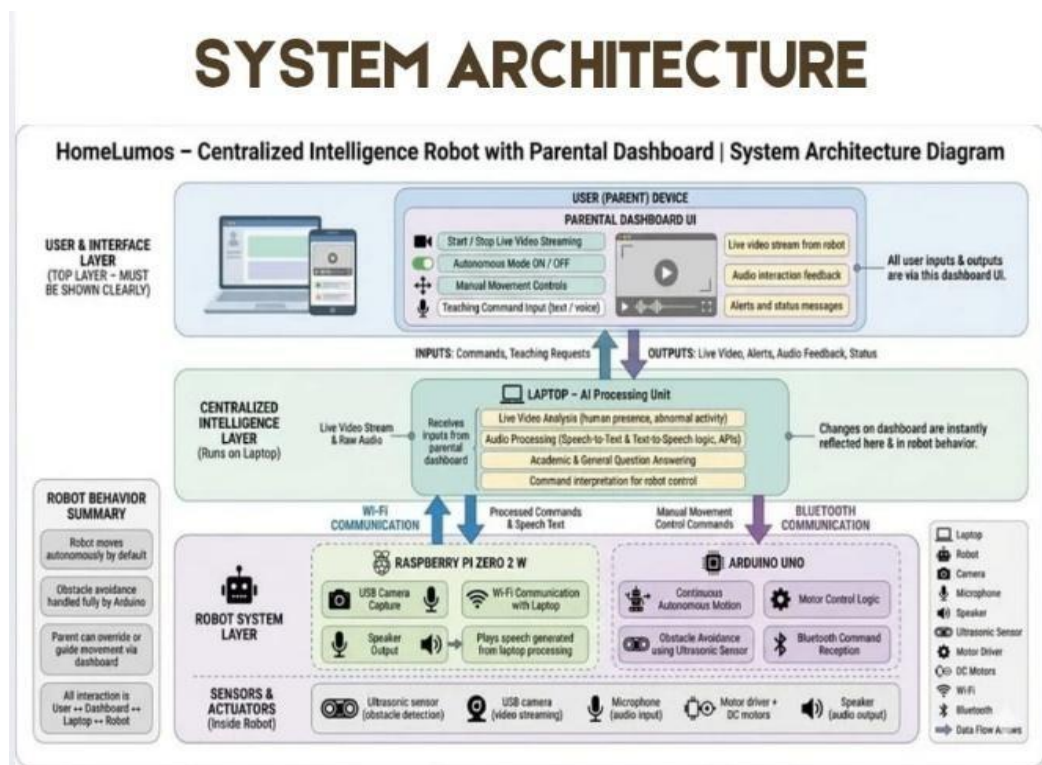


Fig. 1.2 Hardware Architecture Image

Fig. 1.2 shows Hardware Architecture Image Physical hardware layout and interconnections of the HomeLumos robot.

5. Software Architecture

The software architecture of HomeLumos is designed to achieve high reliability, modularity, and smooth coordination between artificial intelligence processing and physical robot operation. A layered architectural approach is adopted so that each software module performs a well-defined role without interfering with other modules. This separation of responsibilities reduces system complexity, prevents execution conflicts, and improves overall system stability. By organizing the software into independent layers, the system becomes easier to debug, maintain, and extend in the future. Any modification in one

layer, such as improving the AI model or updating the user interface, can be carried out without affecting other layers. This design approach is particularly important in real-time systems where continuous operation and predictable behavior are required. The HomeLumos system avoids complex software dependencies by centralizing all computationally intensive tasks on a local laptop, while allowing the robot hardware to operate autonomously for movement-related functions. This ensures that delays in video processing or decision-making do not interrupt basic robot navigation. As a result, even if one software module experiences delay or temporary failure, the overall system continues to function safely and reliably.

Perception and Intelligence Layer

The Perception and Intelligence Layer acts as the core brain of the HomeLumos system. It is responsible for all intelligent decision-making and runs entirely on a local laptop to avoid cloud dependency. This layer continuously receives live video and audio streams from the robot through the Raspberry Pi and processes them in real time. The primary function of this layer is child detection and activity analysis. Video frames are analyzed to identify the presence of a child and to understand movement patterns. These observations are compared with predefined normal behavior profiles. If the system detects unusual activity, such as unsafe movement, prolonged inactivity, or deviation from normal patterns, it classifies the event as abnormal. Anomaly detection logic ensures early identification of potentially unsafe situations, allowing the system to immediately generate alerts. This real-time analysis is lightweight enough to run continuously on local hardware without affecting system performance. In addition to monitoring, this layer also implements teaching and interaction logic. Based on commands received from the parental dashboard, the system generates appropriate instructions and responses for the robot. These may include initiating learning sessions or guiding the robot to interact with the child. Since all processing is performed locally, the system achieves low latency, predictable response time, and complete privacy of sensitive data.

Control and Communication Layer

The Control and Communication Layer serves as the bridge between high-level intelligence and low-level robot hardware. It translates abstract decisions, such as movement direction or alert actions, into specific control signals that can be executed by the Arduino and motor driver.

This layer manages all data exchange between the laptop, Raspberry Pi, and Arduino, ensuring proper synchronization of commands and sensor feedback. It also handles communication reliability by managing message delivery, acknowledgments, and error handling.

Two communication methods are used to improve robustness:

- Wi-Fi for high-bandwidth data such as video streaming, AI commands, and dashboard communication
- Bluetooth for manual override and emergency control

This dual communication strategy ensures that the system remains controllable even if one communication channel experiences interference or delay.

User Interface Layer

The User Interface Layer provides a simple, intuitive, and user-friendly interaction platform for parents. It is implemented as a browser-based parental dashboard, eliminating the need for installing dedicated applications.

The dashboard displays:

- Live video feed from the robot
- Alert notifications for abnormal events
- System status indicators
- Control options for autonomous and manual modes

Parents can easily monitor their child, respond to alerts, and initiate teaching sessions without technical knowledge. The clean interface design ensures ease of use and avoids information overload.

Being browser-based, the interface is compatible across multiple devices and maintains a stable layout when printed or documented.

6. Methodology

The methodology of the HomeLumos system explains the sequential operation of the robot from sensing the environment to parental interaction. The system follows a structured workflow to ensure continuous monitoring, quick response, and reliable operation.

Step 1: System Initialization

When the system is powered on, all hardware and software components are initialized. The Raspberry Pi activates the camera and audio devices, while the Arduino initializes motor drivers and ultrasonic sensors. The laptop establishes communication with the robot over Wi-Fi

Let the system state be represented as:

$$S_0 = \{C, M, U, N\} \quad (1)$$

where

C = Camera initialized M = Motors ready



U = Ultrasonic sensors active

N = Network connection established

If all components are active, the system enters autonomous mode.

Step 2: Autonomous Navigation and Obstacle Detection

The robot begins moving autonomously inside the home environment. Ultrasonic sensors continuously measure the distance to nearby objects.

Distance is calculated using:

$$D=2v \times t \quad (2)$$

where

D = Distance to obstacle v = Speed of sound

t = Time taken for echo to return

If $D < D_{min}$, the robot changes direction to avoid collision.

Step 3: Video and Audio Data Acquisition

The camera mounted on the robot captures live video frames, and audio input is collected using a microphone. These data streams are sent to the local laptop through Wi-Fi for processing.

Let the incoming data stream be:

$$I(t) = \{V(t), A(t)\} \quad (3)$$

where

V(t) = Video frame at time t A(t) = Audio signal at time t

Step 4: Child Detection

The perception model analyzes each video frame to detect the presence of a child. Feature extraction is performed on the incoming video frames.

$$F_t = f(V(t)) \quad (4)$$

where

F_t= Extracted features

f(.)= Feature extraction function

If a child is detected, the system switches to monitoring mode.

Step 5: Activity Monitoring and Anomaly Detection

The system continuously compares the current activity features with normal behavior patterns stored in memory. $A_t = \|F_t - \mu\|^2$ (5)

where

A_t= Anomaly score

μ = Mean feature vector of normal activity

If:

A_t > θ then the activity is classified as abnormal and an alert is generated. **Step 6: Alert Generation and Notification**

When an abnormal event is detected, the system generates an alert and sends it to the parental dashboard.

$$\text{Alert} = g(A_t) \quad (6)$$

where

g(.)= Alert generation function

The alert includes timestamp, event type, and live video feed.

Step 7: Parental Interaction and Control

Parents receive the alert on the dashboard and can issue commands such as:

- Continue monitoring
- Manual robot control
- Initiate teaching session Command signal:

$$C_p = h(U_p) \quad (7)$$

where

C_p= Parent command U_p= User input

Step 8: Teaching Interaction

If teaching mode is activated, the robot delivers instructions through audio output and guided interaction.

$$T_o = k(C_p) \tag{8}$$

where

T_o = Teaching output

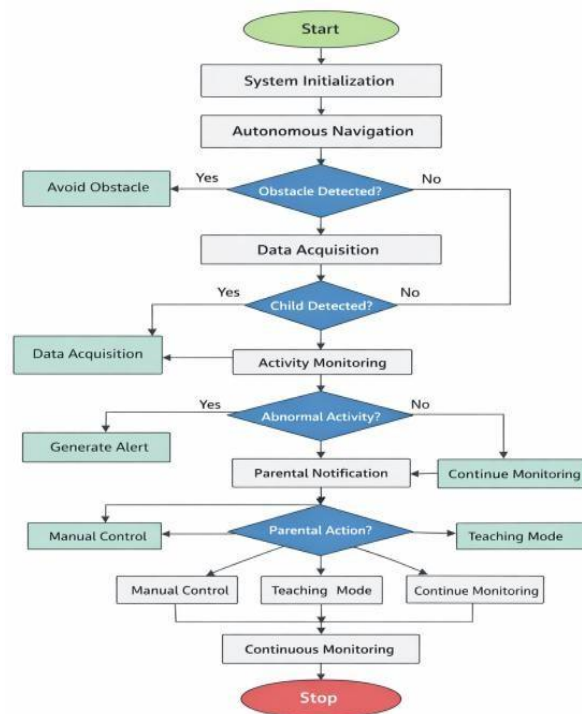
$k(.)$ = Teaching logic function

Step 9: Continuous Loop Operation

The system repeats the above steps continuously until manually stopped.

$$S(t+1) = S(t) \tag{9}$$

This loop ensures uninterrupted monitoring and interaction.



Methodology of the HomeLumos System

Fig. 1.3 Flowchart representing the step-by-step methodology of the HomeLumos system

Fig. 1.3 say The methodology flowchart illustrates the complete operational workflow of the HomeLumos system, showing how the robot performs monitoring, decision-making, and parental

interaction in a continuous loop. The process begins when the system is powered ON, after which all hardware and software components are initialized, including activation of the camera and communication modules by the Raspberry Pi, initialization of motors and ultrasonic sensors by the Arduino, and establishment of Wi-Fi connectivity with loading of artificial intelligence models on the laptop. Once initialized, the robot starts autonomous navigation within the home environment while continuously monitoring its surroundings for obstacles. Using ultrasonic sensors, the system checks for obstacles; if an obstacle is detected, the robot performs obstacle avoidance by changing direction, otherwise it continues moving forward. Simultaneously, the robot captures live video and audio data through the camera and microphone and transmits this data to the local laptop for processing.

The perception system then analyzes video frames to detect the presence of a child; if no child is detected, data acquisition continues, while detection of a child triggers activity monitoring. During activity monitoring, the child's movements and behavior patterns are continuously analyzed and compared with normal behavior profiles to identify abnormal activity. If abnormal behavior is detected, an alert is generated and sent to the parental dashboard along with live video and event details, whereas normal behavior results in continued monitoring. Upon receiving the alert, parents decide the next action using the dashboard, such as manual control of the robot, initiation of teaching interaction, or continuation of normal monitoring. After executing the selected action, the system returns to continuous monitoring, ensuring uninterrupted supervision, and the process continues in a loop until the system is manually turned OFF.

7. Implementation

The implementation of HomeLumos involved the careful integration of hardware and software components into a fully functional prototype. Hardware modules were securely mounted on a mobile chassis, ensuring stable sensor positioning and safe cable routing. Proper power management was implemented to avoid voltage fluctuations and ensure continuous operation. The Raspberry Pi Zero 2 W was configured to optimize video streaming by balancing resolution and frame rate to reduce latency and bandwidth usage. The Arduino Uno was programmed independently with obstacle avoidance and navigation algorithms to ensure uninterrupted movement.

Communication routines were extensively tested to minimize packet loss, delays, and synchronization errors. The parental dashboard underwent usability testing to ensure that video feeds, alerts, and control inputs responded correctly during prolonged operation. Multiple test cycles were conducted to evaluate fault tolerance and long-term system stability.

Parameter	Observation
Video Latency	Low, suitable for real-time monitoring
Navigation	Stable obstacle avoidance

Alert Response	Immediate upon threshold breach
User Control	Responsive dashboard interaction

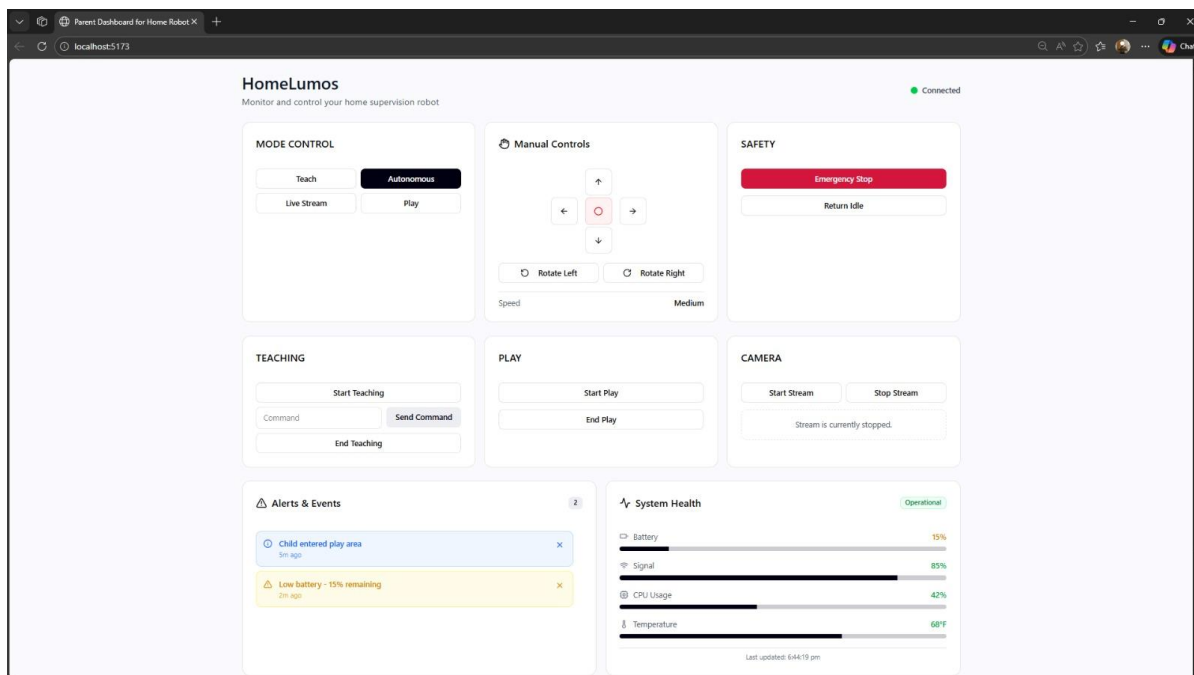
Table III: Experimental Observations

The results indicate that local intelligence can effectively replace cloud-based processing for home monitoring tasks without sacrificing functionality.

8. Results and Discussion

Experimental evaluation of the HomeLumos system demonstrates reliable performance under typical indoor conditions. The prototype was tested in a simulated home environment containing common obstacles such as furniture, walls, and moving individuals. During testing, the robot successfully performed autonomous navigation while continuously monitoring the surrounding environment.

Live video streaming exhibited consistently low latency, enabling parents to monitor their child in real time without noticeable delay. The use of local processing significantly reduced the response time compared to cloud-based monitoring systems, where network latency can affect system performance. The camera module successfully captured clear video frames, which were processed by the centralized intelligence layer for child detection and activity monitoring.



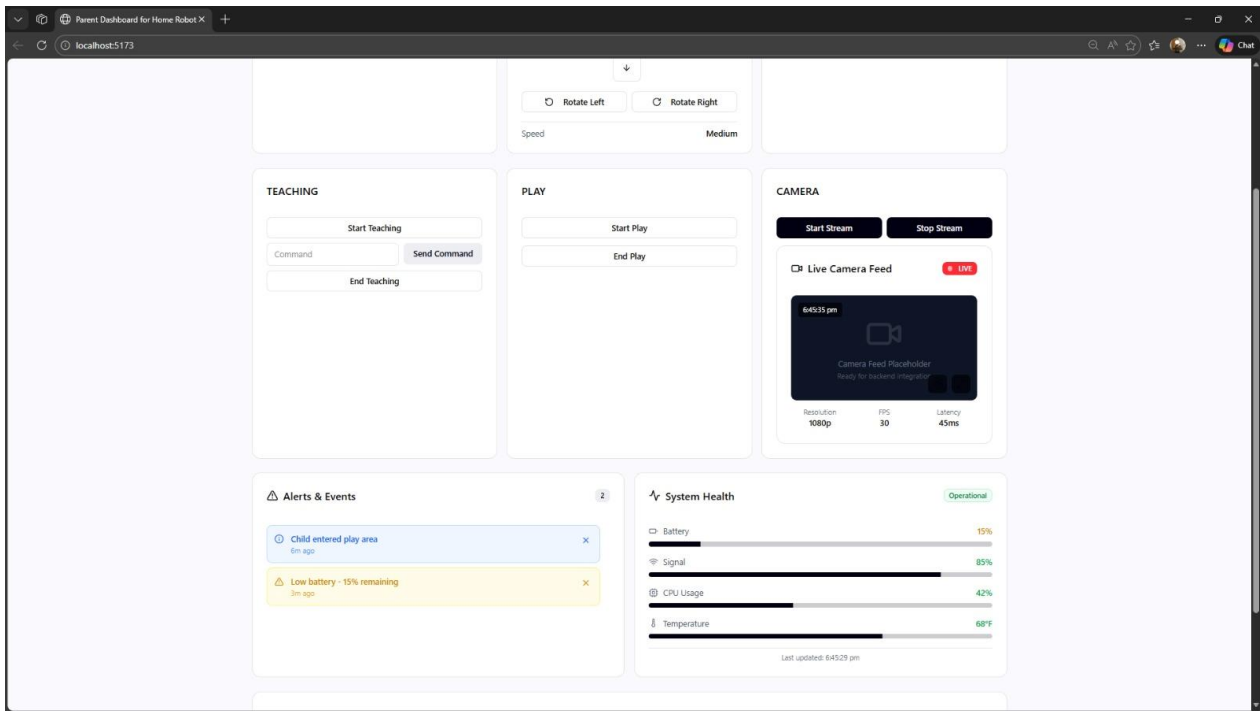


Fig. 1.4 HomeLumos integrated dashboard showing live video, controls, alerts, and system monitoring

Autonomous navigation remained stable even in cluttered environments, confirming the effectiveness of the ultrasonic sensor-based obstacle detection and avoidance mechanism. The robot was able to adjust its movement direction when obstacles were detected within the predefined threshold distance. This ensured safe navigation within indoor spaces and prevented collisions with surrounding objects.

Alert generation occurred immediately upon detecting abnormal activity. The system compared real-time behavioral patterns with predefined normal activity profiles to identify unusual events. When abnormal behavior was detected, the system generated instant alerts that were transmitted to the parental dashboard. Parents were able to view live video feeds and respond quickly using manual control or teaching mode options.

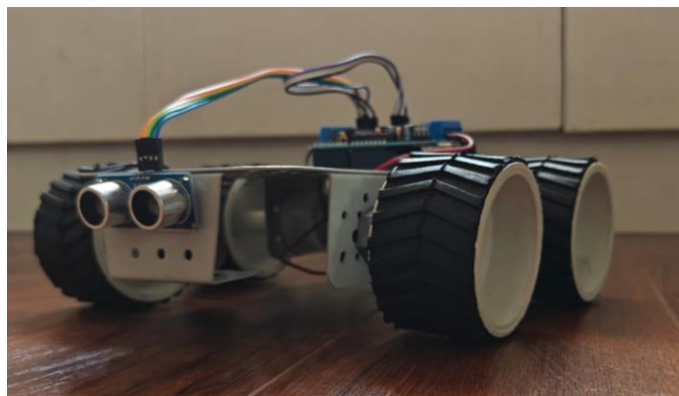


Fig. 1.5 Fully assembled HomeLumos robot with all hardware components connected

The parental dashboard interface was also evaluated for usability and responsiveness. The browser-based interface provided clear visualization of system status, video streaming, and alert notifications. Parents could easily switch between autonomous mode and manual control, demonstrating the practicality of the interface for real-world home environments.

Compared to traditional cloud-based monitoring systems, HomeLumos provides faster response, predictable behavior, and enhanced privacy since all data processing occurs locally. This local-intelligence approach eliminates the need for continuous internet connectivity and ensures that sensitive child monitoring data remains within the home network.

Parameter	Test Condition	Observed Result	Remarks
Video Streaming Latency	Indoor Wi-Fi network	Low latency (~0.3–0.5 s)	Suitable for real-time monitoring
Child Detection Accuracy	Normal indoor lighting	High detection reliability	AI model correctly identified child presence
Obstacle Avoidance	Furniture and wall obstacles	Successful avoidance	Ultrasonic sensors prevented collisions
Alert Response Time	Abnormal activity detection	Instant alert (<1 s)	Immediate notification on parental dashboard
Navigation Stability	Cluttered home environment	Stable movement	Robot maintained smooth path planning
Dashboard Responsiveness	Manual control & alerts	Highly responsive	Easy interaction for parents

Table IV: Performance Evaluation of HomeLumos System

Overall, the experimental results confirm that the HomeLumos system successfully integrates real-time monitoring, autonomous navigation, and parental interaction into a reliable and privacy-preserving platform. These findings demonstrate the potential of local AI-based robotic systems to provide effective child safety monitoring and teaching assistance in modern smart homes.

9. Conclusion and Future Work

The HomeLumos project successfully demonstrates the design and implementation of a locally intelligent autonomous robot for child monitoring and teaching. By integrating autonomous navigation, real-time perception, parental supervision, and educational interaction into a single platform, the system addresses the major limitations of existing cloud-dependent solutions. The use of local processing

ensures enhanced privacy, reduced latency, and reliable operation, making HomeLumos suitable for real-world domestic environments.

The successful prototype confirms that centralized local intelligence is a practical, efficient, and scalable approach for smart home applications. Future enhancements to HomeLumos can focus on expanding intelligence and interaction capabilities. Adaptive learning algorithms can be incorporated to personalize teaching based on the child's behavior and learning pace.

Multimodal anomaly detection using both audio and visual inputs can further improve safety monitoring accuracy. Navigation performance can be enhanced using mapping and localization techniques such as SLAM to improve movement precision. Battery optimization and intelligent power management can extend operational duration, making the system more suitable for daily use.

These improvements will further strengthen HomeLumos as a comprehensive and intelligent domestic assistant for child safety and education.

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