REAL-TIME IOT-BASED MONITORING AND AI-DRIVEN INSIGHTS FOR BEE COLONY MANAGEMENT

Project Reference No.: *49S_BE_1077*

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Keywords:

Internet of Things (IoT), Bee Colony Monitoring, Swarm Prediction, Acoustic Signal Analysis, Machine Learning, YOLO-based Classification, Spectrogram Analysis, MFCC, Real-Time Monitoring, Environmental Sensing, Smart Beekeeping, ESP32, Hive Health Detection, Anomaly Detection, Wireless Sensor Networks.

Introduction:

India's apiculture industry, valued at over 20 billion rupees and producing approximately 95,000 metric tons of honey annually, faces significant challenges such as disease outbreaks, hive thefts, labor-intensive inspections, and the absence of real-time monitoring. HiveLink, developed by students of St Joseph Engineering College, addresses these critical issues through an innovative technology-driven solution. Designed at a cost of 2500 per device, HiveLink integrates IoT sensors, wireless communication, cloud computing, and machine learning technologies to provide real-time insight into hive conditions. The system utilizes an ESP32S3 microcontroller, DHT22 temperature and humidity sensors, liquid level sensors, and load cells to continuously monitor environmental parameters, hive weight, and sugar supplement levels. Data is transmitted via Wi-Fi to a cloudbased server and managed using Firebase platforms. Advanced analysis is conducted through machine learning algorithms developed using TensorFlow, allowing predictive alerts for swarming, absconding, pest attacks, hive falls, and supplement requirements. Beekeepers can access this data through a secure, mobile application developed using Flutter, ensuring timely interventions and minimizing manual inspections. Additionally, integration with the National Beekeeping and Honey Mission database supports broader policy initiatives and facilitates direct market connectivity. HiveLink not only enhances operational efficiency but also promotes sustainable and scientific beekeeping practices. By reducing hive losses and enabling remote monitoring of dispersed apiaries, it contributes significantly to strengthening India's apiculture sector. HiveLink represents a scalable, cost-effective model for modern beekeeping, aligning with the nation's goals of agricultural innovation and rural development.

Objectives:

1. To design and implement a comprehensive Internet of Things (IoT)–based monitoring system capable of continuously tracking essential beehive parameters such as temperature, humidity, and supplement levels. In addition to

environmental sensing, the system captures and records bee acoustic signals, enabling advanced audio-based processing forhive condition assessment and prediction.

2. Create and put into use an AI model to evaluate the health of the hive, find the queen bee, recognize unusual hive conditions including swarming, absconding, and pest attacks, and forecast the cycle of supplement refills based on usage patterns and colony conditions.
3. Create a smartphone application that allows beekeepers to easily manage hive status and supplement refill schedules, display hive data, and receive real-time notifications.
4. To create an India-specific beehive condition database that systematically documents regional differences in hive health, environmental conditions, disease patterns, and seasonal variability, enabling informed decision-making and targeted interventions.

Methodology:

- **Objective 1:**
  An IoT device was developed by integrating sensors capable of measuring temperature, humidity, noise levels, and supplement levels within the beehive. The ESP32 microcontroller served as the central processing unit, coordinating data collection and transmitting the information wirelessly to a remote server.

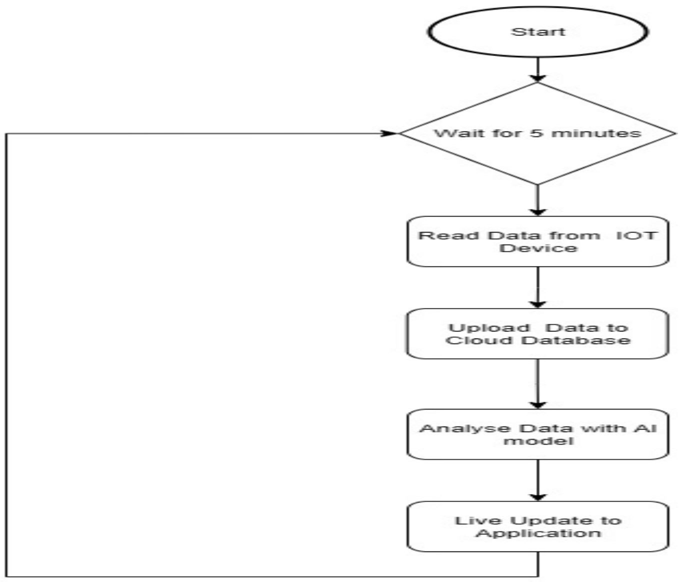

Figure 1: General Block Diagram

The system initiates by entering a timed loop, where it waits for a 5-minute interval before proceeding. Upon each cycle, the IoT device reads environmental and sensor data, which is then uploaded to a cloud-based database. Once the data is stored, it is processed and analyzed using an AI model hosted on the cloud. The results of this analysis are used to provide real-time updates to the connected application, enabling dynamic monitoring and decision-making. This loop continues indefinitely, ensuring continuous and intelligent data-driven updates.

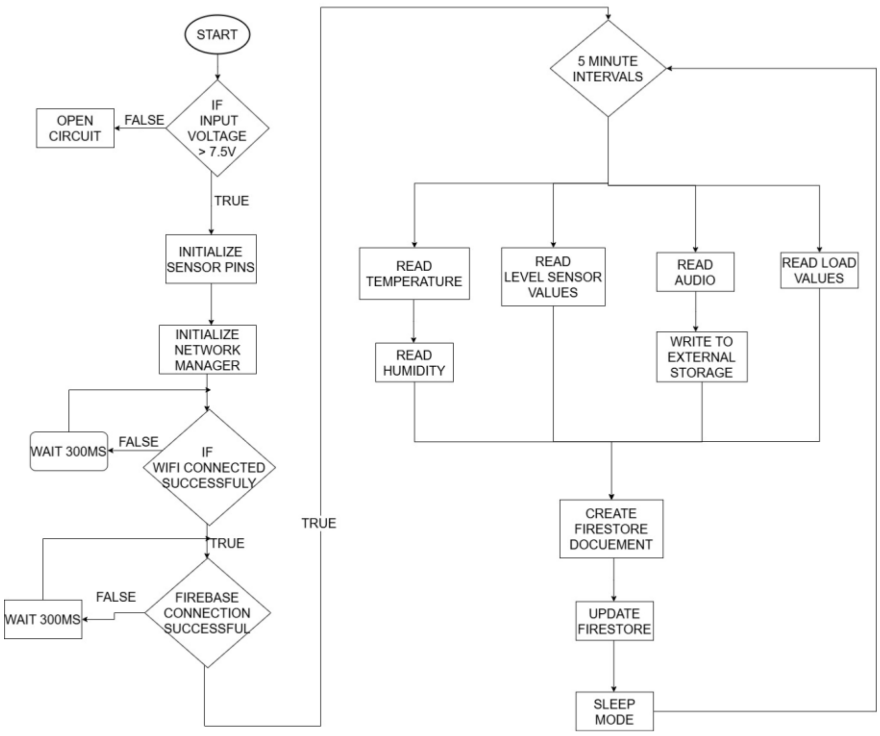

Figure 2: Software Flow Diagram

The system begins by verifying that the input voltage exceeds 7.5V. Upon validation, it initializes the sensor interfaces and network components. A connection is then established with Wi-Fi and Firebase. Once connected, the system enters a 5-minute interval loop, during which it reads data from temperature, humidity, load, level, and audio sensors. Audio data is stored externally, while all other sensor data is compiled and uploaded to Firestore. After updating the database, the device enters sleep mode to conserve power, repeating the cycle periodically.

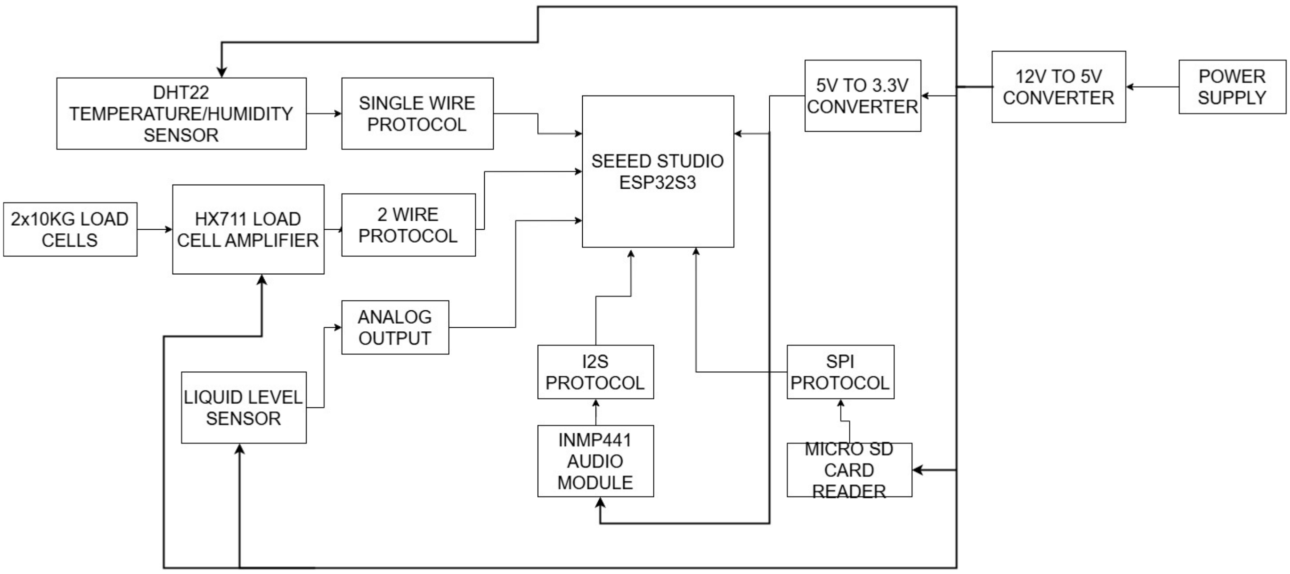

Figure 3: Hardwawre Block Diagram

The system is powered by a 12V supply, which is stepped down using 12V to 5V and 5V to 3.3V converters to meet the voltage requirements of the components. The central controller is the Seeed Studio ESP32-S3 microcontroller. It interfaces with various sensors using different communication protocols. A DHT22 sensor measures temperature and humidity using a single-wire protocol. Two 10 kg load cells and a liquid level sensor connect via an HX711 amplifier using a 2-wire protocol and analog signal. An INMP441 digital microphone captures audio via the I²S protocol, while data is stored using an SPI-based microSD card module.

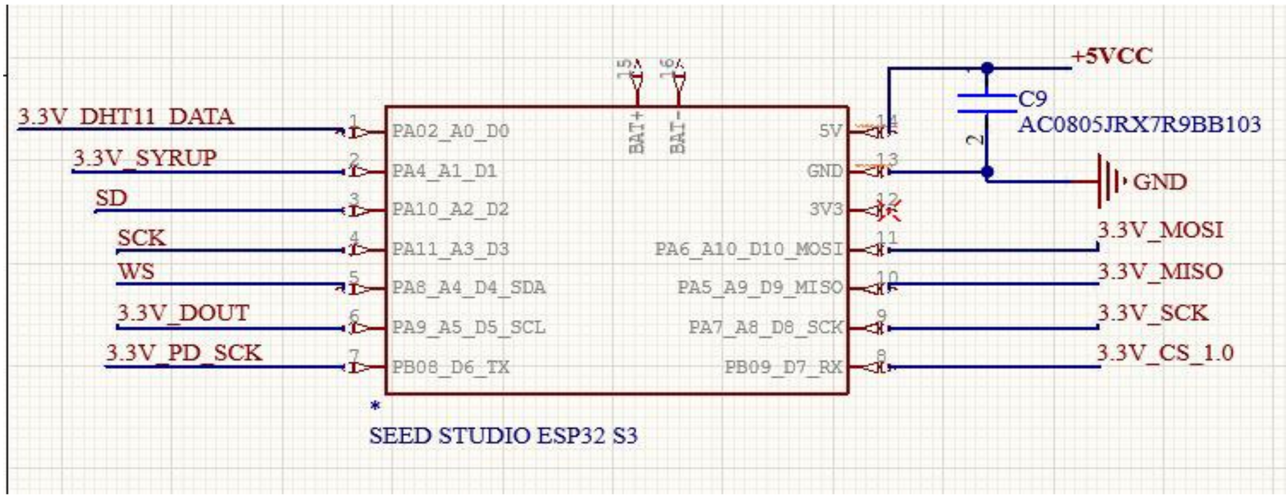

Figure 4: XIAO ESP32S3 Microcontroller

The XIAO ESP32S3 is an ultra-compact microcontroller module based on the ESP32- S3 chip, featuring a dual-core 32-bit LX7 processor. It supports 2.4GHz Wi-Fi and Bluetooth 5.0 (BLE), making it suitable for IoT and wireless applications. With 11 multifunctional GPIO pins, USB-C connectivity, and low-power operation, it serves as the central controller in the system, handling sensor data, control logic, and wireless communication.

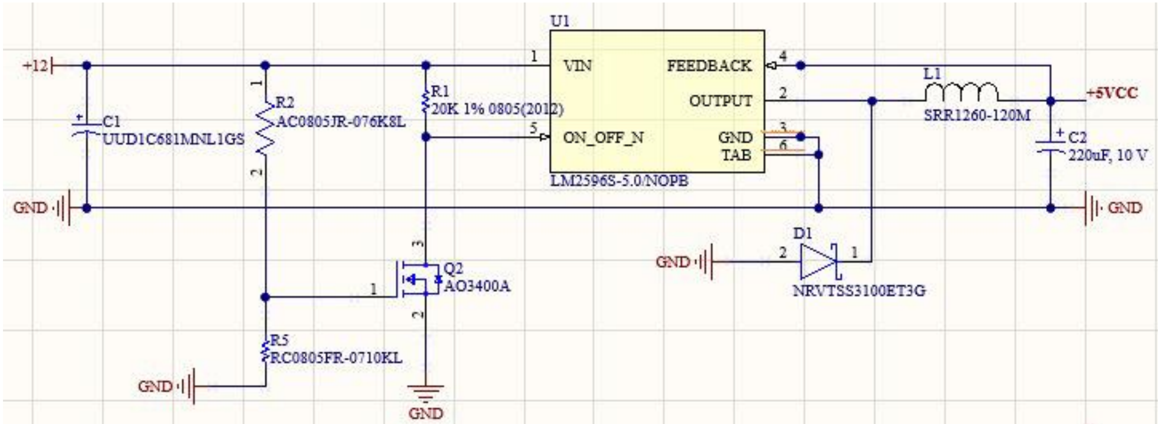

Figure 5: 12V to 5V converter

The buck converter (LM2596R-5.0) is used to step down the input voltage from 12V to a stable 5V output. This regulated 5V is used to power various components in the system efficiently, supporting up to 3A of output current with minimal heat generation due to its switching operation.

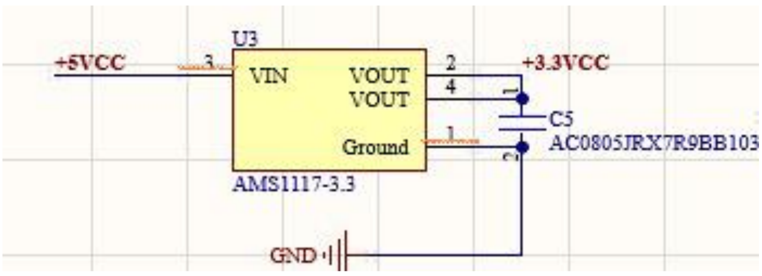

Figure 6: 5V to 3.3V converter

The linear regulator (AMS1117-3.3) steps down the voltage from 5V to 3.3V to provide stable power to the system.

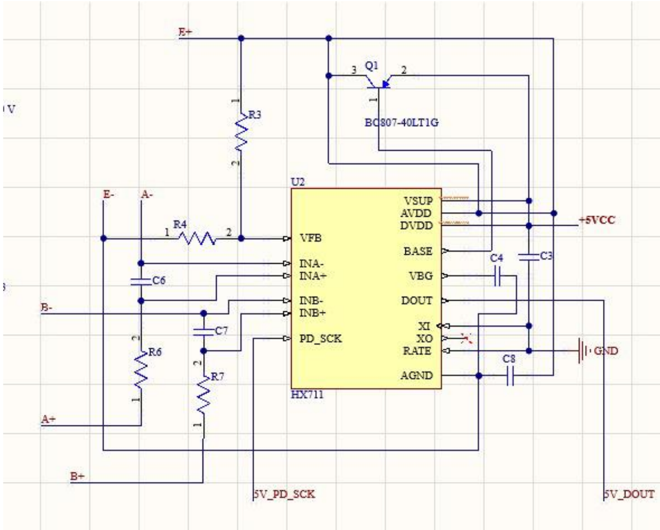

Figure 7: HX711 Weight Sensor Module

The HX711 is a dual-channel, 24-bit precision analog-to-digital converter (ADC) designed specifically for weigh scales and industrial control applications. It amplifies the small analog signals from load cells and converts them into digital values. The module operates on 2.6V to 5.5V and communicates with microcontrollers using a two-wire interface (clock and data).

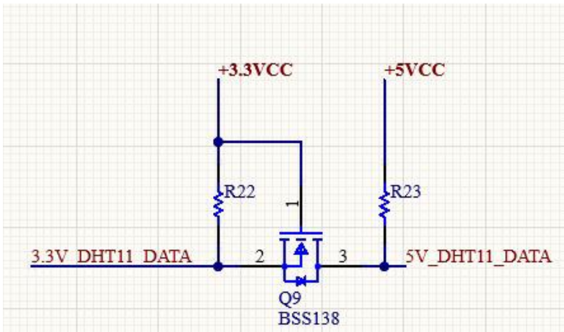

Figure 8: Level shifter

The BSS138-HXY is a general-purpose N-channel MOSFET housed in a compact SOT-23 package. It is capable of handling up to 50V drain-source voltage and 220mA continuous drain current. With a low gate threshold voltage of 1.5V, it can be driven directly by 3.3V or 5V logic levels, making it suitable for level shifting and low-power switching applications. The on-resistance is approximately 2 Ω at 10V gate drive.

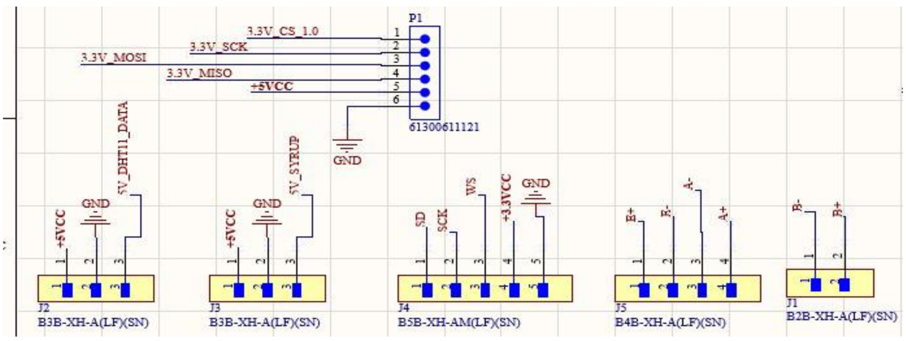

Figure 9: Connectors

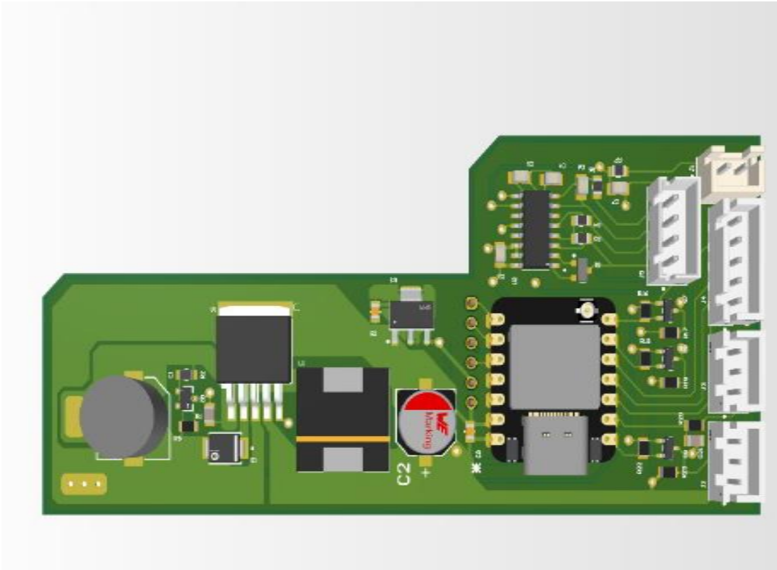

Figure 10: PCB

Objective 2:

To develop an AI-based acoustic analysis model for classifying hive conditions such as queen loss, swarming, absconding, pest infestation, and abnormal activity using honeybee sound patterns. The system analyzes acoustic signatures produced by bees, where variations in buzzing indicate different behavioral states like normal activity, reduced activity, agitation, and pre-swarming conditions.

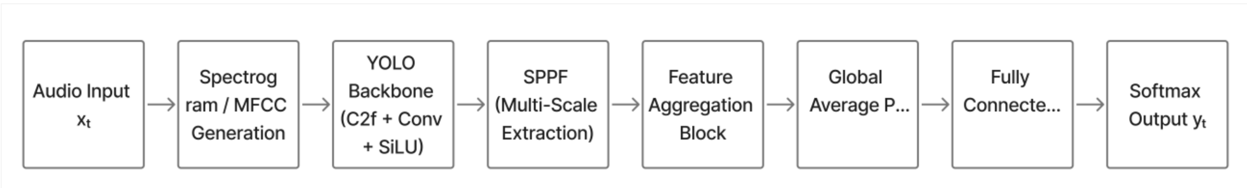

Figure 11: Spectrogram Generation for Hive Audio

The model processes raw hive audio through multiple signal processing and deep learning stages. Initially, the audio signal is converted into spectrogram representations using Mel-Frequency Cepstral Coefficients (MFCC) and Short-Time Fourier Transform (STFT), capturing frequency, intensity, and temporal patterns of bee activity. These spectrogram images are resized and used as input to the deep learning model.

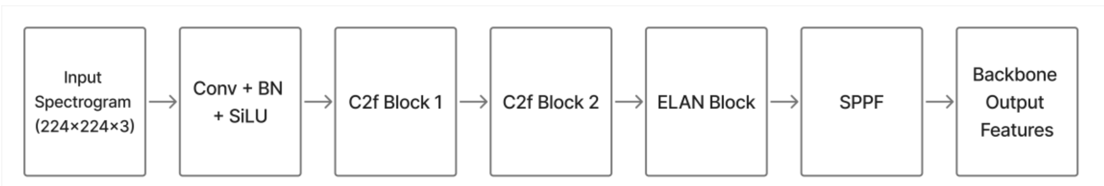

Figure 12: YOLO Backbone Architecture

Feature extraction is performed using a YOLO-based backbone architecture incorporating Convolution, Batch Normalization, and SiLU activation, along with C2f blocks, ELAN modules, and Spatial Pyramid Pooling Fast (SPPF) to capture multi-scale acoustic features and improve feature representation.

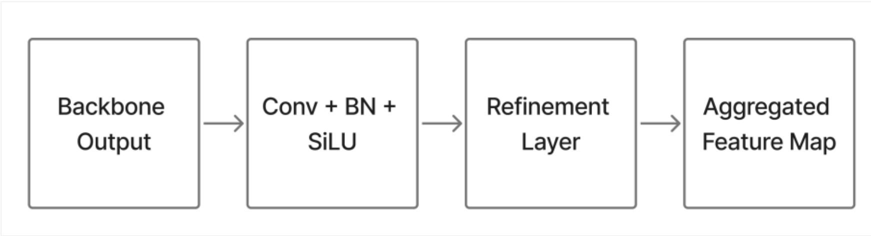

Figure 13: Feature Aggregation Block

The extracted features are refined through a Feature Aggregation Block, which enhances important patterns related to hive conditions. Finally, a Classification Head consisting of global average pooling, fully connected layers, and softmax activation is used to predict hive states such as normal activity, low activity, swarming, and distress conditions.

The overall model can be represented as:
$\hat{y} = fYOLO(Spectrogram(x))$

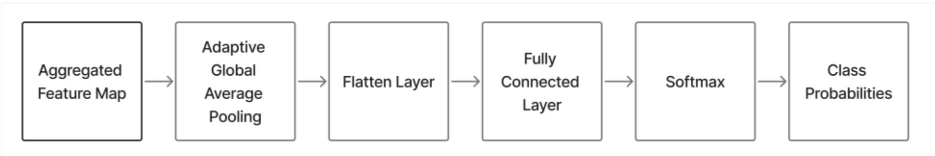

Figure 14: Classification Head

This architecture enables accurate, real-time, and non-invasive monitoring of hive conditions across varying environmental scenarios.

Objective 3:

A dedicated mobile application has been designed and developed as an essential component of this project ecosystem. The application serves as the primary interface between the beekeeper and the central database, providing real-time visualization of hive health metrics, historical insights, and AI-driven predictions through an intuitive and multilingual user interface.

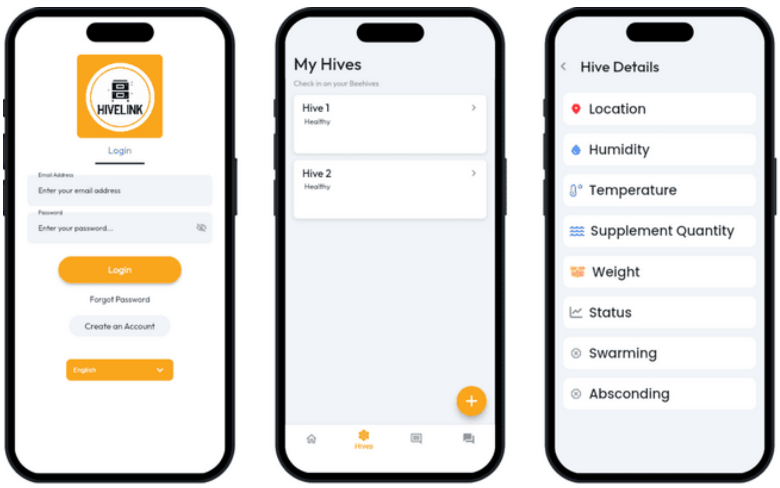

Figure 15: Home screen of the mobile application in English, Kannada, and Hindi.

The application retrieves sensor data—including temperature, humidity, hive weight, supplement level, and colony activity—from the cloud database, where the hardware module continuously updates readings. These parameters are displayed through dynamic graphs and trend lines, enabling beekeepers to analyze short-term fluctuations as well as long-term colony behavior. By organizing the data into visually informative formats, the mobile interface reduces the cognitive effort required for manual interpretation and supports data-driven decision-making.

A significant enhancement of the updated application is its seamless integration with the AI-based acoustic analysis module. Spectrogram-derived predictions, such as swarming tendencies, colony weakness, disturbance, or absconding risk, are displayed instantly within the app. Users receive real-time alerts when the model detects abnormal acoustic activity or any deviation from optimal hive conditions. These notifications enable rapid intervention, preventing colony losses and enhancing operational efficiency.

The mobile application also incorporates automated supplement management. Using weight and consumption patterns, the predictive model estimates when the syrup reservoir will deplete and schedules timely alerts for refill. This eliminates guesswork, reduces manual checking efforts, and ensures that bees receive adequate nutrition during critical periods such as monsoon months and low-nectar seasons.

Additionally, the application centralizes hive-level information by providing:

• Hive details dashboard displaying sensor parameters, colony health, environmental conditions, and AI predictions
• GPS-based hive tracking, allowing beekeepers to easily manage widely distributed hives
• Historical data repository for reviewing past environmental patterns and colony responses
• In-app notification system to alert users of critical events, such as hive falls, theft attempts, swarming likelihood, or abnormal temperature/humidity patterns
• Feeding Schedule Module, automatically optimized using predictive analytics
• Community Hub, enabling knowledge sharing and expert-driven discussions
• Secure authentication mechanisms, including multilingual support and Aadhaarbased login, ensure that the application remains accessible, trustworthy, and safe.

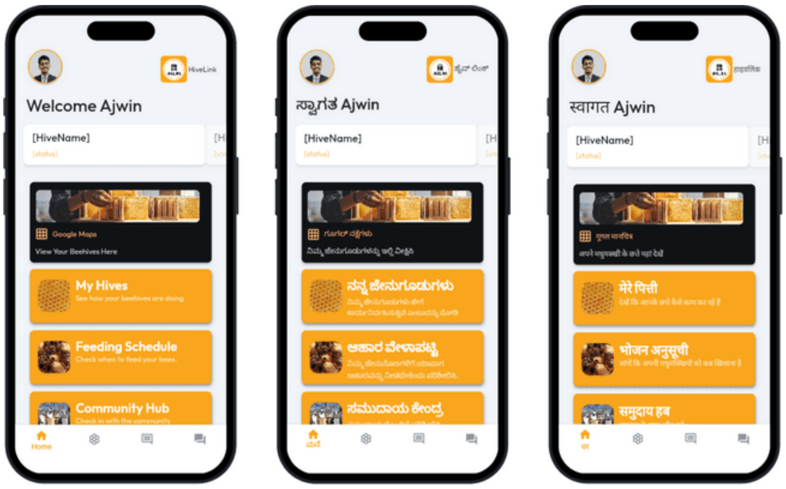

Figure 16: Application feature overview.

With its intuitive design and powerful analytical capabilities, this project mobile application significantly enhances hive management efficiency, reduces inspection time, and empowers beekeepers with accurate, real-time insights. This integration of IoT, cloud computing, and mobile technology ultimately supports sustainable apiculture and promotes data-driven agricultural practices in India.

Objective 4:

To develop a regionally relevant dataset for AI-driven hive monitoring, this project collected and logged real-time sensor and acoustic data from multiple hive locations across diverse climatic zones. This approach enabled the creation of a high-resolution dataset tailored to Indian apiculture, supporting accurate machine learning models and decision-making systems.

Data was collected from geographically distinct locations including Bantwal, Kinnigoli, Puttur, and SJEC Mangaluru, each contributing unique environmental characteristics such as temperature variations, humidity patterns, nectar flow cycles, and seasonal changes. This ensured that the dataset captures real-world variability in beekeeping conditions across South India.

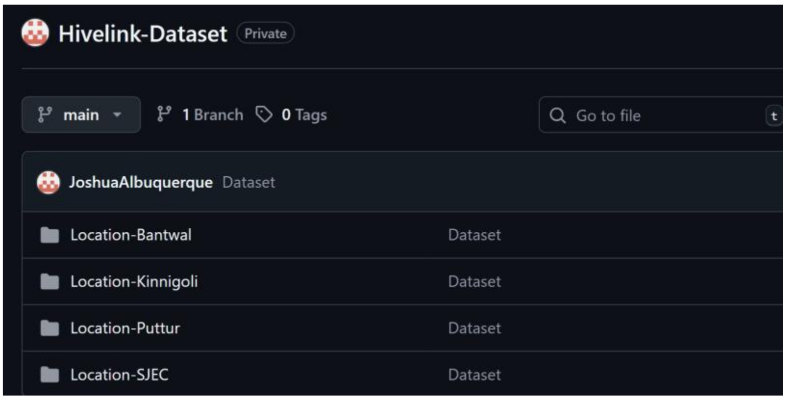

Figure 17: github repository

The collected data was organized into a structured repository, where each location was assigned a separate folder containing time-stamped sensor logs and corresponding audio recordings. This organization enabled efficient preprocessing, annotation, and training of AI models.

Continuous monitoring across locations helped capture key hive behavior patterns, including seasonal variations (monsoon humidity, summer heat, winter brood expansion), swarming and absconding indicators through weight and acoustic changes, environmental stress conditions, and location-specific productivity trends. It also recorded variations in supplement consumption based on forage availability.

The dataset includes temperature and humidity logs, hive weight trends, supplement level variations, acoustic recordings for swarm and distress detection, and historical behavioral patterns across seasons. Additionally, dedicated audio directories for each location ensured clean and organized data for spectrogram generation and YOLO-based classification.

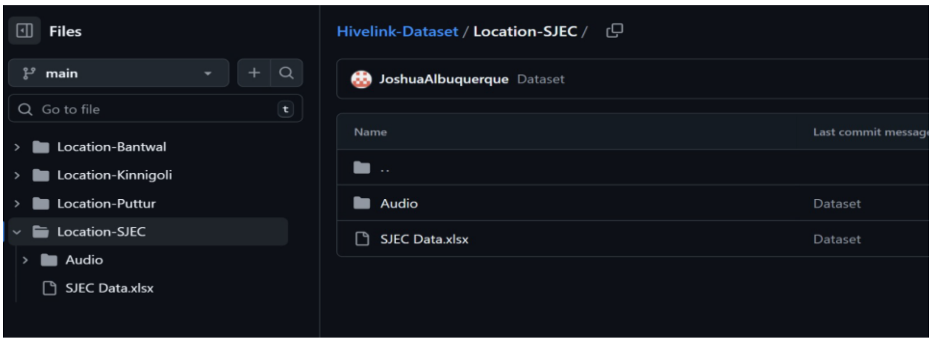

Figure 18: audio folder

Result and Conclusion:

- **Hive Humidity over Time:**

Humidity levels within the hive also remain within a relatively narrow range, displaying smooth diurnal variations. Although slight declines and recoveries in humidity are observed, there are no significant deviations that could indicate environmental stress or a failing colony. Stable humidity is vital for brood health and nectar conversion, and the observed patterns support the conclusion that the hive conditions are well-maintained by the colony.

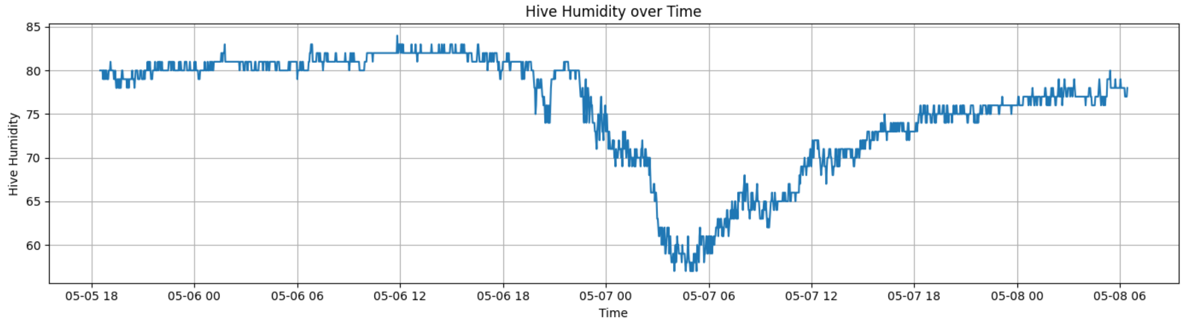

Figure 19: Hive Humidity over Time

- **Hive Temperature over Time:**

The internal hive temperature remains relatively stable, exhibiting only minor fluctuations throughout the monitoring period. The temperature consistently stays below the critical threshold of 40°C, which is essential for maintaining optimal brood development and colony health. These stable temperature readings suggest that the bees are actively regulating the internal hive environment, a key indicator of a healthy and well-functioning colony.

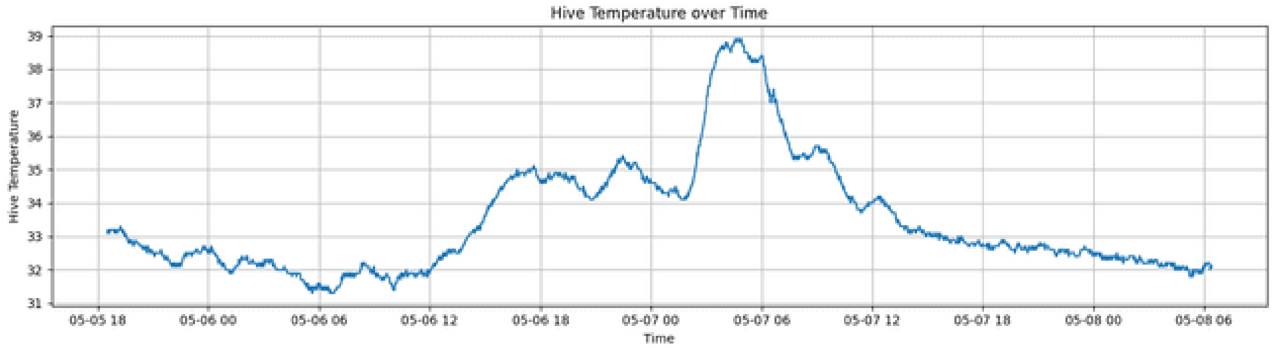

Figure 20: Hive Temperature over Time

- **Supplement Quantity Over Time:**

The quantity of supplemental feed (typically sugar syrup) decreases steadily over time, indicating consistent consumption by the colony. This trend aligns with expected behavior, particularly in scenarios where natural forage may be limited or environmental conditions necessitate additional nutrition. Periodic spikes or abrupt drops in the supplement graph could be attributed to manual refilling events or sensor calibration variances. Overall, the consumption pattern validates the effectiveness of the supplement delivery and monitoring system in HiveLink.

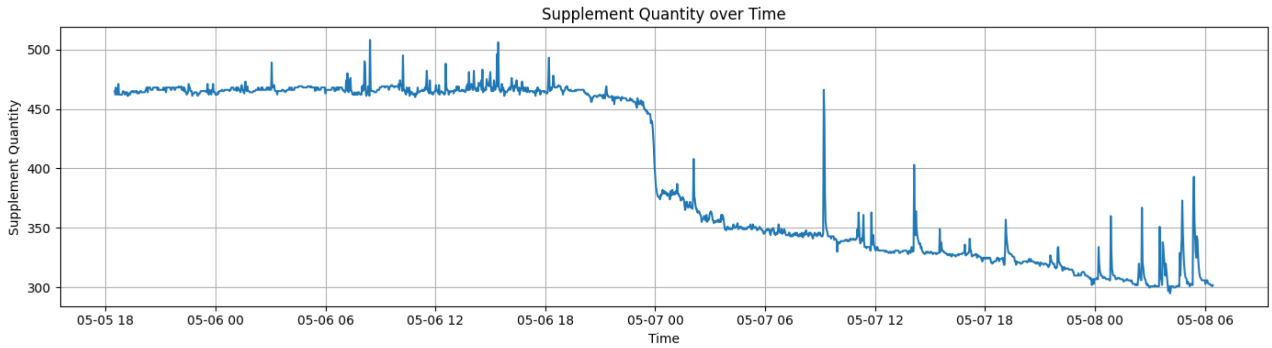

Figure 21: Supplement Quantity Over Time

- **Hive Weight over Time:**

The hive weight exhibits a consistent diurnal pattern. During daylight hours, the weight gradually decreases as bees leave the hive to forage. Conversely, as evening approaches and bees return, a noticeable increase in hive weight is observed, followed by a plateau throughout the night. This cyclical behavior strongly correlates with expected bee foraging activity and confirms that the colony is functioning normally. The sharp fluctuations in weight during certain intervals may indicate transient hive disturbances or anomalous events, which warrant further investigation.

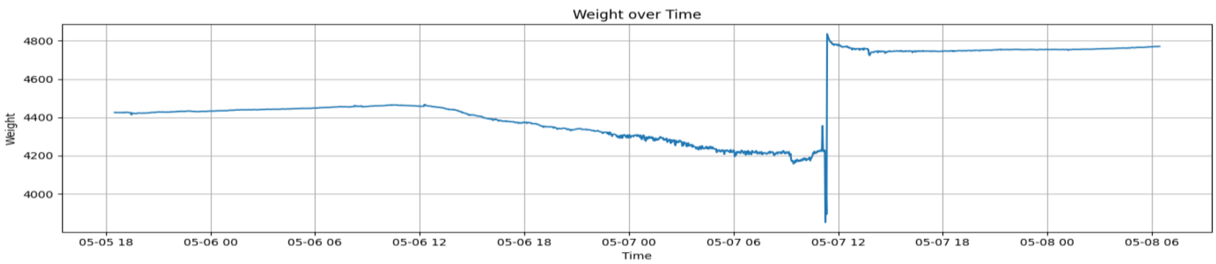

Figure 22: Weight

- **Correlation Matrix:**

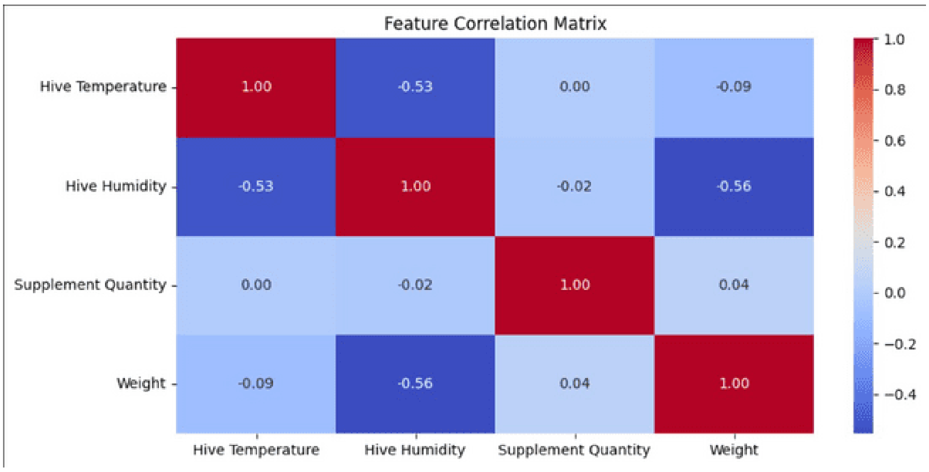

Figure 23: Correlation Matrix

The correlation analysis reveals several noteworthy relationships between hive parameters. Hive temperature and hive humidity exhibit a moderate negative correlation of 0.53, indicating that as temperature increases, humidity tends to decrease. Hive temperature and supplement quantity show no correlation (0.00), suggesting that feeding schedules are determined by colony health or seasonal factors rather than immediate temperature changes. Similarly, hive temperature and hive weight display a very weak negative correlation (−0.09), which may result from increased foraging activity or reduced nectar moisture on hotter days. Hive humidity and supplement quantity demonstrate a negligible correlation (−0.02), implying that feeding is independent of moisture levels.

A moderate negative correlation of −0.56 is observed between hive humidity and hive weight, potentially due to humid conditions reducing foraging activity or slowing honey curing through increased evaporation time. Lastly, supplement quantity and hive weight show almost no correlation (0.04), indicating that supplements are primarily consumed for colony maintenance rather than stored in a manner that significantly increases hive weight.

- **Model Performance Test Data And Detailed Anomaly Attribution:**

```
================================================================================
--- MODEL PERFORMANCE ON TEST DATA & DETAILED ANOMALY ATTRIBUTION ---
================================================================================
276/276 ━━━━━━━━━━━━━━━━━━━━ 1s 4ms/step

Total test sequences evaluated: 8829
Sequences detected as overall anomalies: 18 (0.20%)

--- Detailed Anomaly Attribution for Each Sequence ---
Sequence 8569: POTENTIAL SWARMING / ABSCONDING. Weight Error: 0.0001 (Thresh: 0.0003). Last Weight: 3699.70 units.
Sequence 8570: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0003 (Thresh: 0.0002). Last Supp. Qty: 9.00 units.
Sequence 8571: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0004 (Thresh: 0.0002). Last Supp. Qty: 9.00 units.
Sequence 8572: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0004 (Thresh: 0.0002). Last Supp. Qty: 9.00 units.
Sequence 8573: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0005 (Thresh: 0.0002). Last Supp. Qty: 10.00 units.
Sequence 8574: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0005 (Thresh: 0.0002). Last Supp. Qty: 9.00 units.
Sequence 8575: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0005 (Thresh: 0.0002). Last Supp. Qty: 9.00 units.
Sequence 8576: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0005 (Thresh: 0.0002). Last Supp. Qty: 9.00 units.
Sequence 8577: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0005 (Thresh: 0.0002). Last Supp. Qty: 10.00 units.
Sequence 8578: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0004 (Thresh: 0.0002). Last Supp. Qty: 10.00 units.
Sequence 8579: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0003 (Thresh: 0.0002). Last Supp. Qty: 9.00 units.
Sequence 8580: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0002 (Thresh: 0.0002). Last Supp. Qty: 9.00 units.
Sequence 8581: UNUSUAL SUPPLEMENT PATTERN. Supplement Qty Error: 0.0002 (Thresh: 0.0002). Last Supp. Qty: 10.00 units.
Sequence 8582: POTENTIAL SWARMING / ABSCONDING. Weight Error: 0.0002 (Thresh: 0.0003). Last Weight: 3697.43 units.
Sequence 8585: POTENTIAL THEFT / HIVE FALL. Weight Error: 0.0006 (Threshold: 0.0003). Last Weight: 3696.18 units.
...
General Unattributed Anomaly: 0 sequences (0.00% of Total Test, 0.00% of All Detected Anomalies)
No Anomaly Detected: 8811 sequences (99.80% of Total Test)
```

Figure 24: Model Performance Test Data And Detailed Anomaly Attribution

- **Spectrogram Patterns:**

In the Low Activity condition, the spectrogram is dominated by low-energy broadband hive noise, with relatively stable intensity across the frequency spectrum. Only mild fluctuations appear in the 100–300 Hz band, indicating normal colony buzzing and minimalqueen movement.

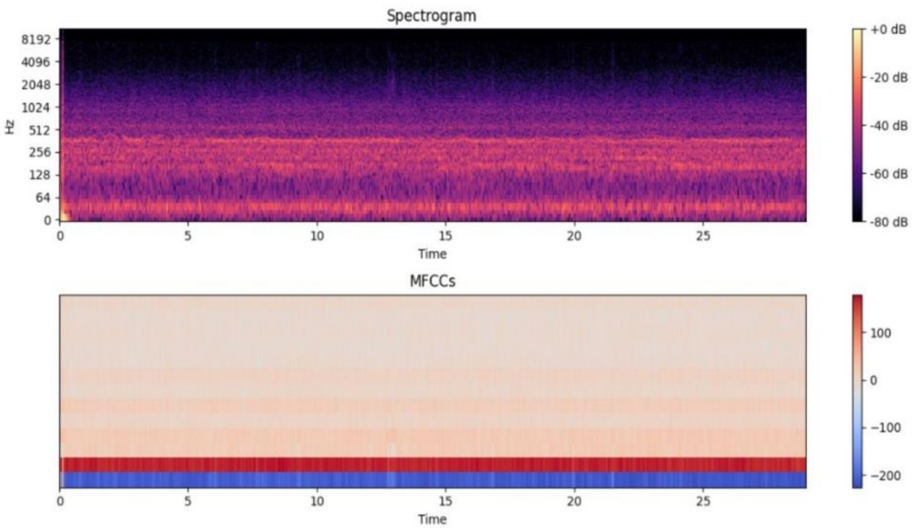

Figure 25: Low Activity / Low Frequency Hive Spectrogram

In contrast, the High Activity spectrogram shows:
• Increased energy distribution across the 200–800 Hz band,
• More frequent and dense harmonic structures,
• Noticeable bursts of mid-frequency vibrations associated with queen movement and modulation calls.

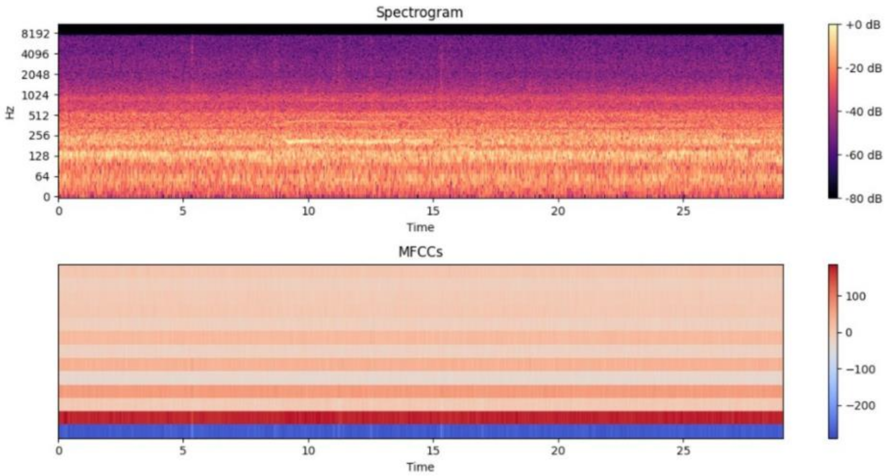

Figure 26: High Activity / High Frequency Hive Spectrogram

These visual differences confirm that hive acoustics physically change during periods when the queen is more active.
The Real-Time IoT-Based Monitoring And AI-Driven Insights For Bee Colony Management presents a comprehensive and technologically advanced solution for modern beekeeping, enabling beekeepers to effectively monitor, analyze, and manage hive conditions.

with minimal manual intervention. By integrating IoT modules, environmental sensors, and an AI-powered acoustic analysis system, the project provides a multi-layered approach to hive health assessment and early anomaly detection.

The system continuously monitors critical hive parameters such as temperature, humidity, hive weight, syrup level, day/night conditions, and honey filling status. These parameters are analyzed in real time to help beekeepers make informed decisions that directly impact colony productivity and longevity. Early signs of disease and brood abnormalities. It can be detected using temperature–humidity correlations, allowing for preventive intervention. Hive weight trends aid in predicting swarming behavior, identifying potential absconding incidents, and even detecting theft or hive tipping.

A major enhancement in the updated project is the integration of an AI-based acoustic monitoring model. By converting hive audio into spectrograms and analyzing them using a YOLO-based deep learning classifier, the system can detect subtle behavioral patterns such as low colony activity, distress signals, hive disturbances, and pre-swarm acoustic cues.

This enables continuous non-intrusive monitoring of colony vitality and supports early intervention strategies that were previously impossible using sensor data alone. The AI module adds a powerful predictive layer that enhances reliability, reduces inspection frequency, and improves the ability to detect abnormalities that are otherwise invisible through traditional sensing methods.

Monitoring syrup levels ensures timely refilling of feeding supplements, while supervision of the honey super chamber optimizes honey extraction cycles and increases yield.
Overall, the project significantly reduces manual inspection time, enhances decisionmaking accuracy, and empowers beekeepers with actionable insights. By combining hardware intelligence, environmental sensing, and advanced AI-driven acoustic diagnostics, the updated project provides a robust, scalable, and sustainable platform for modern apiculture. This holistic approach ultimately improves hive management efficiency, promotes colony health, and supports the long-term growth of the beekeeping industry.

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Future Scope:

Future enhancements to this project system can focus on increasing the spatial scalability and communication reliability of acoustic hive monitoring, particularly for apiaries distributed across large geographic areas. One promising direction is the integration of LoRa communication technology to extend transmission capabilities beyond the limitations of conventional Wi-Fi networks.

The future scope of this project includes:

In its current configuration, each node of this project relies on direct Wi-Fi connectivity to transmit sensor data to the cloud. This requirement restricts deployment to areas with consistent network availability and limits the number of hives that can be monitored simultaneously. To overcome these constraints, a LoRa-enabled hierarchical communication model is proposed, where:

1. A single Gateway Hive is equipped with dual-mode communication (LoRa + WiFi)
2. Peripheral hives operate as LoRa sensor nodes, transmitting low-bandwidth acoustic features and telemetry to the Gateway Hive.
3. The Gateway Hive aggregates incoming data streams and relays them to the cloud via Wi-Fi or Ethernet.