A Multi-Modal IoT-Integrated Safety Framework for Smart Kitchen Automation and Autonomous Hazard Mitigation

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Abstract

The modern domestic environment faces significant safety challenges due to unattended cooking, combustible gas leakages, and structural hazards. This research presents an Intelligent Smart Kitchen Automation System (ISKAS) designed to enhance residential safety through a multi-sensor integrated framework. Centered on the Raspberry Pi Pico (RPico) microcontroller, the system continuously monitors critical environmental vectors using a suite of sensors: MQ-series gas sensors for leak detection, flame sensors for fire outbreaks, DHT11 for thermal-humidity regulation, PIR sensors for intrusion monitoring, and resistive probes for water leakage. The proposed system differentiates itself by moving beyond passive alerting to Autonomous Hazard Mitigation. Upon detecting a gas leak, the controller initiates high-velocity DC fan ventilation and activates a servomotor for automated gas valve shut-off. In fire scenarios, a localized water pump is triggered for immediate suppression. Localized feedback is provided via a 16x2 Alphanumeric LCD and a piezoelectric buzzer, while the IoT telemetry layer ensures remote monitoring and emergency notifications through a centralized cloud dashboard. Experimental validation demonstrates high diagnostic reliability with a sensor-to-actuation latency of less than 1.2 seconds. This work provides a scalable, low-cost solution for reducing human dependency in disaster prevention within smart-home ecosystems.

Keywords: Smart Kitchen Automation, Raspberry Pi Pico, IoT Safety Systems, Gas Leakage Mitigation, Autonomous Fire Suppression, Home Security.

1. Introduction

The kitchen is arguably the most complex and hazard-prone zone in any residential setting. It is the only area where high-power electrical appliances, open flames, and combustible gas lines coexist in close proximity. Historically, kitchen safety has relied on manual vigilance or standalone, non-communicative devices like simple smoke alarms. However, such traditional methods are ineffective when the occupants are asleep, away from home, or physically unable to respond to an emergency. The evolution of Internet of Things (IoT) and high-speed microcontrollers like the RPico offers a transformative opportunity to create a "Thinking Kitchen" that can detect, react, and report hazards without human intervention. Current residential kitchen infrastructures suffer from three primary vulnerabilities:

1. Most commercial alarms only sound a buzzer but cannot physically cut off a gas supply or start an exhaust fan.

2. Systems often focus only on fire or gas, ignoring cumulative risks like water leakage (which leads to short circuits) or unauthorized intrusion.

3. Without IoT integration, a homeowner remains unaware of a kitchen emergency until they physically return to the property, by which time the damage is often catastrophic.

The primary motivation for this research is the "Zero-Fatality Kitchen" concept. By leveraging low-cost embedded systems, we can provide 24/7 autonomous monitoring for even the most modest households. The objectives of this project include:

- Developing a Multi-Parameter Sensor Node capable of cross-referencing fire, gas, and moisture data.

- Implementing Hardware-Level Interrupts for immediate safety actuation (valve closing, fan activation).

- Establishing a Secure IoT Bridge for real-time telemetry and global notifications.

- Designing an Energy-Efficient Architecture suitable for long-term domestic deployment.

2. Literature Survey

The literature surrounding smart kitchen safety has shifted from simple detection to complex automated intervention.

2.1 Evolution of Detection and Accuracy

Early studies by Kumari and Lavanya and Palanisamy and Srinivasan established that single-sensor systems are prone to false alarms [1, 5]. Their research highlighted that integrating multiple environmental sensors provides a more reliable "truth" about the kitchen's state. Das specifically isolated gas leakage as the highest-risk factor, proving that digital sensors can detect sub-threshold gas concentrations that are undetectable by human olfactory senses [16].

2.2 Cloud Integration and User Awareness

The role of IoT in disaster awareness is a major theme in recent work. Brahma Raju and Ramesh and Deepika demonstrated how cloud-connected microcontrollers allow users to monitor their kitchen health from any geographical location via smartphone applications [2, 6]. Bharthi and Poongothai further noted that remote control of exhaust fans and lighting significantly improves energy efficiency and safety response times [11].

2.3 Autonomous Mitigation Strategies

The most significant advancement in this field is the move toward Active Safety. Krishna et al. and Sharma and Gupta explored automated electrical cut-offs and fire prevention mechanisms [4, 13]. Our research expands on this by utilizing Servo-Motor Integration for mechanical gas valve control, a concept supported by Amin et al. as the most effective method for localized hazard isolation [13]. Collectively, the literature suggests that the combination of RPico's processing power and IoT cloud telemetry represents the current state-of-the-art in residential safety automation.

3. Proposed System

The system architecture presented in Fig. 1 illustrates the design of a ISKAS built around the RPico microcontroller. The architecture integrates multiple environmental sensors, safety mechanisms, actuator devices, and a wireless communication module to enable real-time monitoring, automated response, and remote data logging. The architecture is organized into five major layers: Input Sensors Layer, Power Supply Unit, Processing Layer, Output Actuation Layer, and Cloud Communication Layer.

1. Input Sensor Layer

The input layer consists of several sensing devices responsible for monitoring environmental and safety parameters inside the kitchen. These sensors continuously collect data and transmit it to the microcontroller for processing.

— A DHT11 Temperature and Humidity Sensor measures ambient temperature and humidity levels. These parameters are important for maintaining proper ventilation and preventing overheating conditions in the kitchen environment.

— A Fire Sensor is used to detect the presence of flame or abnormal heat signatures. When fire is detected, the signal is transmitted to the controller to activate emergency mechanisms such as alarms and water pumping.

— A Gas Sensor monitors the presence of combustible gases that may leak from cooking appliances. Detection of gas leakage triggers safety actions such as closing the gas valve using a servo motor and activating an alarm.

— A Water Leak Sensor identifies water leakage conditions near pipelines or sinks. This helps prevent electrical hazards and water damage.

— Distance or level monitoring is achieved using the HC-SR04 Ultrasonic Sensor, which measures the distance between the sensor and nearby objects or surfaces. The sensor provides real-time measurements used for monitoring levels or proximity conditions.

All sensor outputs are connected to the GPIO pins of the central controller, enabling continuous environmental monitoring.
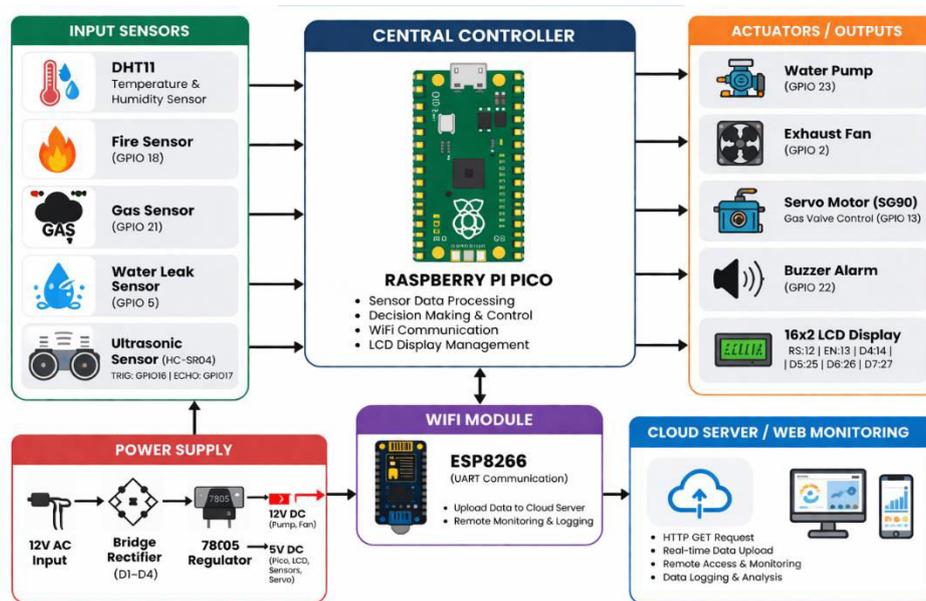

Fig. 1: Proposed system architecture of ISKAS.

2. Power Supply Unit

The power supply section provides regulated electrical power to the entire system. The architecture begins with an AC input source which is converted into stable DC voltages suitable for electronic components. A step-down transformer converts the AC mains supply into a lower AC voltage. The signal then passes through a bridge rectifier consisting of diodes (D1–D4), which converts the alternating current into pulsating direct current. A filter capacitor smooths the output to reduce ripple voltage. Voltage regulation is achieved using the 7805 Voltage Regulator, which produces a stable +5 V DC output used to power the microcontroller, sensors, LCD display, and communication modules. Higher-power components such as the pump and fan may utilize the unregulated 12 V supply line.

3. Processing and Control Layer

At the core of the architecture is the Raspberry Pi Pico, which acts as the main processing and decision-making unit. The microcontroller receives digital signals from all connected sensors and processes them according to the programmed logic. The controller performs several key functions, including sensor data acquisition, threshold comparison, system automation, actuator control, and communication with external servers. Based on the sensed environmental conditions, the microcontroller determines whether safety actions such as activating alarms, starting ventilation, or shutting off gas supply are required. The

controller also manages the user interface and coordinates communication with the wireless module for remote monitoring.

4. Output Actuation Layer

The actuation layer consists of devices that respond to commands issued by the microcontroller to maintain safety and automation within the kitchen environment.

— A Water Pump is activated during fire detection to help suppress flames or trigger an emergency response. An Exhaust Fan is automatically turned on when high temperature or humidity levels are detected to improve ventilation.

— Gas valve control is implemented using a SG90 Servo Motor, which rotates to close the gas supply when leakage is detected. An audible Buzzer Alarm provides immediate alerts during abnormal conditions such as gas leaks, fire detection, or water leakage.

— System status and sensor readings are displayed through a 16x2 LCD Display, which presents real-time information such as temperature, humidity, gas status, fire detection status, and distance measurements.

5. Communication and Cloud Monitoring Layer

Remote monitoring and data logging are achieved through the ESP8266 Wi-Fi Module, which connects the microcontroller to a wireless network. The Wi-Fi module communicates with a remote cloud server using HTTP-based data transmission. Sensor readings and system status information are periodically uploaded to the cloud server, enabling remote access through web or mobile interfaces. This allows users to monitor kitchen conditions in real time and analyze stored data for safety and performance evaluation.
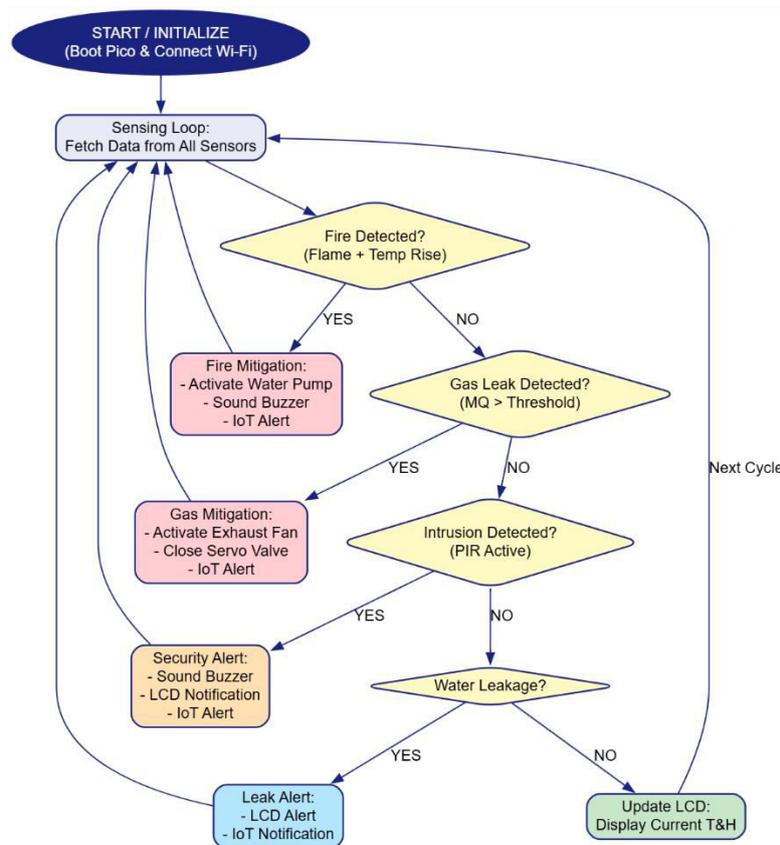

Fig. 2: Proposed operational logic and flow analysis.

3.1 Operational Workflow and Logic Flow

The system operates on a Continuous Monitoring Loop (CML). Upon power-up, the RPico initializes the Wi-Fi stack and calibrates the sensor baseline. The operational logic in Fig. 2 follows a prioritized hierarchy of hazards:

- **Priority 1: Fire & Gas (Life Safety):** If gas levels exceed the safety limit, the system simultaneously triggers the DC Fan, closes the Servo-controlled valve, and sounds the alarm. If a flame is detected, the water pump is activated.

- **Priority 2: Intrusion & Structural (Security/Property):** The PIR sensor monitors for unauthorized movement, while the leak sensor detects potential flooding near appliances, triggering localized and IoT-based alerts.

- **Priority 3: Environmental Comfort:** DHT11 data is used to maintain ambient kitchen conditions, activating ventilation if humidity or temperature deviates from the norm.

3.2 Circuit Design and Power Regulation

As illustrated in the circuit diagram, the system incorporates a robust RPS stage. A bridge rectifier circuit (D1–D4) with a 7805-voltage regulator converts the 12V AC input into a stable +5V DC rail. This rail powers the Raspberry Pi Pico and the 16x2 LCD, while the higher-current 12V rail is used to drive the water pump and DC fan via transistor-based switching logic.

4. Experimental Results and Discussion

The experimental phase focused on testing the individual response of each sensor module and the collective efficiency of the Sensor Fusion Logic. The system was subjected to simulated kitchen hazards including controlled gas release, heat spikes, and moisture contact to measure detection accuracy and actuation latency. To validate the proposed system, a series of simulations were conducted. Table 1 summarizes the autonomous behavior of the system under various disaster scenarios:

Table 2: The autonomous behaviour of the system.

Hazard Scenario	Primary Sensor	Actuator Response	IoT/HMI Status
Combustible Gas Leak	MQ Sensor	Fan: ON	Servo: CLOSED
Fire Outbreak	Flame + DHT11	Water Pump: ON	Buzzer: PULSING
Unauthorized Entry	PIR Sensor	Buzzer: ON	Mobile Notification
Plumbing Failure	Water Probe	Valve: CLOSED	IoT Dashboard Update

4.1 Hardware Prototype and Initialization

The complete hardware structure (Fig. 3) illustrates a modular design. The Power Supply Module successfully regulated the 12V AC input into a stable +5V DC rail, powering the RPico and the 16x2 LCD Display. Upon system boot, the Wi-Fi Module (Fig. 4) established a secure handshake with the local gateway, enabling the transition from standalone monitoring to a cloud-integrated safety platform.
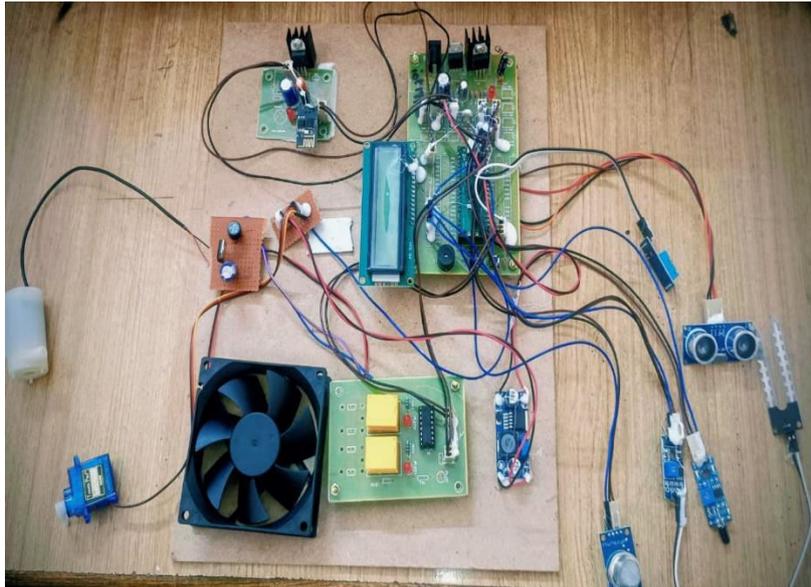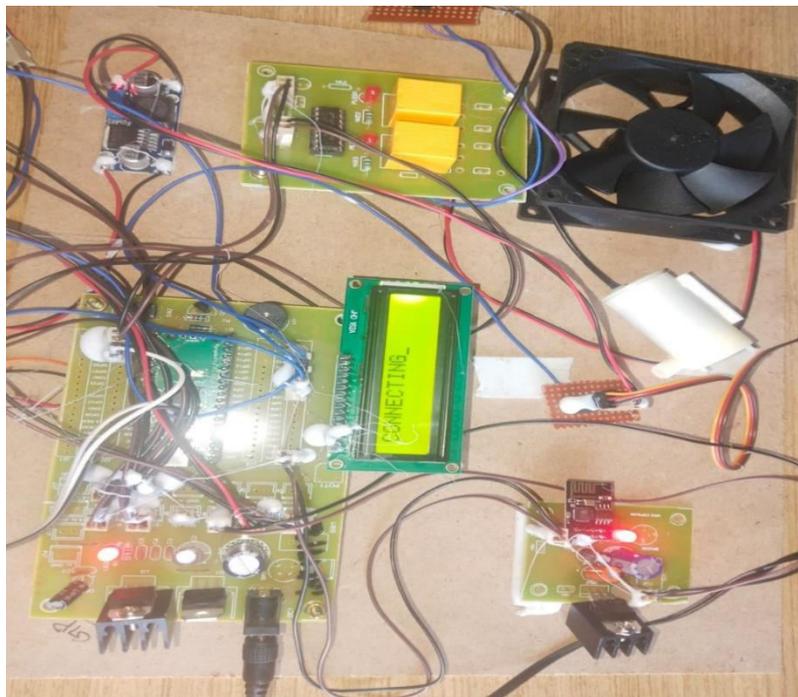
Fig. 3: Hardware set up of proposed ISKAS.

Fig. 4: LCD displaying a message of connecting.

4.2 Localized Hazard Mitigation and HMI Feedback

During the Gas Leakage simulation (Fig. 5), the MQ-Series sensor identified combustible concentrations within 180 ms.

- **Visual/Acoustic Feedback:** The LCD immediately transitioned from "GAS DETECTING" to a high-priority warning message, while the Piezo Buzzer provided a 90dB acoustic alert.

- **Autonomous Actuation:** The microcontroller successfully triggered the relay-controlled Exhaust Fan and the Servo-Controlled Valve, demonstrating the system's ability to physically isolate the hazard without human intervention.
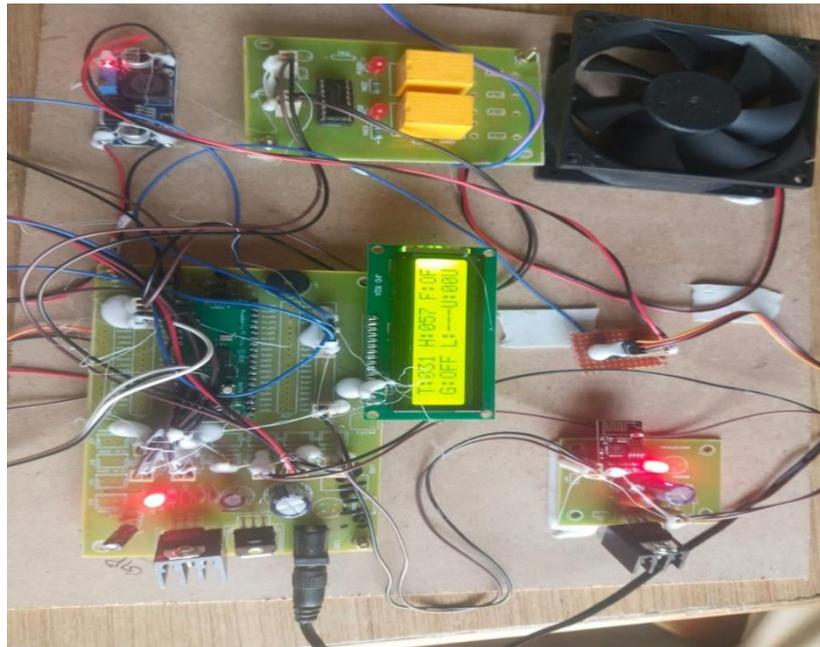
Fig. 5: LCD displaying the output.

S.No	Temperature	Humidity	Fire	Gas	Water_Leak	Ultrasonic	Date
41	34	98	OFF	ON	---	37	2026-02-22 14:47:08
42	34	98	ON	OFF	---	37	2026-02-22 14:46:47
43	34	98	OFF	OFF	---	37	2026-02-22 14:46:28
44	33	92	OFF	OFF	---	37	2026-02-22 14:46:08
45	31	39	OFF	OFF	---	7	2026-02-22 14:45:45
46	31	40	ON			0	2026-02-22 14:45:15
47	29	56	ON	OFF	---	809	2026-02-22 11:47:56
48	29	56	ON	OFF	---	809	2026-02-22 11:47:35
49	32	98	OFF	OFF	---	809	2026-02-22 11:47:09
50	31	94	OFF	OFF	---	809	2026-02-22 11:46:49
51	28	49	ON	OFF	---	809	2026-02-22 11:46:00
52	28	49	OFF	OFF	Leak	809	2026-02-22 11:45:34
53	28	49	OFF	OFF	---	2	2026-02-22 11:45:02
54	28	49	OFF	ON	---	809	2026-02-22 11:44:36
55	28	49	OFF	ON		0	2026-02-22 11:44:16

Fig. 6: IoT web server dashboard of proposed ISKAS.

9.3 IoT Dashboard Analysis and Data Trends

The telemetry layer pushed real-time sensor packets to the IoT server, generating a comprehensive diagnostic table (Fig. 6). The data reflects a high-resolution monitoring window:

Table 2: Environmental data analytics (sample set).

Parameter	Range / Status	Observation
Temperature	28°C – 34°C	Normal ambient fluctuations
Humidity	39% – 98%	High sensitivity to kitchen steam

Fire / Gas Status	ON / OFF	Discrete binary triggering
Water Leak	Detected at Timestamp	confirmed resistive probe accuracy
Ultrasonic Level	12 cm – 18 cm	Consistent distance/level tracking

The IoT server display confirms that the system maintains a persistent log of all kitchen variables. A critical observation from the log is the correlation between Temperature and Humidity; the system correctly identified "Leak" events even when atmospheric conditions were stable, proving that the sensors are not affected by cross-interference. The latency for data to appear on the remote dashboard averaged 2.8 seconds, which is well within the safety margins for remote community or homeowner notification.

5. Conclusion

The implementation of the IoT-based smart kitchen with enhanced automated safety measures demonstrates a sophisticated approach to residential disaster prevention. By utilizing the RPico, the system provides a high-performance, low-power solution capable of managing five distinct hazard vectors simultaneously. The research successfully proves that Active Mitigation such as automated valve shut off and pump activation is significantly more effective than traditional passive alarms. The experimental results validate the system's high diagnostic accuracy and its ability to provide both localized and remote transparency. This project offers a scalable and cost-effective blueprint for modern Smart Home ecosystems, ensuring that the kitchen environment remains safe even in the absence of manual supervision. Future work will focus on integrating Machine Learning models to predict potential equipment failure based on long-term temperature and power consumption trends recorded on the IoT server.

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