RESEARCH PROJECT REPORT

Motion detection of Bees Using Electrostatic Sensors

Jayti Pattni

Co-worker: Arnesh Sharma

Supervisor: Dr Nitish Patel

Department of Electrical, Computer and Software Engineering
The University of Auckland

October 2025

ABSTRACT

Honeybees play a vital role in global ecosystems and agriculture, yet current methods for monitoring their activity are often invasive or unreliable. While non-invasive electrostatic field (ESF) sensing is a promising alternative, existing systems suffer from high inter-sensor variability, limiting their accuracy. This project aimed to solve this limitation by designing and evaluating novel sensor configurations. We developed and benchmarked several prototypes, including a self-biasing JFET sensor and a capacitive sensor array with an instrumentation amplifier, against the baseline BeeSpy system. The key finding is that the new designs, particularly the instrumentation amplifier-based capacitive sensor, exhibit exceptional inter-sensor consistency, effectively overcoming the primary weakness of current hardware. Furthermore, the capacitive array demonstrated the ability to resolve the spatial location of a signal. These results validate a significantly more reliable and scalable sensor topology, representing a crucial step towards robust, low-cost systems for large-scale hive health assessment and behavioural analysis.

DECLARATION

Student

I hereby declare that:

1. This report is the result of the final year project work carried out by my project partner (see cover page) and me under the guidance of our supervisor (see cover page) in the 2025 academic year at the Department of Electrical, Computer and Software Engineering, Faculty of Engineering, University of Auckland.
2. This report is not the outcome of work done previously.
3. This report is not the outcome of work done in collaboration, except that with a potential project sponsor (if any) as stated in the text.
4. This report is not the same as any report, thesis, conference article, journal paper, or any other publication or unpublished work in any format.

In the case of a continuing project, please state clearly what has been developed during the project and what was available from previous year(s):

Signature: Jayti Pattni

Date: 4/10/2025

Table of Contents

Acknowledgements

This project would not have been possible without the support and guidance of those who contributed their time, expertise, and encouragement throughout its development.
I would like to thank my project partner, Arnesh Sharma, for his dedication and hard work put into this project.

I am deeply grateful to our supervisor, Dr Nitish Patel, for his mentorship, technical guidance, and ongoing support. His expertise in sensor design and signal processing helped guide the project's direction and ensured its scientific rigour.

I would also like to thank our co-supervisor, Dr David Cumin. He was instrumental in giving us access to the BeeSpy boards and was continuously contacting the BeeSpy team in Germany.

Lastly, I would like to thank my family and friends for their patience and encouragement throughout this research journey, especially during the long hours of experimentation and report writing.

Glossary of Terms

Electrostatic Field	The field produced around a stationary charged object.
Triboelectric Effect	Describes the transfer of electric charge from one object to another when they make contact or rub against each other.

Abbreviations

Electrostatic Fields	ESF

1. Introduction

Honeybees play a vital role in global ecosystems as primary pollinators, contributing significantly to biodiversity and agricultural productivity. The health of bee colonies is therefore a critical indicator of environmental conditions, reflecting factors such as disease, pesticide exposure, and food availability. Monitoring hive activity provides valuable insights into colony health and wider ecological stability. However, current monitoring techniques are often invasive, relying on visual inspection or optical methods that disturb the colony and provide limited temporal resolution. This highlights the need for non-invasive, continuous monitoring systems capable of detecting subtle behavioural and environmental changes within the hive.

Bees generate small electrostatic fields during flight and social interactions due to the triboelectric effect, which is an accumulation of charge through friction between body parts and with the surrounding air. Recent studies have shown that these fields are not incidental but play a communicative role in bee behaviour, particularly in the waggle dance used to convey foraging information. Harnessing this phenomenon offers a promising pathway for contactless sensing of bee activity. Unlike optical systems, electrostatic field (ESF) sensors can operate in complete darkness and be integrated directly into standard hive structures, making them ideal for scalable, non-disruptive monitoring.

However, existing electrostatic sensing systems, such as the BeeSpy platform, face key challenges that limit their reliability and deployment potential. These include low sensitivity to weak field variations, high inter-sensor variability, and vulnerability to environmental noise, leading to inconsistent data and high false-negative rates in detecting waggle dance activity. Addressing these limitations is critical for advancing the viability of electrostatic sensing as a tool for long-term behavioural monitoring.

This project investigates improved electrostatic sensing methods for detecting bee motion by leveraging the charge generated during flight and social behaviour. The objective is to design, prototype, and evaluate novel sensor configurations, specifically capacitive sensing, that address the shortcomings of existing ESF systems. The report begins with a literature review outlining the biological basis of bee electrostatics and current state-of-the-art sensing technologies. It then presents the systematic design and development of new sensor prototypes, followed by a controlled experimental evaluation of their performance both in laboratory and preliminary in-hive environments. The report concludes with a discussion of the results, key limitations, and recommendations for future work toward a scalable, non-invasive monitoring system for honeybee behaviour.

2. Literature Review

Despite the clear benefits of monitoring hive health, traditional inspection methods are intrusive, stress the colony, and prevent frequent check-ups. This has created a critical need for non-intrusive sensing methods. This review provides an overview of the current state of research on electrostatic sensing, a promising approach for detecting bee motion. It first explores the foundational research linking bees to electrostatic fields and examines the biological significance of key communication signals, like the waggle dance, that indicate hive health. It then evaluates the state-of-the-art sensor technology, focusing on the performance and documented limitations of existing in-hive systems to identify the specific technological gap this project aims to address.

2.1. Electrostatic Fields in Bee Ecology

While it's well known that bees use chemical cues, such as pheromones, and physical movement for communication, research over the last decade has revealed that electrostatic fields (ESFs) play a significant role in social interactions inside the hive.

Honeybees and bumblebees naturally accumulate a positive electrostatic charge during flight and through friction with body parts due to the triboelectric effect. Research has shown that these electric fields are not merely an incidental byproduct of their activity but play a functional role in their ecology. Bees can detect and learn from weak electric fields, which are used in foraging to discriminate between rewarding and unrewarding flowers [1].

Crucially for in-hive monitoring, these electric fields are also emitted during key social behaviours. It has been demonstrated that bees emit both constant and modulated electric fields while walking, and significantly, during the waggle dance. Mechanoreceptors in the antennae have been identified as sensitive to these electric stimuli, providing a neurological basis for electroreception [2]. Further research on bumblebees offered compelling evidence that sensory hairs on the bees' bodies are a primary site of electroreception [3]. It was demonstrated that external electric fields cause these hairs to deflect, which in turn elicits neural activity, whereas the antennae did not exhibit a similar electrophysiological response [3].

The biological significance of monitoring these dance-related fields is profound. The waggle dance is a sophisticated form of symbolic communication used by honeybees to recruit nestmates to a profitable resource [4]. First decoded by Karl von Frisch, this "dance language" conveys precise vector information: the angle of the dance's central 'waggle run' on the vertical comb, relative to gravity, indicates the direction of the resource relative to the sun, while the duration of this run is directly proportional to the distance of the resource from the hive [4]. The enthusiasm and speed of the dance can also communicate the quality or profitability of the source, influencing how many new foragers are recruited.

The waggle dance, therefore, acts as a real-time report from the colony's most successful foragers. By eavesdropping on these signals, researchers can map foraging activity, understand landscape use, and assess the health of the surrounding ecosystem [5]. Crucially, the dance is also a sensitive indicator of colony health. It is well-documented that social signals, including the waggle dance, are compromised by stressors such as exposure to insecticides, which can impair a bee's ability to perform or interpret the dance correctly [5]. Monitoring the ESF signals associated with the waggle dance thus provides a powerful, non-invasive window into not only hive behaviour but also the overall health of the colony and its environment.

2.2. Electrostatic Sensor Technology

2.2.1. Principles of Electrostatic Sensing

The principle behind electrostatics is in electrostatic induction and charge transfer, which describe how nearby electric charges influence conductive materials. When a charged object moves close to a sensor's electrodes, it causes a disturbance in the electric field. This variation in the electric field induces charges within the electrode, resulting in a measurable current or voltage. Electrostatic sensors can be broadly classified based on whether the sensing electrode is insulated or exposed [6]. When the electrode is exposed, both electrostatic induction and charge transfer occur, in which electrons move between the object and the electrode upon contact. With insulated electrodes, the sensor responds only to electrostatic induction, where the electric field of the nearby object induces a charge on the electrode. This makes it ideal for non-invasive sensing applications.

Table 1 - Comparison of electrostatic sensors and capacitive sensors

Feature	Electrostatic Sensors	Capacitive Sensors
Field Source	External charged object (passive sensing)	Sensor generates an electric field (active sensing)
Operating Principle	Electrostatic induction or charge transfer	Capacitance change due to object proximity or permittivity
Sensing Mechanism	Measures the electric field variation caused by a moving charged object	Measures the change in capacitance due to a change in distance or dielectric

The sensing principle of electrostatic sensors can also be explained like that of capacitive sensors, where the object being detected serves as one plate of the capacitor, and the other plate is the electrode itself. Therefore, any movement of the charged object changes the distance between the plates and, consequently, the value of the capacitance. As shown in Table 1, unlike capacitive sensors, electrostatic sensors generate the field through the movement of the object, causing fluctuations in the electric field [6].

2.2.2. KCL Electrode Sensor

The detection of these weak biological electric fields requires sensitive, non-contact sensors. An early implementation involved a potassium chloride (KCl) electrode [2]. This transparent sensor was positioned near the bee, forming a capacitive coupling that allowed the time-varying signals from the bee's movement to be measured by an AC amplifier without direct contact.

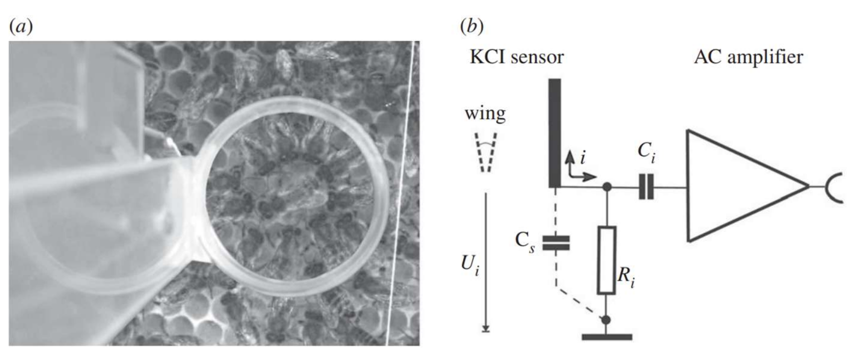


Figure 1-A simplified circuit diagram of the KCL electrode sensor, illustrating the capacitive coupling (Cs) between the bee (wing) and the sensor electrode [2].

While effective for targeted laboratory studies, this approach is not easily scalable for continuous, large-area monitoring inside a standard beehive.

2.3. Current State-of-the-Art: The BeeSpy System

A novel, non-invasive system for monitoring the health and social communication of honeybee colonies has been developed based on the principle of electrostatic field (ESF) recording [8]. This "Electronic Bee Spy" utilises a set of specialised sensors, created from modified capacitive microphones, installed within a standard beehive that is shielded to act as a Faraday cage. The system continuously records the characteristic ESF patterns generated by the bees' movements, which are caused by friction between body parts and interactions within the crowded hive rather than just flight-related charges. By analysing the unique frequency profiles of these signals, the system can automatically identify and classify key social behaviours, including waggle-dance-related signals (WRS), short-pulse-related signals (SRS), and fanning-related signals (FRS).

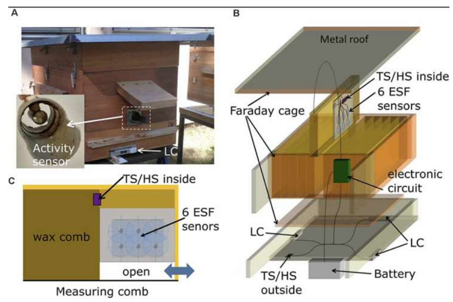


Figure 2-Sensing setup of BeeSpy in a beehive [8]

The system uses a standard wooden hive that is transformed into a Faraday cage to shield against external electrical noise. As shown in Figure 2 above, one of the frames is for the measuring devices. The backside of the sensor frame is shielded with a grounded mesh, so the sensors only detect fields from the open side that faces the bee. The entrance and exit of the hive are equipped with a capacitive sensor-based counter to record bee traffic [8]. Figure 2 (c) shows the measuring comb frame with six ESF sensor units arranged on the comb surface. This arrangement concentrates the region near the hive entrance, referred to as the "dance floor", where waggle dances are most frequent [8].

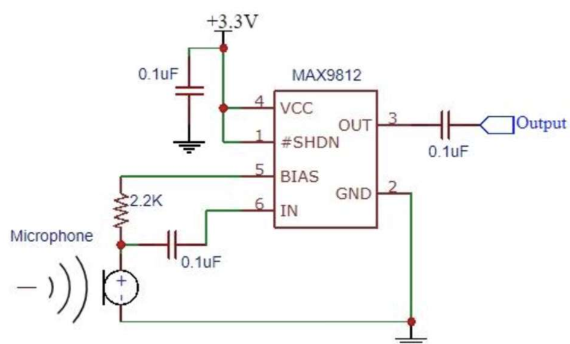


Figure 3-Electrostatic field sensor circuit diagram [8]

The original 'BeeSpy' electrostatic sensors themselves are based on electret microphone circuits that have been modified to detect static field changes rather than sound. An electret is a material with a permanent, built-in electric charge, much like a permanent magnet holds a magnetic field. In a standard microphone, this charged material creates a stable electric field, which is used to sense the movement of a sound-sensitive diaphragm.

The system uses six electret microphone capsules (CJMCU-9812 MAX9812L, capacitive microphones with a microphone preamplifier board) mounted on the custom frame, arranged in two rows of three sensors each. To convert these microphones into ESF sensors, their normal sound-responsive membranes were removed, exposing the internal Field-Effect Transistor (FET) gate that can pick up ambient electric field fluctuations. With the diaphragm gone, the microphone's FET essentially acts as a sensitive antenna for electrostatic charges moving nearby, and it is no longer responsive to air pressure.

While the 'BeeSpy' system successfully proved the concept of in-hive electrostatic monitoring, its validation studies revealed critical performance limitations. The most critical weakness lies in the signal processing algorithm's high false-negative rate for detecting waggle dances. The authors report that while 85% of the signals identified as dances were correct, the system failed to detect 84% of the total waggle runs that were visually confirmed [8]. This inaccuracy is attributed to "biological noise" from other bees and the difficulty in distinguishing the waggle dance from other social behaviours, like grooming dances, that produce electrostatic fields (ESF) in a similar frequency range.

Furthermore, the system was documented with several practical and technological limitations, including:

- The hardware relied on "hundreds of hand-soldered connections that caused instabilities and errors" [8]
- All signal classification was performed "offline" rather than in real-time on the device, and the current analysis does not use any "machine-learning approaches," which the authors identify as an "obvious goal for the future" [8]
- There is an interpretive gap, as the authors admit it has "not been possible, yet, to relate these ESF signals, specifically Short-Pulse-Related Signals, to specific behaviours" [8]
- The system required weekly battery changes, making it impractical for long-term, low-intervention studies [8]

These documented shortcomings, particularly the high false-negative rate and sensor variability, highlight a clear technological gap. While the principle of electrostatic monitoring is sound, the hardware implementation is not yet reliable enough for robust scientific use.

The research presented in this report is positioned to address this technological gap directly. Through a collaboration with the original BeeSpy development team, this project utilises the same electret-based sensor system. A primary objective of this report is to provide a more detailed, independent analysis of this sensor's effectiveness at detecting specific electrostatic frequencies, which will be presented in the Results section.

Furthermore, this collaboration has provided access to a next-generation, unreleased version of the system, the BeeSpy 5, which was delivered in June. This new hardware is intended to resolve the documented performance and practical limitations of the original electret sensor. As no published literature yet exists for the BeeSpy 5, this report will present the first independent performance characterisation and experimental results for this new sensor. This work, therefore, bridges the gap between the published limitations of the first-generation BeeSpy and the empirical validation of its successor.

2.4. Capacitive Sensor Technology

Capacitive sensors operate on the principle of detecting changes in capacitance caused by the presence or motion of nearby objects. Unlike traditional electrostatic field (ESF) sensors, which passively detect naturally occurring charges from bees, capacitive sensors actively generate an electric field and detect changes in capacitance caused by the movement of nearby objects or changes in dielectric properties.

At its core, capacitive sensors can be modelled as a simple capacitor, where the equation defines the capacitance C:

$$C=\varepsilon A/d$$

Where ε is the permittivity of the medium between electrodes, A is the surface area of the electrodes, and d is the distance between them. When a enters the sensing zone, it either becomes part of the dielectric or acts as a floating electrode, which changes the permittivity or distance and thus the capacitance. Since the value of the capacitor is directly related to its size, a small capacitor means high noise susceptibility; therefore, capacitive sensors should be as large as possible [7].

In the current sensor design, the electrodes are primarily sensitive to electric fields coming from one direction. This means that some parts of the electric field created by a moving bee may go undetected, especially if the bee flies at an angle or from the side. By arranging the sensors in a curved or hemispherical shape, it becomes possible to detect electric fields from more directions [8]. This could provide extra information, such as the direction the bee is moving. The existing setup is mainly designed to detect whether a bee with a charge is present. However, by increasing the number of sensors in an array and optimising their placement, we can gather more detailed signals from the same area.

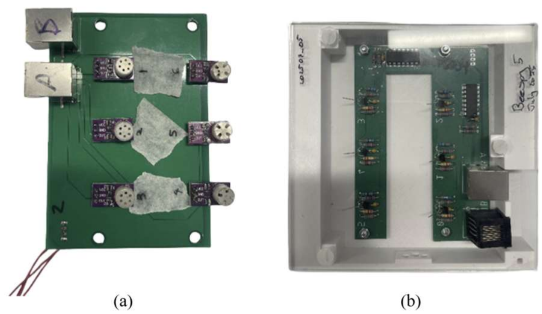
In summary, capacitive sensors offer a promising and complementary alternative to ESF sensors for bee monitoring. They can overcome many of the limitations seen in current electrostatic implementations, such as inconsistent sensitivity and limited spatial coverage. Their flexibility in design and integration also makes them ideal candidates for widespread deployment in realistic beekeeping conditions.

3. Sensor Design and Prototyping

This section outlines the design and prototyping process undertaken to develop a more reliable electrostatic field (ESF) sensor for detecting honeybee motion. The primary objective was to address the documented performance issues of existing sensors, namely inter-sensor variability. The process began by establishing the performance of baseline sensors from the BeeSpy project, followed by an iterative development of several new designs: three JFET-based configurations to improve stability, a novel capacitive sensor with an instrumentation amplifier for enhanced consistency and spatial resolution, and finally, an exploration of experimental relaxation and crystal oscillator circuits.

3.1. Baseline Sensors for Performance Comparison

To quantitatively assess the performance of any new design, it was essential first to establish a performance benchmark. Two existing sensor designs from the BeeSpy project were utilised for this purpose: the original electret microphone BeeSpy and the BeeSpy 5 JFET sensors (as of June 2025).



(a) (b)

Figure 4-Electret and JFET BeeSpy sensors

The electret microphone BeeSpy sensor, used in the original BeeSpy system, consists of modified electret microphones with their diaphragms removed. This modification exposes the internal JFET to external electric fields. An array of these sensors served as the primary baseline to evaluate inter-sensor consistency. This second-generation sensor is a JFET-based design configured as a common source with a floating gate acting as the sensing probe. Both baselines were tested to quantify the variability that this project aims to solve.

3.2. JFET-Based Sensors

Junction Field-Effect Transistors (JFETs) were selected as a promising alternative to electrets due to their inherent high input impedance, which makes them well-suited for detecting the minimal changes in electric fields generated by bee movements. A JFET acts as an electronic valve controlling current flow from the drain to the source. The amount of current allowed through this channel is controlled by the voltage applied to a third terminal, the gate. Because the gate draws negligible current, the JFET presents a very high input impedance. This characteristic makes the gate extremely sensitive to small voltage changes. In this sensing application, the weak electric field produced by a nearby bee directly influences the voltage on the JFET's gate. This minute voltage variation then modulates a significantly larger current flowing through the JFET's channel. By measuring the voltage developed across a resistor (R_D) as these current flows, an amplified signal corresponding to the bee's electric field is obtained.

To address potential instability and noise issues associated with high-impedance inputs, a systematic and iterative design process using the BF245A N-channel JFET was employed. Three circuit configurations were prototyped and evaluated, as shown in Figure 5.

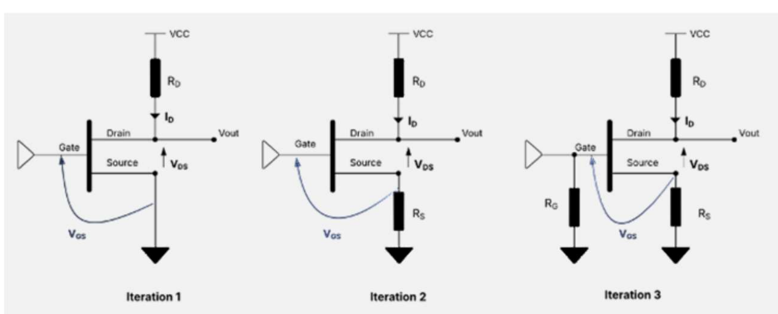


Figure 5-JFET sensor configurations

The first design (Figure 5, Iteration 1) configured the JFET in a basic common-source topology, where the JFET's gate is left unterminated, or "floating," to act as a sensitive antenna to external electric fields. When an external electric field is applied, it alters the voltage at the gate, which in turn affects the amount of current flowing from the drain to the source. This change can be seen as a voltage change across the resistor. While early tests showed this configuration produced a strong response, the floating gate provided no stable DC reference. This made the sensor highly susceptible to DC drift from ambient charge accumulation and prone to picking up low-frequency environmental noise, rendering it unreliable for stable measurements.

The second iteration of the JFET sensor includes a resistor between the source terminal and ground (R_S). As the drain current increases, a voltage develops across the source resistor, which then raises the source voltage, V_{RS}. This introduces negative feedback (source degeneration), which helps stabilise the transistor's operating point against variations. As the drain current increases, the voltage across R_S rises, making the gate-to-source voltage V_{GS} more negative, which in turn reduces the drain current. This feedback loop helps stabilise the operating point of the transistor, although the gate's voltage can still slowly drift or pick up random charge, which isn't ideal for a sensor.

The final design (Figure 5, Iteration 3) incorporated a high-value resistor (R_G, 10 MΩ) connecting the gate to ground. This crucial component provides a stable DC path, preventing long-term drift by referencing the gate to ground potential for DC signals. Simultaneously, the high resistance ensures that the gate remains highly sensitive to the AC electric fields generated by the bee's motion.

Among the three designs, this self-biasing configuration provided the best observed balance between sensitivity, operational stability, and repeatability during the prototyping phase. Consequently, it was further developed by the BeeSpy team on a dedicated Printed Circuit Board (PCB). However, a different JFET, the 2SK596S, was used, and further amplification of the signal was applied.

3.3. Electrostatic Induction-Based Sensor

An alternative sensing approach, based on electrostatic induction, was also investigated. This method was initially considered due to its inherent simplicity and passive nature, drawing inspiration from prior successful implementations by Yan et al [6].

The core concept relies on detecting the influence of a nearby moving charged object on a stationary conductor. As depicted in the general structure shown in Figure 6, the sensor is comprised of a sensing electrode that is electrically isolated by an insulator and enclosed within a grounded shield to minimise external interference. When a charged body, such as a bee, approaches the electrode, its electric field causes a rearrangement of charges on the electrode's surface through electrostatic induction. This charge movement results in a slight current. By connecting the electrode to ground via a high-value resistor (R_i). This induced current generates a detectable potential difference across the resistor. This mechanism is sometimes described analogously to capacitive coupling, where the object and electrode form a variable capacitor.

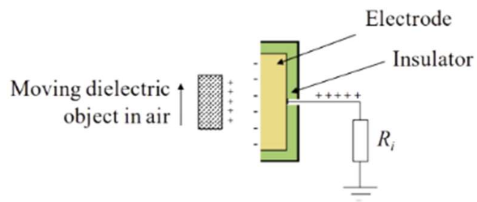


Figure 6- Sensing of a moving non-conducting object via electrostatic induction [6]

Two iterations of the induction-based sensor were constructed. The first version was a proof-of-concept that used an approximately 40 mm x 10 mm copper strip as the electrode, insulated with hot glue, and shielded with aluminium tape. A 10 MΩ resistor was connected between the electrode and ground to generate a measurable voltage drop.

The second version was made into a 3x3 PCB sensor array, designed with each electrode measuring 10 mm x 10 mm. However, a layout oversight resulted in the ground plane being restricted to the bottom PCB layer, offering incomplete shielding. Functionality was notably enhanced by adding aluminium tape to the top layer, connected to ground, which effectively created a more complete shield and likely reduced parasitic capacitance and charge accumulation on the board surface.

During initial testing of the induction sensors, the viability of this sensor remained questionable. Despite the method being validated by Yan et al. [6], further research was deemed necessary to confirm that the sensor was operating as expected and to definitively understand what was being sensed. Due to these uncertainties and the more reliable performance of other prototypes, this design was not pursued for final evaluation in this project.

3.4. Capacitive Sensing with an Instrumentation Amplifier

In parallel with the development of the JFET sensor designs, a capacitive sensing approach was investigated. This design utilises an INA823 precision instrumentation amplifier to measure the small voltage changes induced across a sensing plate (capacitor) by a nearby electric field. The goal of this approach was to create a highly sensitive and scalable sensor array that could provide greater spatial granularity, allowing for the tracking of bee motion across the sensor grid.

A

B

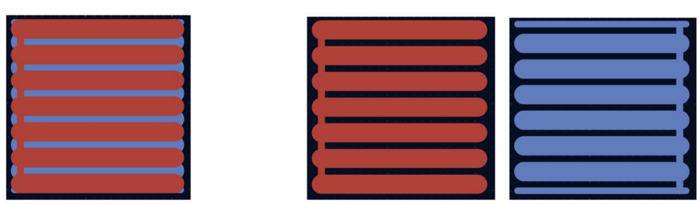


Figure 7-Proposed offset capacitive sensor. (a) Shows the overlapped sensor. (b) Shows the shift of the capacitive sensor top and bottom plates

This method leverages the principle of capacitive coupling. The sensor element itself is designed as a capacitor formed on a PCB, as depicted in Figure 7(A, B). This structure maximises the interaction area and the associated fringe electric fields extending beyond the electrode edges. The fundamental hypothesis is that the weak, time-varying electric field generated by a nearby bee perturbs these fringe fields. This perturbation alters the effective capacitance between the interdigitated plates, resulting in minute voltage fluctuations.

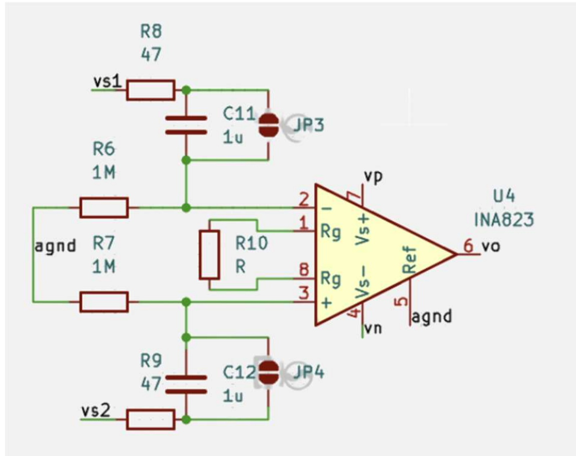


Figure 8-Instrumentation amplifier circuit diagram for Capacitive Sensor

To detect these subtle voltage changes, a high-sensitivity differential amplifier circuit based on the INA823 instrumentation amplifier was designed (Figure 8, circuit diagram). The INA823 was specifically selected for its high common-mode rejection ratio (CMRR), crucial for suppressing environmental noise like 50 Hz mains hum that affects both sensing plates similarly, and its low input bias current, which prevents loading of the high-impedance capacitive sensor plates. The differential nature of the IA amplifies the slight voltage difference between the sensor plates caused by the bee's field, while rejecting common noise sources.

Three variations of the instrumentation amplifier circuit were prototyped to explore the effects of input impedance and gain on performance:

1. A baseline version using 1 MΩ input resistors (R6, R7 in Figure 8)
2. A high-impedance version using 10 MΩ input resistors. Increasing the input impedance was expected to enhance sensitivity to smaller signals and potentially lower the high-pass cutoff frequency of the sensor system
3. A high-gain version, configured using the gain-setting resistor (R10) for a voltage gain of approximately 200, to evaluate the maximum achievable signal amplification and assess signal-to-noise ratio limits

The capacitive sensors were fabricated as a 5x5 array on a single PCB, with each individual sensor element occupying a 10x10 mm footprint. This array format inherently supports the goal of spatial sensing. By measuring the signal strength across multiple adjacent sensors, it is possible to determine the approximate location and track the movement of a bee across the sensor surface. This contrasts significantly with the single-point measurements provided by individual JFET sensors and offers the potential for much richer behavioural data, such as mapping the specific path and orientation of a waggle dance. While potentially requiring a larger PCB footprint compared to simpler JFET circuits, the expected improvements in consistency (due to repeatable PCB manufacturing) and the added spatial information make this a highly promising approach for robust in-hive monitoring.

3.5. Direct Sensing with PSOC Integrated CapSense Module

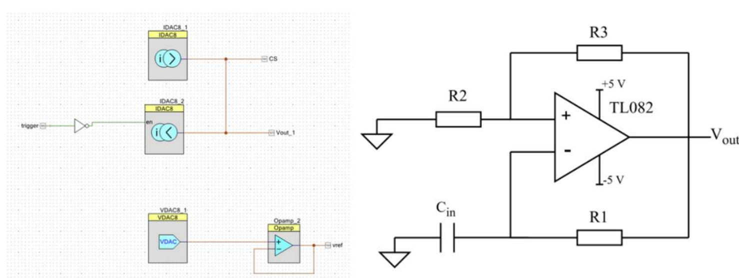
An approach was aimed at leveraging the PSoC's built-in, high-sensitivity capacitive sensing (CapSense) system. This system is primarily designed for touch-sensing applications and utilises a Capacitance Sigma-Delta (CSD) measurement technique. We hypothesised that this sensitive module could be repurposed to detect minute changes in an external capacitor exposed to an electric field.

The experimental setup involved connecting an external capacitor, acting as a sensing plate, to one of the PSoC's CapSense input pins. The theory was that an external electrostatic field would interact with the capacitor, altering its effective capacitance. It was hoped that the CapSense module, with its fine-grained control over parameters like scan resolution and modulation current (adjustable via the EZ-I²C interface), would be able to resolve these subtle changes.

However, despite systematic tuning of the module's sensitivity, the results were inconclusive. The output signal was dominated by noise, and no discernible correlation could be established between the sensor readings and the presence or strength of the applied electric field. The inherent noise floor of the system proved too high for the subtle capacitive shifts induced by the external ESF, leading to the discontinuation of this method.

3.6. Relaxation Oscillator-Based Sensing Method

A novel sensing method using a relaxation oscillator circuit was also explored. The concept was to create a circuit where changes in the local electrostatic field would modulate the frequency of a relaxation oscillator. This method involved designing a relaxation oscillator circuit, as depicted in the schematic below.



(a) (b)

Figure 9- Shows the relaxation oscillator sensor design. (a) PSoC capacitive sensing design. (b) Relaxation oscillator circuit diagram

This circuit employed a Schmitt trigger comparator (implemented with a TL082 op-amp) to create a stable charge-discharge cycle for an external sensing capacitor, Cin. The PSoC's role was to provide highly stable and configurable current sources using its internal current DACs (IDACs). One IDAC was configured to source current, charging the capacitor, while a second was configured to sink current, discharging it.

The sourcing IDAC charges Cin, causing its voltage to rise. When the voltage crosses the Schmitt trigger's upper threshold, its output flips. This state change is detected by the PSoC, which then deactivates the sourcing IDAC and activates the sinking IDAC. The capacitor then discharges until its voltage falls below the Schmitt trigger's lower threshold, at which point the process repeats. This cycle generates a continuous triangular wave with a natural frequency of around. The hypothesis was that an external electric field interacting with the capacitor's fringing field would alter its capacitance, leading to a measurable shift in the oscillator's frequency, which could be precisely captured by the PSoC's timer/counter peripherals.

However, early experimental testing revealed that the sensitivity of this prototype was insufficient for detecting the weak electric fields associated with bee movement. While the design was functional, its response was too small to be practical for this application without significant further development. This finding suggests that a different circuit topology or sensor geometry would be required to make an oscillator-based approach viable.

In summary, the design phase progressed from benchmarking existing BeeSpy sensors to iteratively developing and prototyping several new JFET and capacitive sensor configurations. Each design aimed to address the key limitations of inter-sensor variability and noise susceptibility identified in the literature. The following section details the experimental methodology established to evaluate and compare the performance of these prototypes quantitatively.

3.7. Crystal Oscillator Design

Another approach we explored was using a crystal oscillator, aiming to see if an external electric field could predictably disturb its highly stable frequency. The core idea relies on the piezoelectric effect in the quartz crystal: an electric field, in theory, should cause mechanical strain in the crystal, altering its resonant frequency. Any such frequency shift would indicate the presence and strength of the field.

The implemented circuit, shown in Figure 10, follows the Pierce oscillator topology, which is a standard configuration for generating highly stable sinusoidal signals. The design utilises a logic inverter (implemented with a NAND gate), a 16 MHz quartz crystal resonator, a feedback resistor (Rf), and two load capacitors (Cin and Cout), each with a value of 12 pF. The capacitors provide the necessary phase shift and define the load capacitance required for stable oscillation. The resistor Rf, typically in the range of 1–10 MΩ, introduces a small amount of negative feedback to bias the inverter in its linear region and sustain oscillation startup.

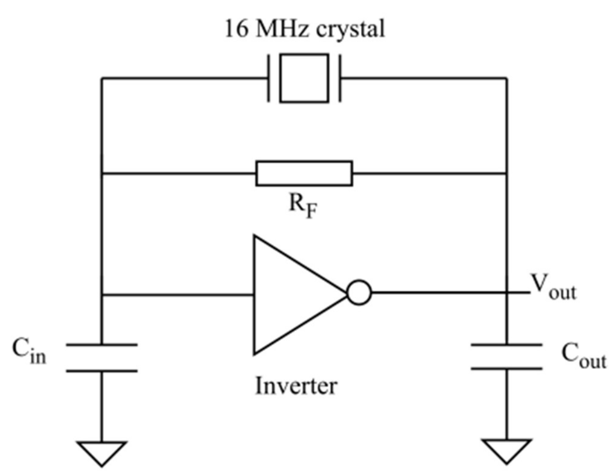
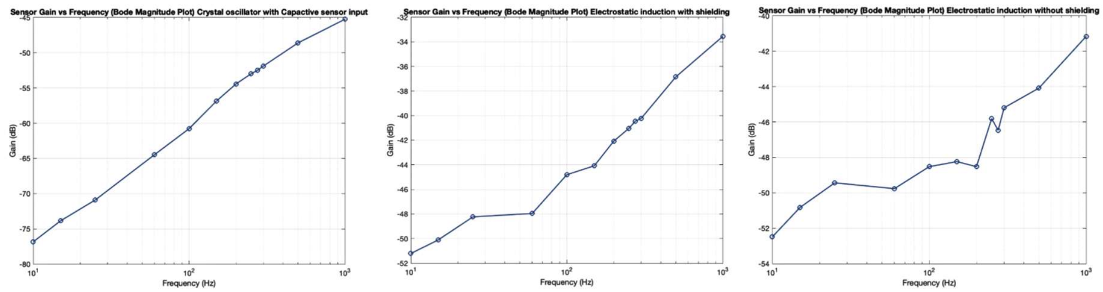


Figure 10-A crystal oscillator circuit used to sense electric fields

To examine the circuit's sensitivity to external electric fields, two experimental setups were explored. In the first configuration, the crystal oscillator was positioned directly between two parallel plates driven by a sinusoidal excitation source. This setup aimed to determine whether the applied electric field could directly influence the oscillation frequency through mechanical deformation of the quartz element. In the second configuration, a capacitive sensing plate was connected to the input node of the oscillator circuit. The sensor, previously developed as a standalone electrostatic field probe, was placed between the plates while the oscillator remained shielded. This approach tested how changes in external field-induced capacitance at the input node affect the oscillator's frequency response.



(a) (b) (c)

Figure 11-Bode Magnitude plots of different crystal oscillator circuits. (a) Show the bode plot for the crystal oscillator with the capacitive sensor as the input capacitor. (b) Shows the bode plot for the shielded Electrostatic induction sensor. (c) Shows the bode plot for the non-shielded Electrostatic induction sensor.

Initial prototypes were constructed on Veroboard using wired interconnections and header pins for the crystal and passive components. However, inconsistencies observed during testing raised the possibility that the long, unshielded traces were unintentionally acting as antennas, introducing parasitic coupling that masked the crystal's proper response. To address this, a dedicated PCB was fabricated to systematically study the impact of trace length, width, and routing layer on oscillator stability and sensitivity. Several variants were tested, including short top- and bottom-layer traces, extended traces of varying widths, and surface-mount layouts with direct connections.

While the circuit successfully generated stable oscillations, the results suggested that the response to external fields may have been dominated by parasitic coupling effects rather than direct crystal deformation. Further investigation is therefore needed to isolate the mechanism of sensitivity to determine whether the crystal itself responds measurably to low-frequency electrostatic fields or if the surrounding circuit geometry and capacitance changes are the primary contributors to the observed signal variations.

4. Experimental Setup

To evaluate the performance of the sensor prototypes detailed in Section 3, a consistent and repeatable testing methodology was required. This section describes the experimental apparatus and procedures designed to facilitate a fair comparison between sensor designs. The setup was designed to address three key challenges: simulating a bee's electric field, mitigating ambient electromagnetic noise, and ensuring the consistency of physical measurements.

4.1. Bee and Waggle Simulation

A primary challenge in this project was the difficulty of creating a calibrated "bee simulator" that could produce a known and controllable electrostatic charge. To overcome this, a comparative testing methodology was adopted. Instead of measuring absolute sensitivity to a calibrated source, the approach focused on measuring the relative performance of each sensor under identical and repeatable conditions.

A standardised test signal was used for all comparative evaluations to characterise the frequency response of each sensor. A 2.5 Vpp (Volts peak-to-peak) signal with frequencies ranging from 10Hz to 10kHz was

To assess the baseline performance of the sensors, the sensors were tested in a uniform field between two parallel plates. A signal generator was used to apply a test signal to one plate, creating a consistent field across the sensor array being tested.

To simulate the localised field of a single waggle-dancing bee, a small copper plate was excited with a sinusoidal signal. This allowed for the evaluation of a sensor's response to a non-uniform, point-source field and helped to observe the signal coupling between adjacent sensors in an array.

4.2. Controlled Testing Environment and Noise Control

The high-impedance nature of sensor designs makes them highly susceptible to ambient electromagnetic interference (EMF), particularly at the 50Hz frequency from mains power supplies. Additionally, the gain of the sensors is highly dependent on the distance of the signal source and the sensor.

To address these issues, a controlled testing environment was constructed. A Faraday cage shielded the sensors from EMF interference, and this enclosure significantly reduced the noise floor, allowing for a more precise measurement of the sensor's response to the test signal. To have a consistent distance for sensor tests, a physical testing rig was built to ensure that all sensors were tested under the same geometric conditions. The rig fixed the distance between the emitting plate and the sensing plate to approximately 2.5 cm, with a ground plate positioned less than 1 cm behind the sensor. The position of all components was recorded to ensure consistency across all experimental runs.

4.3. Data Acquisition

A digital oscilloscope was used to capture the output waveform from the sensor under test. It was noted during testing that the unshielded oscilloscope probes were susceptible to acting as antennae, picking up some residual noise. For future experiments, the use of shielded BNC cables, connected directly to the oscilloscope, is recommended to improve signal integrity further.

4.4. Preliminary In-Hive Set Up and Testing

To validate the functionality of the sensors in a live environment, a preliminary beehive test was conducted within an active observation beehive. The objective was to capture initial real-world electrostatic data and identify potential operational challenges, including environmental noise and signal integrity issues.

The test involved the sequential placement of three distinct sensor prototypes: the original electret-based 'BeeSpy', a JFET-based 'BeeSpy' variant, and the custom capacitive sensor coupled with an instrumentation amplifier. To ensure comparable testing conditions, each sensor was individually positioned at the exact fixed location within the hive. Due to the hive environment, the distance between the sensor and the bees could not be precisely controlled but was maintained at less than 1 cm. The setup of the observation hive test is shown in Figure 12.

Figure 12-Observation hive test setup

Data acquisition methods were adapted for each sensor type. For the two 'BeeSpy' variants, data was logged for 15 minutes using a Programmable System-on-Chip (PSoC) data acquisition unit. The capacitive sensor, however, produced an output signal range of ±5V, which exceeded the PSoC's analogue-to-digital converter (ADC) input specifications. Consequently, data for this sensor were captured and qualitatively assessed using a portable digital oscilloscope.

A significant observation during this preliminary stage was the persistent presence of 50 Hz mains hum across the output of all sensors. This interference was prominent despite the application of preliminary electromagnetic shielding to the sensor assemblies. The magnitude of this noise highlights the importance of robust EMI (Electromagnetic Interference) mitigation as a critical design consideration for the final in-hive system.

5. Results

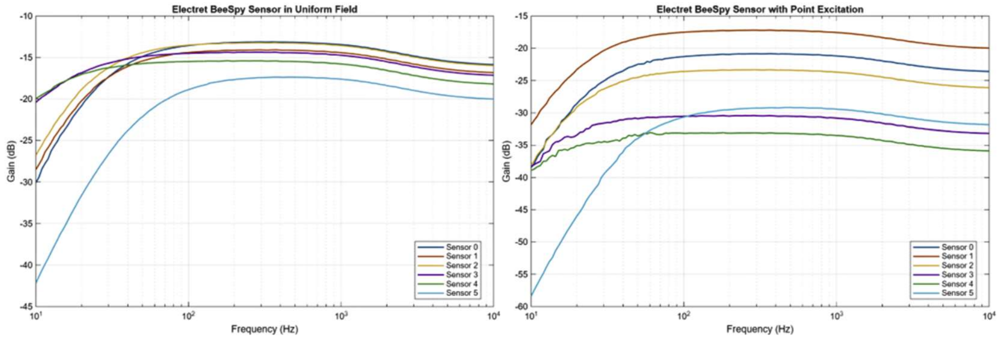
This section presents experimental results from the comparative evaluation of the baseline sensor prototype and the newly developed sensor prototypes. From the sensors explored in Section 4, two sensors were chosen, the JFET-based sensor and the capacitive sensor with an instrumentation amplifier, as they showed promising results during development.

The primary focus is on characterising the frequency response, inter-sensor consistency, and noise immunity of each design.

5.1. Baseline Sensor Performance

5.1.1. Electret BeeSpy Sensor Array

The electret-based sensors were tested under a uniform electric field to assess their consistency. Figure 13 shows the results for tests in a uniform electric field and with a single point of excitation, respectively.



(a) (b)

Figure 13-Frequency-gain response of the Electret BeeSpy sensor array. (a) The test was conducted under a uniform electric field (b). The test was conducted with a point excitation at the centre of the board

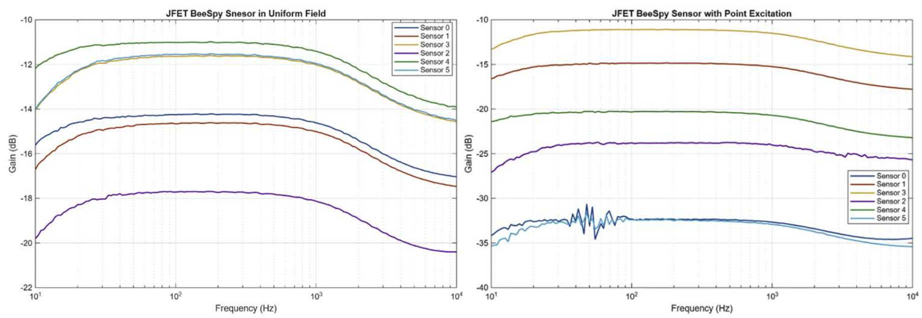
Under a uniform electric field (Figure 13a), all six electret sensors exhibit a similar characteristic. The gain increases sharply from 10 Hz, peaks between approximately 100 Hz and 1 kHz, and then gradually rolls off at higher frequencies. This response shape indicates that the sensors are most sensitive within the mid-frequency range, covering signals such as fanning. Still, sensitivity is lower at the fundamental frequencies of the waggle dance (often 15 Hz). Crucially, Figure 13a clearly shows significant inter-sensor variability. At the peak sensitivity around 1 kHz, the gain differs by approximately 5 dB between the most sensitive sensors and the least sensitive (Sensor 5). At lower frequencies, this variation is even more pronounced; for example, at 20 Hz, the gain spread exceeds 13 dB.

When tested with a point excitation source simulating a single bee at the centre of the board (Figure 13b), a similar gain characteristic is observed. However, the overall gain is generally lower compared to the uniform field test, likely due to reduced field coupling. The point excitation test further exacerbates the inter-sensor variability. At the 1 kHz peak, the difference between the highest-performing sensor (Sensor 1) and the lowest (Sensor 5) increases to approximately 17 dB. Sensor 5 consistently demonstrates significantly lower gain across both test conditions, underscoring the inherent inconsistency within this sensor type.

These results quantitatively confirm the variability problem highlighted in previous studies. The inconsistent gain between individual electret sensors necessitates complex calibration for each sensor in an array, making reliable data collection difficult, and directly motivates the search for more consistent and reliable sensor designs pursued in this project

5.1.2. JFET BeeSpy 5 Sensors

The baseline JFET BeeSpy 5 sensors were also tested in the uniform field. The results, shown in Figure 14, show a similar trend to that of the electrets.



(a) (b)

Figure 14-Frequency-gain response of the JFET BeeSpy 5 sensors. (a) The test was conducted under a uniform electric field (b). The test was conducted with a point excitation at the centre of the board

In the uniform electric field test (Figure 14a), the BeeSpy 5 JFET sensors exhibit a bandpass-like frequency response. The gain rises from 10 Hz, plateaus between approximately 50 Hz and 2 kHz, and then begins to roll off slightly towards 10 kHz. Like the electret sensors, this suggests good sensitivity in the mid-frequency range, which is relevant to several bee communication signals. However, significant inter-sensor variability is immediately apparent. The sensors appear grouped into distinct performance tiers. At 1 kHz, the gain ranges from approximately -11 dB (Sensor 1) to nearly -18 dB (Sensor 3), resulting in a spread of roughly 7 dB. This variation is consistent across the passband.

Under point excitation at the centre of the board (Figure 14b), the same general bandpass shape is maintained, though overall gain levels are reduced compared to the uniform field. The variability between sensors persists, and in some frequency ranges, it appears even more pronounced. For instance, at 1 kHz, the gain now spans approximately 12 dB, ranging from about -12 dB (Sensor 1) to -24 dB (Sensor 3). Notably, Sensors 0 (blue) and 5 (light blue) exhibit significant noisy oscillations in the 30 Hz to 100 Hz range during the point test, which were not present in the uniform field test. As suggested in preliminary analyses, this specific disturbance might be attributable to connection issues or localised noise pickup rather than an inherent sensor characteristic, but it requires further investigation.

Overall, while the BeeSpy 5 JFET sensors demonstrate sensitivity within a relevant frequency band, these tests confirm that they still suffer from substantial inter-sensor gain variability, similar to or even exceeding that of the electret sensors under certain conditions. This inherent variation, likely due to manufacturing tolerances in discrete JFET components, necessitates individual sensor calibration and complicates the deployment of large, reliable sensor arrays, further motivating the development of the more consistent sensor topologies explored later in this report

5.2. Performance of Developed Sensor Prototypes

The newly designed sensors were evaluated using the same methodology to allow for direct comparison against the baseline.

5.2.1. Single-Stage JFET Sensor (Iteration 1)

The single-stage JFET configuration (Iteration 2 in Fig. 5) was also tested in the uniform field, with the results shown in Figure 15. Unlike the other JFET configurations, the data obtained from this prototype is highly erratic and noisy, particularly below approximately 500 Hz. The gain fluctuates wildly over tens of dB, and no consistent frequency response trend can be discerned between the two tested units or compared to the other sensor types.

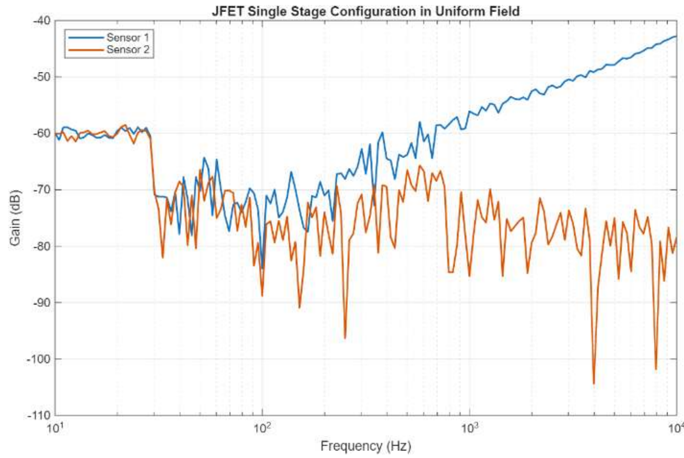


Figure 15-Frequency response of the single-stage JFET sensors in a uniform field

As noted during development, these results are considered questionable and are likely not representative of the true potential of the circuit topology itself. The poor signal quality is *likely* attributed to unstable connections and potential noise pickup inherent in the Veroboard construction used for this specific prototype. Consequently, due to the unreliable nature of the collected data, this iteration could not be meaningfully evaluated or directly compared against the baseline or the more robust self-biasing JFET design.

5.2.2. Self-Biasing JFET Sensor (Iteration 3)

The final self-biasing JFET sensor design (Iteration 3) demonstrated an improvement in consistency compared to the baseline sensors. Figure 16 presents the frequency response of two units of this design when tested in a uniform electric field.

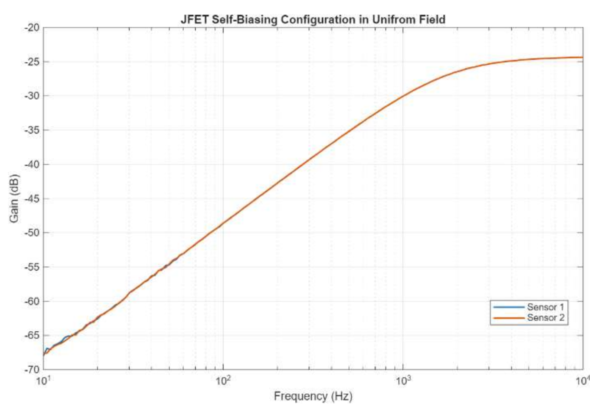


Figure 16- Frequency response of the self-biasing JFET sensors in a uniform field

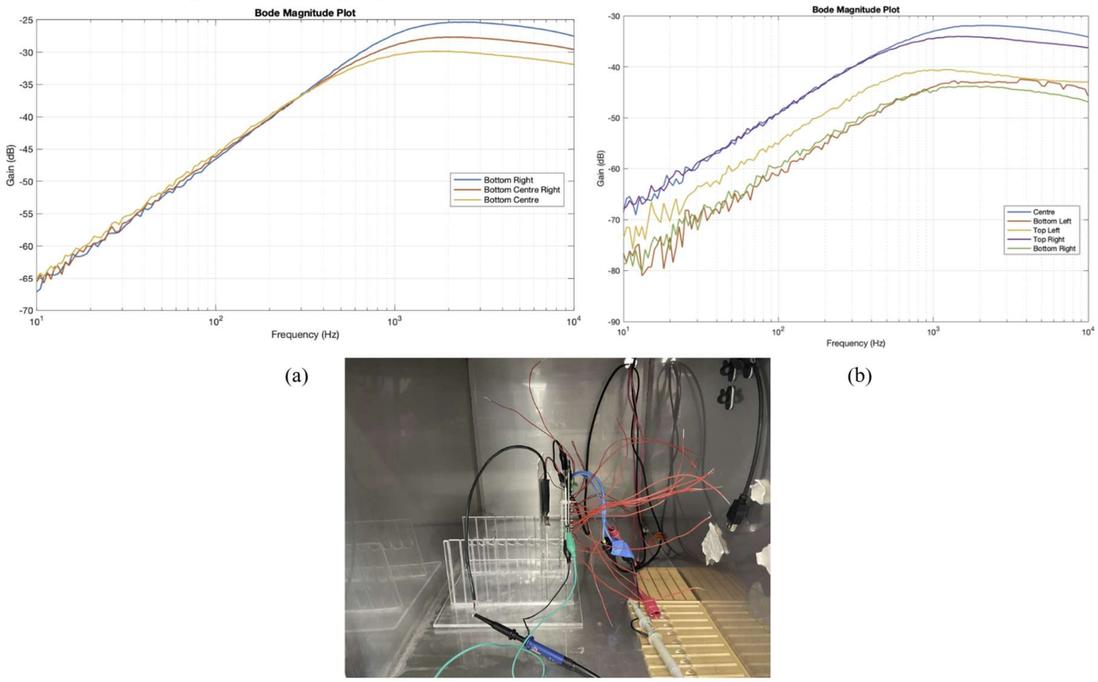
Both self-biasing sensors exhibit a clear high-pass filter characteristic. The gain starts significantly lower than the BeeSpy sensors at lower frequencies, measuring approximately -67 dB at 10 Hz. However, the gain increases steadily and consistently with frequency, plateauing around -24 dB above 2 kHz. This contrasts with the bandpass response observed in the BeeSpy JFET sensors, indicating different filtering properties inherent to this self-biasing topology.

The most compelling result shown in Figure 16 is the consistency between the two sensors. The traces for Sensor 1 and Sensor 2 are virtually indistinguishable across the entire tested frequency range (10 Hz to 10 kHz). This near-perfect overlap indicates that the self-biasing configuration successfully mitigates the effects of component-level variations inherent in JFETs.

While this configuration exhibits lower gain at the lowest frequencies compared to the BeeSpy 5 sensors, its high stability and, most importantly, its excellent inter-sensor consistency make it a promising candidate for developing reliable and scalable sensor arrays for in-hive monitoring.

5.2.3. Capacitive Sensor with Instrumentation Amplifier

The capacitive sensor with an instrumentation amplifier was evaluated for both inter-sensor consistency and spatial sensitivity, with the results presented in Figure 17. This design represents a significant departure from the JFET-based approaches and yielded highly promising results. The results showed that across an array of identical sensors, the frequency-gain relationship was highly consistent, with minimal variation between units.



(a) (b) (c)

Figure 17 - Frequency-gain response of the Capacitive Sensor with Instrumentation amplifier, with a uniform field. (a) The test was conducted under a uniform electric field (b). The test was conducted with a point excitation at the centre of the board. (c) Shows the experimental setup for the point excitation test.

Figure 17a shows the frequency-gain response of three adjacent sensors from the array when subjected to a uniform electric field. The sensors exhibit a distinct high-pass filter characteristic, similar in shape to the self-biasing JFET prototype, with gain rising steadily from approximately -67 dB at 10 Hz to a peak of around -25 dB near 1 kHz.

The most compelling result from this test is the exceptional consistency between the three sensor units. Below approximately 300 Hz, the performance of the "Bottom Right," "Bottom Centre Right," and "Bottom Centre" sensors is virtually identical, with their response curves overlapping almost perfectly. This demonstrates that the IA-based capacitive design effectively overcomes the significant inter-sensor variability that plagued both the electret and BeeSpy 5 JFET baseline sensors. While minor divergence (less than 3 dB) is observed at higher frequencies, the consistency in the critical low-frequency band (10-300 Hz) for waggle dance and fanning detection is a significant improvement.

To assess the array's ability to provide spatial information, a point test was conducted using the "waggle" simulator positioned at the centre of the 5x5 sensor board. As shown in Figure

17b, the results clearly demonstrate a strong correlation between signal strength and proximity to the source. The "Centre" sensor recorded the highest gain, peaking around -35 dB. The corner sensors ("Top Left," "Top Right," "Bottom Left," "Bottom Right") recorded progressively lower gains based on their distance from the central excitation point, with the bottom corner sensors showing the lowest gain, approximately 10-15 dB below the centre sensor at the 1 kHz peak.

An interesting observation from Figure 17b is that the two top corner sensors ("Top Left" and "Top Right") consistently exhibit a slightly higher gain (approximately 3-5 dB higher) than their bottom corner counterparts ("Bottom Left" and "Bottom Right"). While the overall trend of decreasing gain with distance from the centre holds, this top-bottom asymmetry was unexpected. It is hypothesised that this minor discrepancy may be due to the experimental setup (visible in Figure 17c). The connecting wires leading to the top row of sensors might have inadvertently acted as small antennae, providing a slight additional signal boost that was less pronounced for the bottom row sensors situated closer to the grounded base plate.

Taking it all together, the high consistency and demonstrated spatial resolution of the Capacitive Sensor with an instrumentation amplifier make it an excellent and significant improvement over the baseline BeeSpy technologies. This result confirms that the sensor array can successfully detect the location of a localised signal source, a key requirement for tracking the motion of a single bee during a waggle dance. The clear differentiation in gain across the array validates the design's potential for providing spatial granularity.

5.3. Preliminary In-Hive Test Results

The brief 15-minute test in a live beehive provided valuable qualitative data. The sensors were able to detect general hive activity. However, due to the short duration of the recording and the time of year, no distinct waggle dance events could be definitively identified from the captured data. The following results show the electret and JFET BeeSpy sensors.

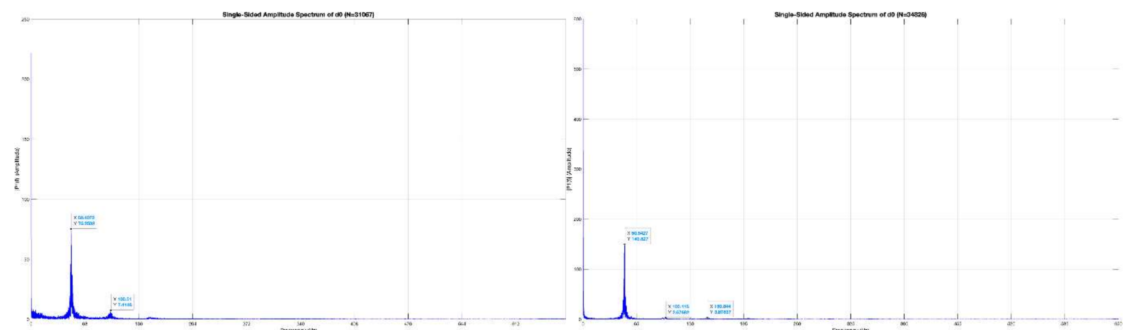


Figure 18-Fast Fourier Transform (FFT) of sensor data collected from the beehive test. (left) Shows the (left) Shows the FFT analysis of one of the electret-based BeeSpy sensors. (right) Shows the FFT analysis of one of the JFET-based BeeSpy sensors

The primary data from this test is presented as a Fast Fourier Transform (FFT) analysis for both the electret and JFET-based BeeSpy sensors (Figure 18). This analysis reveals the frequency components of the signals recorded inside the hive.

A critical and immediate finding, visible in both plots, is the presence of a highly dominant signal peak at approximately 50 Hz. This peak corresponds to electromagnetic interference (EMI) from the building's mains power supply, commonly known as "mains hum". This interference was persistent across all tested sensors, and as shown in the FFT, its amplitude is significantly larger than any other detected signal.

6. Discussion

The experimental results clearly validate the initial premise: the baseline BeeSpy sensors (both electret and JFET BeeSpy 5) exhibit substantial performance variations between individual units. This inconsistency, quantified as gain differences exceeding 10 dB in some frequency ranges (Figs. 13, 14), necessitates complex individual calibration and likely contributes to the high false-negative rates reported in identifying behaviours like the waggle dance.

Two of the developed prototypes demonstrated significant improvements in reducing variability. The self-biasing configuration achieved excellent inter-sensor consistency, with nearly identical frequency responses between the tested units (Figure 16). This directly addresses the variability issue inherent in floating-gate JFET designs. While exhibiting lower gain at very low frequencies (< 50 Hz) compared to the BeeSpy 5 baseline, its stable high-pass characteristic offers good sensitivity across the broader range relevant to bee signals (including fanning and potentially stop signals). Further optimisation of the gain stage could enhance low-frequency performance if needed.

This capacitive sensor with an instrumentation amplifier design demonstrated outstanding consistency among tested units, particularly below 300 Hz (Fig. 17a). This suggests that the manufacturing process for the capacitive plates is highly repeatable, overcoming the component tolerance issues commonly seen in JFETs. Furthermore, the point excitation test (Fig. 17b) confirmed the array's spatial sensitivity, successfully differentiating signal strength based on proximity to the source. This capability opens the door for not just detecting signals, but potentially tracking bee movement, offering richer behavioural data than single-point measurements. The slight asymmetry observed between top and bottom sensors is likely an experimental artefact related to wiring rather than a fundamental design limitation.

The exploration of alternative designs, such as the single-stage JFET, electrostatic induction, and oscillator circuits, reinforced the challenges in achieving reliable performance, often due to prototyping limitations (e.g., noise on Veroboard, PCB grounding issues).

6.1. Noise, Shielding, and Practical Considerations

The experiments highlighted the importance of electromagnetic shielding in high-impedance electrostatic measurements. The Faraday cage effectively mitigated mains hum in the laboratory setting. However, the persistence of 50 Hz noise during the preliminary in-hive test, despite shielding efforts, highlights a significant real-world challenge. This suggests that some digital filtering (e.g., a 50 Hz notch filter) will be needed in the data processing pipeline for any practical deployment, complementing physical shielding.

Furthermore, the high consistency of the capacitive sensor array offers a distinct advantage in this regard. A predictable, uniform response across the array means that a single, well-tuned 50 Hz notch filter can be applied universally to the data. In contrast, the significant gain variability of the baseline sensors (as shown in Figures 13 and 14) would complicate this process, potentially requiring individual filter calibration for each sensor's unique noise profile to avoid distorting the underlying biological signals.

6.2. Implications and Relation to Literature

The improved consistency demonstrated by the self-biased JFET and capacitive sensors, when used in conjunction with an instrumentation amplifier, directly addresses the primary technological gap identified in the literature review. By reducing the need for complex individual calibration, these designs are inherently more scalable and reliable. While this project couldn't definitively measure a reduction in false-negative rates due to limited in-hive testing, the enhanced consistency strongly suggests the potential for more dependable signal detection compared to the baseline systems. The spatial resolution capability of the 25-board capacitive sensors with an instrumentation amplifier sensor array represents a novel advancement beyond the current state-of-the-art described by Paffhausen et al. [8].

6.3. Limitations and Future Work

This study was subject to limitations. The absence of a calibrated charge source meant that performance was assessed relatively rather than absolutely. The preliminary in-hive testing was brief and conducted outside peak foraging season, preventing validation against known waggle dance signals. Furthermore, laboratory conditions, even shielded, cannot fully replicate the complex thermal, humidity, and electrostatic environment within an active hive.

Despite these constraints, the project successfully demonstrated a promising sensor design and a robust methodology for comparative evaluation. To further advance this work, several key areas are recommended for future investigation:

- **Develop a Dedicated PCB:** To move from prototype to a deployable system, a compact and robust Printed Circuit Board (PCB) should be designed for the finalised self-biasing JFET sensor. This will enhance reliability and facilitate easier installation in a real hive.
- **Conduct Long-Term In-Hive Studies:** The most critical next step is to deploy an array of the new JFET sensors in a beehive for an extended period. This will be essential to validate their long-term stability in the challenging hive environment and, most importantly, to determine if their improved consistency translates to a lower false-negative rate for detecting waggle dances.
- **Create a Calibrated "Bee Simulator":** To enable quantitative sensor calibration, future work should focus on developing a reliable method for creating a known, controllable charge source that accurately mimics the electrostatic properties of a bee.
- **Revisit and Refine Capacitive Sensing:** The high consistency of the instrumentation amplifier design warrants further investigation. Future efforts could focus on improving its sensitivity, perhaps by exploring alternative sensor geometries to maximise fringing field effects.
- **System Integration:** For a truly comprehensive monitoring solution, the ESF sensor array could be integrated with other environmental sensors (e.g., temperature, humidity, CO2). This would allow researchers to correlate bee behaviour with a broader range of hive conditions, providing deeper insights into colony health.

By addressing these directions, future research can transform the current prototype into a scalable, field-ready system capable of long-term, non-invasive monitoring of honeybee behaviour and colony health.

7. Conclusion

This project set out to address the critical limitations of existing electrostatic field (ESF) sensors for monitoring honeybee behaviour. Current systems, while conceptually sound, are hindered by issues of low sensitivity, high inter-sensor variability, and environmental susceptibility, resulting in unreliable data and a high rate of false negatives in detecting key behaviours, such as the waggle dance.

Through a systematic process of design, prototyping, and comparative testing, this project has successfully developed and validated a sensor design that directly addresses these shortcomings. The experimental results confirmed that baseline electret and floating-gate JFET sensors exhibit significant performance variation, reinforcing the need for a more stable solution. A highly consistent instrumentation amplifier-based capacitive sensor was developed, demonstrating the potential for creating scalable arrays with spatial sensing capabilities.

References

[1] D. Clarke, E. Morley and D. Robert, "The bee, the flower, and the electric field: electric ecology and aerial electroreception," *J Comp Physiol A,* vol. 203, *(9),* pp. 737, 2017. DOI: 10.1007/s00359-017-1176-6.

[2] U. Greggers *et al*, "Reception and learning of electric fields in bees," *Proc. R. Soc. B.,* vol. 280, *(1759),* 2013. . DOI: 10.1098/rspb. 2013.0528.

[3] G. P. Sutton *et al*, "Mechanosensory hairs in bumblebees (Bombus terrestris) detect weak electric fields," *Proc. Natl. Acad. Sci. U. S. A.,* vol. 113, *(26),* pp. 7261, 2016. DOI: 10.1073/pnas. 1601624113.

[4] K. v. Frisch, The Dance Language and Orientation of Bees. 1967.

[5] D. M. Eiri and J. C. Nieh, "A nicotinic acetylcholine receptor agonist affects honey bee sucrose responsiveness and decreases waggle dancing (vol 215, pg 2022, 2012)," J. Exp. Biol., vol. 219, (13), pp. 2081, 2016. DOI: 10.1242/jeb. 143727.

[6] Y. Yan et al, "Electrostatic sensors – Their principles and applications," Measurement, vol. 169, 2020. DOI: 10.1016/j.measurement.2020.108506.

[7] R. Puers, "Capacitive sensors: when and how to use them*,".

[8] B. H. Paffhausen *et al*, "The Electronic Bee Spy: Eavesdropping on Honeybee Communication via Electrostatic Field Recordings," *Front. Behav. Neurosci.,* vol. 15, 2021. DOI: 10.3389/fnbeh. 2021.647224.

[9] W. Storr, "Junction Field Effect Transistor or JFET tutorial," 21 October 2024. [Online]. Available: https://www.electronics-tutorials.ws/transistor/tran_5.html. [Accessed 19 Oct 2025].

[10] X. Tang *et al*, "Analysis of the Dynamic Sensitivity of Hemisphere-Shaped Electrostatic Sensors' Circular Array for Charged Particle Monitoring," *Sensors,* vol. 16, *(9),* 2016. DOI: 10.3390/s16091403.

Appendix A: Sensor Designs

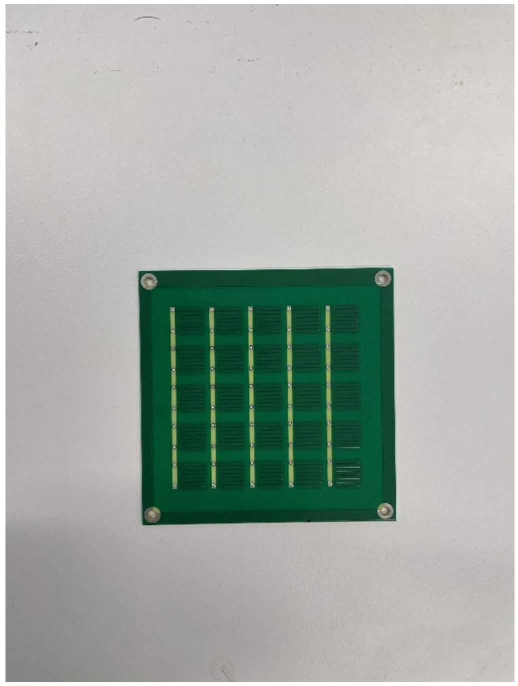


Figure A1-5x5 Capacitive Sensing PCB

Figure A2-Crystal Oscillator PCB. Showcases different track lengths

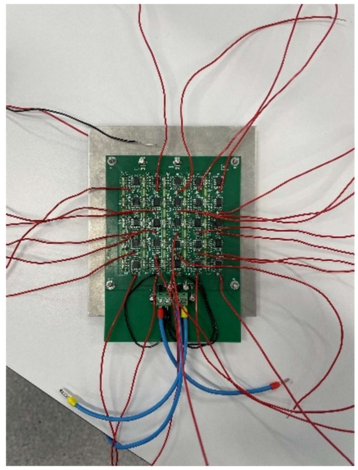


Figure A3-Fully assembled capacitive sensing with instrumentation amplifier PCB

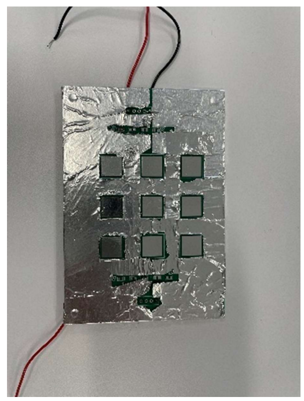


Figure A4-Induction-based sensor PCB.