On pollinator monitoring using mmWave micro-Doppler Radar

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***Abstract*—Pollinators serve a crucial role in our global ecosystem by facilitating the reproduction of plants and crops. Despite their vital contribution, factors like urbanization and pesticide use, pose significant threats to the habitats of various pollinator species, such as bees. Therefore, it is increasingly imperative to devise solutions that allow precise and efficient monitoring of their biodiversity. This study presents a low-cost solution based on mmWave Doppler sensor to extract important characteristic wingbeat information of bumblebees through near-field monitoring. By conducting various simulated and real-life experiments, we demonstrate the feasibility of our approach for providing low-cost and effective portable in-field monitoring of pollinators for biodiversity conservation purposes.**

***Index Terms*—pollinator, micro-Doppler, mmWave, radar, sensor, biodiversity, bee, wingbeat**

I. Introduction

Biodiversity refers to the incredible variety of living beings found within our global ecosystem. Among these organisms are pollinators, including various flying insects, such as butterflies, bees, wasps, etc. The existence of pollinating insects plays a vital role in human activities, ensuring the stability of our ecosystem and global food production, as well as our own well-being [1], [2].

Important pollinator species, such as the bee, for instance, are facing unprecedented decline due to factors like climate change, pesticide overuse, and habitat loss [3], [4]. This decline raises significant concerns due to its potential impact on food security, underscoring the urgent need for effective monitoring and conservation strategies [1], [5]. By embracing real-time monitoring technologies, we can transition from reactive to proactive measures, providing early warning systems of potential threats.

Traditional approaches to insect monitoring, such as human visual surveillance, insect trapping, and manual identification by specialists, are known to suffer from multiple inherent limitations. For example, these methods often require sacrificing the insects themselves and involve labour-intensive data collection. Additionally, many insects remain unseen and uncounted due to their minute size, natural camouflage, and limitations posed by human observers, which create blind spots and further compromise the accuracy of traditional approaches [6], [7].

More recently, the advent of new solutions that allow for the automatic identification of insects aims to combat many of the limitations posed by traditional methods by employing sophisticated sensors and algorithms [8]. These approaches typically offer a cost-effective and non-invasive solution for monitoring large-scale insect populations, while providing a more comprehensive picture of pollinator activity through tireless functioning, eliminating the need for intensive manpower to capture and monitor the insects, and facilitating ethical approaches for a more sustainable ecosystem. Among these approaches, audio and vibration monitoring have become some of the most popular, since they produce distinct vibroacoustic signals in response to various triggers [9]–[15]. In most of the associated literature, acoustic sensors have been used mainly due to their relatively low-cost, portability, and non-invasive nature. These sensors can cover a wide range of spatiotemporal scales [16], [17]. However, they also come with notable limitations, including challenges posed due to ambient background noise which can severely degrade the accuracy of the solution, changes in the proximity of the monitored insects relative to the location of the microphone, and an overlap of extraneous sounds produced by other nearby animal species within the vicinity of the microphone, which has previously been a main cause for their restricted use by researchers [18].

At the same time, there has been a growing number of works that involve the use of radar systems to study insect populations, the history of which dates back approximately seven decades ago [19], [20]. During this period, contributions have expanded upon insect detection [21], [22], determination of size [19], wingbeat analysis [23], density assessment, airspeed-heading [24], and flight duration and range estimations [23]. More recent research has delved into radar cross-section (RCS) processing techniques that can provide more efficient detection [25]–[28], alongside prior findings of correlation between insect body mass and RCS [29]. However, challenges associated with the overall size and expensiveness of rather complex systems based on pulsed radar or frequency-modulated continuous wave (FMCW) hinder their widespread implementation [30], [31].

There have also been progress in the direct identification of aerial targets, such as windborne migration insects or large insects at night, which are carried out by planes, kites, or searchlight trappings. However, these source-intensive and time-consuming methods are generally not useful for real-time monitoring of the migratory patterns of insects.

The emergence of techniques involving wingbeat pattern analysis has offered promising results towards the categorization of insects. For example, in [32], observed wingbeat frequencies are listed as a key feature to include as part of a taxonomy that allows accurate categorization of different species in lab experiments and field observations, enhancing the utility of radar data for environmental monitoring and management.

The wingbeat movement of an insect modulates the incident radar signal amplitude, making it possible to detect and discriminate the target based on radar echo analysis with an approximate success rate of 46% [23], [33]. However, as the size of the monitored insect decreases, so does the intricacy involved in detecting smaller variations in the amplitude become more challenging. Here, the technological leap comes by utilizing both signal amplitude and carrier phase to extract the Doppler frequency, which can be defined as a frequency shift between the transmitted and received signal by the radar caused by the target's motion [34]. Targets, including their vibrations and rotations, generate micro-Doppler effects caused by frequency modulation [35], [36].

This work focuses on the design and implementation of a low-cost, portable, and power-efficient radar system which leverages the benefits of the micro-Doppler effect induced by the wingbeats of bees for their identification. At the heart of this system lies a Doppler radar module which operates at a frequency of 24 GHz. This portable device eliminates the need for human intervention and facilitates in-field monitoring of pollinators, enabling timely warnings about any changes in their biodiversity and the resulting ecological impacts they face.

II. Testing Methodology

A. Proxy target

Experiments were conducted using the CDM324 micro-Doppler radar sensor, a K-Band transceiver that has previously been used in security applications for human intrusion detection with up to 15 m range [37], as well as hand gesture recognition [38]. This sensor operates as a single-frequency transceiver, transmitting a Continuous Wave (CW) signal at 24 GHz. Its output signal is characterized by a maximum peak-to-peak value of 600 mV in the intermediate frequency (IF) band, which is proportional to the difference between the reflected signal from the target and the transmitted signal of the sensor. Moreover, this sensor operates from a 5 V power supply and draws a relatively low current of around 30 mA.

The proposed setup is illustrated in Fig. 1 and Fig. 2. To get precise detection of the micro-movements of small insects, an amplification circuit is integrated into the system and the measurements are conducted using the ADALM2000 oscilloscope [39] highlighted in Fig. 2.

The initial optimisation of the system was achieved using a small piezoelectric buzzer. This methodology allows for realistic micro-Doppler behaviour while limiting the number of required live insects. Piezoelectric, due to their small size and micro-movements of their diaphragm, were chosen as a good candidate to facilitate the initial testing of the system.

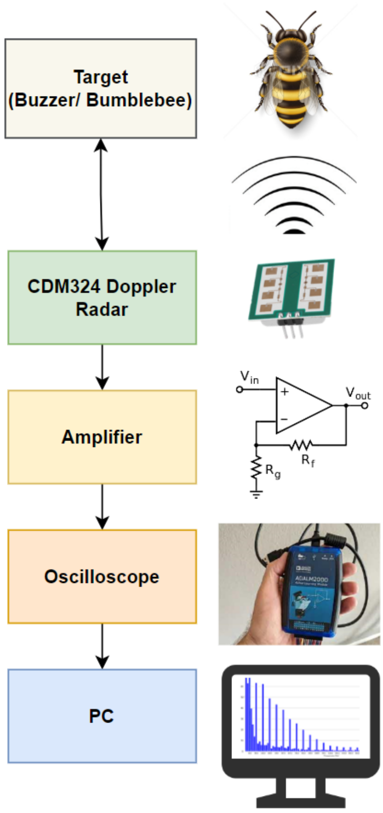

Fig. 1. Block diagram of the system

A validation approach was adopted to assess the precision of the proposed sensor's frequency detection ability. To achieve this objective, a signal generator was employed to produce pure sine waves. The frequency of the generated single-tone signal was swept from DC to 500 Hz while maintaining a constant amplitude of 300 mV to simulate the subtle wing movements. This frequency spectrum was selected based on literature reviews on the observed periodic movement frequencies from different beehives [40].

This method not only upholds ethical considerations but also facilitates numerous accuracy validation practices of our monitoring system.

B. Live Bumblebee target

Following the preceding validation experiments, live bumblebee specimens (Bombus terrestris) were sourced from Trinity College Dublin's Botany Department to serve as the target for this stage of our experiment.

A plastic container with minute holes for ventilation was considered to house each insect being monitored. To make measurements, the Doppler radar module was side-mounted with its main lobe facing towards the mid-centre of the container. The transparency of the container was also leveraged to provide further visual observation and to produce video recordings that could subsequently be used as the reference for the ground truth data. The objective of this experiment was to detect the absence and behavioural modes of the bee, including its presence without movement ("no-flying") and its presence accompanied by definite wing fluttering or flying ("flying").

For each of these modes, multiple measurements were collected using the spectrum analyser function of the ADALM2000 oscilloscope.

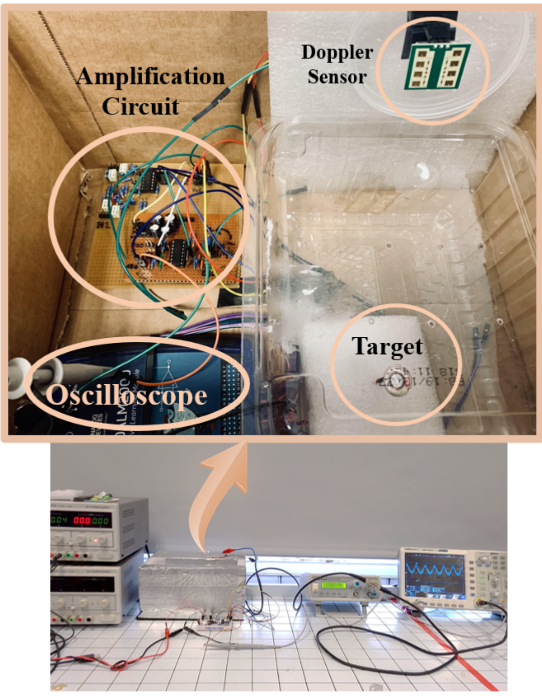

Fig. 2. Experimental setup

III. Results

Fig. 3 displays the recorded signal spectrum as a result of driving the piezoelectric buzzer at various frequencies spaced equally at 100 Hz intervals between 100 Hz to 500 Hz. The amplified outputs of the Doppler sensor at each of these frequencies are depicted in Fig. 3. For this experiment, we developed an amplification circuit of 53.44 dB gain using the Texas Instruments rail-to-rail low-noise TL974 operational amplifier integrated circuit (IC) [41] to amplify the raw output measurements of the CDM324 sensor. The resulting spectrum of the amplified outputs were monitored using the frequency spectrum analyser function provided by the ADALM2000 oscilloscope and Scopy software running on a personal computer with a resolution of 488.28 mHz and set to measure Root-Mean-Square Voltage (Vrms) as the output unit.

The results of this experiment, as indicated by Fig. 3, show that the CDM324 sensor is able to accurately detect and reproduce the same frequencies generated by the excited buzzer. Moreover, the impact of noise is seen to be relatively low across the entire spectrum, apart from a peak appearing at 50 Hz, which we believe most likely originates as AC noise from the mains power supply where these experiments have been conducted. While we plan to further improve the noise immunity of our solution in future work, we believe the results of this experiment help validate the feasibility of employing a low-cost Doppler radar, such as the CDM324, to detect the wingbeat frequencies produced by pollinator insects, such as bees.

The results of our second experiment are shown in Fig. 4, which illustrates the recorded frequency spectrum when live bumblebees were used in place of the proxy buzzer from our previous experiment. Importantly, for this experiment, multiple measurements were taken for each of the two modes of interest, including when the monitored bee was resting ("no flying") and when it was flying or actively fluttering its wings ("flying"). The recorded measurements for each mode resulted in a *distribution of results*, reflecting how each particular frequency component varied across each of these two modes. In Fig. 4, we project the recorded distributions for both modes by plotting the areas bounded by the 25th to 95th and 50th to 75th percentiles of each mode.

As indicated by the flying mode curves, the observed wing-beat patterns of the bumblebee are centered mainly around a frequency of 165 Hz, with a visible harmonic also appearing at 328 Hz. In comparison, the relatively weak amplitudes of the no-flying mode further demonstrate the high sensitivity of the Doppler radar in detecting the wingbeat frequencies of the bees. Across both modes, a similar presence of a 50 Hz spike can be seen as with the previous buzzer experiment, which again can most likely be attributed to the interference of the AC power supply used in the experimental setup.

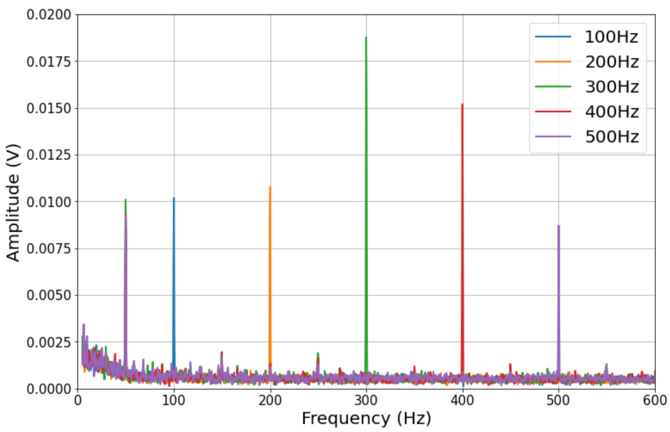

Fig. 3. Frequency spectrum of experiments with the buzzer

Finally, we note that the live bee primarily introduces two distinct signal components, including its body movement and positional changes relative to the radar, which produces mainly low-frequency components; and its wing fluttering, which generates high-frequency harmonics [42]. The latter, which corresponds to our main parameter of interest, facilitates insect identification and can be isolated using high-pass filters. This approach is particularly effective considering that unwanted power concentration can be expected to occur at the baseband region due to human or animal movements during in-field measurements.

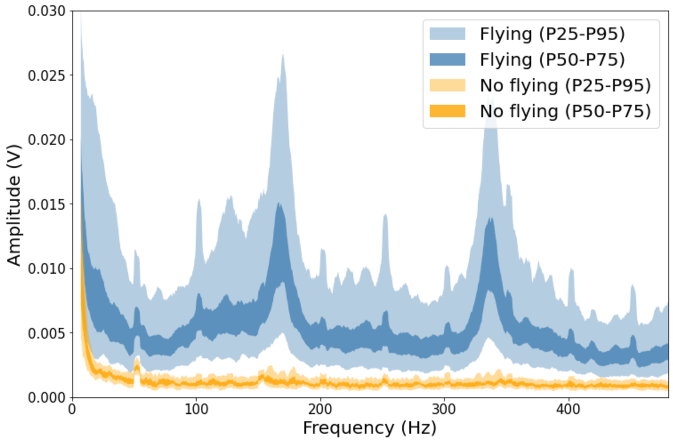

Fig. 4. Frequency spectrum of experiments with Bumblebee

IV. Conclusion

In this study, we explored the application of the micro-Doppler effect for behavioural monitoring of live small insects. Implementing a low-cost simple setup featuring a commercial Doppler radar module operating at 24 GHz, we observed wing flapping patterns of Bumblebees. The presence of related harmonics in our observations validates the periodic nature of their fluttering.

The proposed system has the potential to be portable and developed into automatic extraction method through the integration of simple processors for utilizing machine learning techniques. This advancement facilitates small insect classification for in-field measurements needed for biodiversity conservation purposes.

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