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Evaluating Unmanned Aerial Vehicles for Vibrational Analysis: Exploiting Integrated Capabilities of Nano-Drones as Nodes in a WSN

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Abstract. Addressing the aging infrastructure challenge in both civil and industrial sectors has spurred the development of advanced sensor technologies and novel inspection methodologies, significantly contributing to the field of Structural Health Monitoring (SHM). While conventional sensors, such as structure-mounted accelerometers, have demonstrated high effectiveness, their deployment may be difficult or even impossible in high-risk environments like post-seismic areas, where the installation procedure hampers the operators' safety. Hence, this study aims to evaluate the characteristics of a novel sensing platform compatible with autonomous deployment for vibration inspection of infrastructures.

In particular, we explore the use of Unmanned Aerial Vehicles (UAVs), with a specific focus on nano-drones, as a viable and promising solution due to their compact size and cost-effectiveness. In particular, ‘Crazyflie 2.1’ nano-drones are exploited as reference platforms, given their characteristics in terms of versatility and electrical parameters. The objective is to utilize the on-drone MEMS-based Inertial Measurement and Microcontroller Unit (IMU and MCU) to perform, at the same time, both flight control and navigation, and vibration measurements.

The proposed solution is validated through a comparison with acceleration measurements taken with commercial sensors and exploited for the structural identification of a simply supported beam element. The results indicate that the Crazyflie drone can detect even small variations in the dynamic response, with a maximum deviation of 1% compared to the reference sensor.

Keywords: Nano-Drones · Unmanned Aerial Vehicles · Vibration Analysis · Structural Health Monitoring · Wireless Sensor Network

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Introduction

Between the 19th and mid-20th centuries, advancements in material studies have facilitated the rapid and cost-effective construction of many facilities supporting the modern society. While many of these buildings are still operational today, prolonged use and aging have led to their deterioration. This demands for advanced sensor technologies and new inspection methodologies necessary to evaluate continuously their status of integrity via appropriate Structural Health Monitoring (SHM) procedures. Monitoring buildings through integrated sensor networks allows for on condition maintenance, which requires human intervention only when necessary, without interfering with their normal operations.

As well known, structural changes due to damage provoke modifications in the dynamic response of the asset; hence, frequency-related features can be considered as effective damage indicators. Vibration analysis conducted with conventional sensors, such as accelerometers attached to the structure, has proven highly effective in achieving this goal. However, the deployment of these sensors may not be feasible in high-risk contexts, such as post-seismic areas, where accessing the structure for sensor installation would compromise the safety of operators and personnel, and in complex scenarios like for instance in high towers. Therefore, this research work evaluates the feasibility of employing Unmanned Aerial Vehicles (UAVs), specifically the nano-drone “Crazyflie 2.1”, as a versatile and reliable alternative for remote accelerometers deployment.

Thanks to their low-cost and reduced size, the utilization of nano UAVs offers significant advantages in terms of flexibility in selecting monitoring points and minimal economic impact. However, there are also drawbacks to be considered, including the UAV's limited battery life, imperfect stability, and restricted bitrate of radio transmission. These aspects have been examined thoroughly under a new perspective which differs from the non-contact or visual inspection technique for which UAV are currently exploited.

The main objective of this work is to compare the nano-drone's performance with that of standard sensors in the measurements of accelerations. The figure of merit for the comparison consists in the extraction of the vibration frequencies of a simply supported beam under several damage configurations.

1. Vibrational Structural Health Monitoring

1.2 UAV applications and motivations

The recent developments of UAV technology have found promising applications in the SHM domain. For example, UAVs may offer the versatility to conduct general structural inspections, providing a comprehensive 3D view of buildings using onboard cameras. These visuals facilitate the detection of potential damages [1]. While visual inspection remains the primary application of UAVs in SHM, efforts are underway to utilize these devices for collecting vibration data from structures. This approach could lead to substantial cost savings by eliminating the need for most electrical connections and significantly reducing installation time compared to wired networks. Wireless networks offer greater flexibility in accessing specific areas, allowing for sensor repositioning to gather data from different points on the structure.

Other studies have explored the use of drones for vibration monitoring. However, these measurements typically rely on non-contact methods, such as assessing vibrations by measuring the distance between the drone and the structure [2], or using cameras on drones to monitor the displacement of a visual target attached to the structure [3]. While these techniques offer advantages in accessibility and versatility, they are susceptible to inaccuracies due to the lack of physical contact of the drone with the structure and can result in significant energy consumption by the drone during flight, thereby reducing inspection autonomy.

Each UAV is equipped with an Inertial Measurement Unit (IMU), particularly including an accelerometer. This consideration has led to the concept of utilizing the UAV itself along with its accelerometer as a sensor for vibration inspection, focusing on the selection of a nano-drone to have a flying accelerometer capable of operating even in confined spaces or with limited landing surfaces. Our choice revolved around the “Crazyflie 2.1” due to its small dimensions and open-source nature which can be customized for required monitoring requirements. Its characteristics are reported in Table 1, along with a comparison with other drones used in vibration-based SHM applications.

Table 1. Drones comparison

	DJI Mavic Air [1]	**DJI Matrice 100** [2]	**DJI Mavic Pro** [3]	**DJI Mavic 2** [3]	**Crazyflie 2.1**
Drone Type	Quadcoptor	Quadcoptor	Quadcoptor	Quadcoptor	Quadcoptor
Diagonal Size	213 mm	650 mm	335 mm	354 mm	94 mm
Weight	430 g	2431 g	983 g	1202 g	27 g
Battery Type	2375 mAh LiPo	4500 mAh LiPo	3830 mAh LiPo	3850 mAh LiPo	250 mAh LiPo
Battery Life	21 minutes	22 minutes	30 minutes	31 minutes	7 minutes
Operating Temperature	0 / 40 °C	-10 / 40 °C	0 / 40 °C	-10 / 40 °C	-40 / 85 °C
Maximum Flying Range	4 Km	5 Km	4 Km	18 Km	1 Km

The comparison clearly demonstrates significant differences in the characteristics of the various drones with respect to the “Crazyflie 2.1”. This disparity arises because in these articles, UAVs are required to sustain flight for prolonged periods and maintain maximum stability, serving as a reference point for measurements during flight, or acting as anchors for the sensor node. However, the requirements for vibration-based SHM applications differ from those of traditional UAV missions. While endurance and stability are paramount for extended flight missions, vibration monitoring often involves shorter flights focused on collecting precise data from specific structural points. In this context, the “Crazyflie 2.1” emerges as a compelling option due to its compact size, agility, and ability to navigate confined spaces with ease.

2. Crazyflie Ecosystem

2.1 Hardware architecture

The “Crazyflie 2.1” is an adaptable open-source flying development platform by Bitcraze weighing only 27 grams and measuring 92x92x29 mm from motor to motor, including its mounting feet; hence, it belongs to the class of nano-drones. It is equipped with a low-latency and long-range Bluetooth LE radio, enabling users to control it through a dedicated app available for iOS or Android ("Crazyflie"), or via a PC application requiring connection to the "Crazyradio PA" (a USB dongle with a long-range radio antenna) [4]. Referring to the UAV architecture, it boasts a durable design and is easy to be assembled, as it requires no soldering. Expansion decks are supported only when flying from a computer, and firmware updates can be performed without the need for wired connections. Additionally, it features integrated charging via standard USB. The various parts to compose are "Crazyflie 2.1" motherboard containing all the device's electronics (Fig. 1(a)), five clockwise and five counterclockwise rotating propellers (Fig. 1(b)), six motor mounts (Fig. 1(c)), a LiPo battery (Fig. 1(d)), five coreless DC motors (Fig. 1(e)), two short and two long expansion connector pins (Fig. 1(f)), a battery holder expansion board (Fig. 1(g)), and a USB cable (Fig. 1(h)).

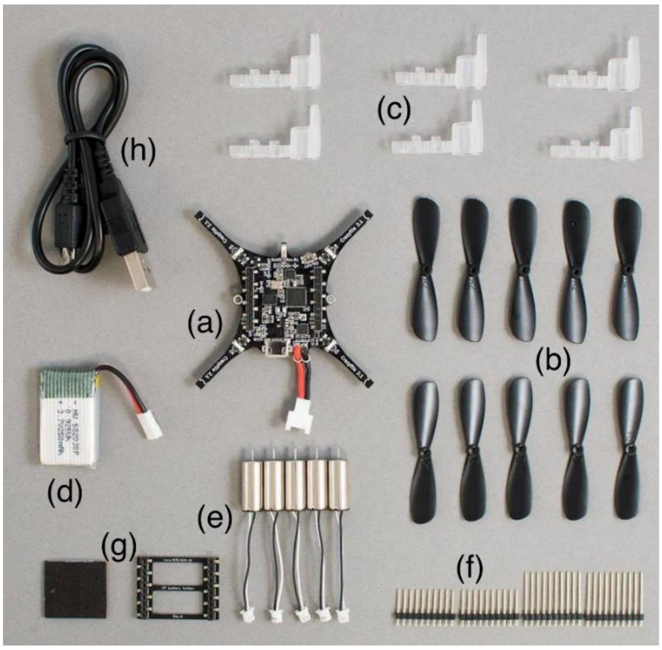

Fig. 1. Components to be assembled to compose the Crazyflie drone.

From an electronic perspective, the drone is managed by an STM32F405 Microcontroller (MCU), housing a Cortex-M4 processor running at 168 MHz, with 192 KB of SRAM and 1 MB of flash memory. Additionally, it incorporates the nRF51822 radio module from Nordic Semiconductor, which integrates an MCU featuring a Cortex-M0 processor operating at 32 MHz, accompanied by 16 KB of SRAM and 128 KB of flash memory. The MCU manages the drone's functionalities, such as flight operations, while the radio module handles communication, whether towards the control unit (the "Crazyflie" app or "Crazyflie PA") or towards the STM32F405 to execute commands or changing settings. Furthermore, it is equipped with a micro-USB connector with a full-speed USB device interface and an 8 KB EEPROM. In terms of sensors, it integrates the BMI088, a 6-axis IMU consisting of a 3-axis accelerometer and a 3-axis gyroscope, along with the BMP388 high-precision pressure sensor, both of which are developed by Bosch Sensortec. As for the "Crazyradio PA", it is a long-range USB radio dongle built upon the Nordic Semiconductor nRF24LU1+, featuring a 20 dBm power amplifier that can extend the communication range up to 1 km under line-of-sight conditions.

2.2 Software architecture

A fundamental aspect enabling the application of a Crazyflie drone in various fields is the extreme ease of use of the development environment, which is available for most subsystems within a virtual machine suitable for "Oracle VM VirtualBox" (Fig. 2(1)), eliminating the need to install any toolchains to begin the development.

Within this virtual machine, Python API known as CFLib (Fig. 2(2)) provided by Bitcraze is available. Through this API, two software approaches are facilitated, enabling interaction with the drone in two distinct manners: i) via the "Crazyflie PC Client" (Fig. 2(3)) and ii) direct utilization of the API within a custom Python script (Fig. 2(4)). The “Crazyflie PC Client” serves as a valuable software tool for both flight operations and drone firmware updates, while employing CFLib in a Python script allows for personalized drone management. Each of these solutions establishes communication with the drone through the USB peripheral “Crazyflie PA” (Fig. 2(5)). This communication enables sending and receiving commands (e.g., flight maneuvers), and setting, or reading parameters (e.g., battery level, internal timer, PID rate, etc.) [5]. This pertains to the drone control software. On the drone side (Fig. 2(6)), there is firmware based on a Real-Time Operating System. This firmware is responsible for managing the drone, from executing received commands to handling internal parameters that can be modified or accessed via specific commands.

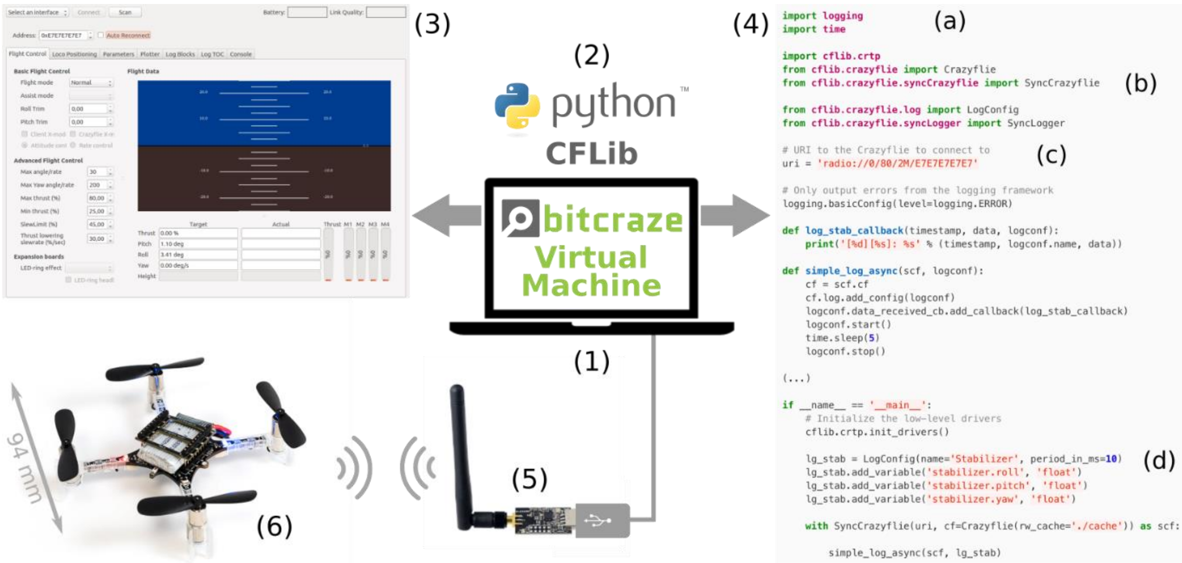

Fig. 2. Crazyflie ecosystem

2.3 Turning” Crazyflie 2.1” into accelerometer sensor for SHM

The crucial components of the drone to be repurposed beyond flight operations is the Inertial Measurement Unit (IMU). The “Crazyflie 2.1” mounts the BMI088 IMU [6] which offers an acceleration range (or Full Scale - FS) from 3 g to 24 g, a sensitivity of 10920 LSB/g (FS at 3 g), a bandwidth range of 5-280 Hz, and an output noise density of 190 µg/√Hz (FS at 3 g), aligning with technical details of widely employed commercial accelerometers. Nevertheless, the native configuration of the drone platform presents three key limitations: i) data acquisition from the accelerometer, ii) communication and configuration management of the drone, and iii) frequency peak detection.

For the first point, the CFLib was chosen, as illustrated in Fig. 2(4), where one of the scripts for downloading accelerometer data is depicted. The script demonstrates the invocation of standard Python libraries (Fig. 2(4-a)), inclusion of the CFLib API (Fig. 2(4-b)), establishment of a link to the “Crazyradio PA” radio module via Uniform Resource Identifier (Fig. 2(4-c)), and the actual request for accelerometer data accompanied by the desired transmission period specified in milliseconds under "period_in_ms". Regarding the modification of this parameter, it was observed that by default, the acquisition rate was set to 100 Hz, a value adequate for navigation and control operations but potentially limited for vibration analysis. Additionally, it was found that setting a higher frequency was not feasible. To surpass this limitation, intervention in the drone's RTOS firmware was necessary, involving the removal of a ×10 operation from the “crazyflie-firmware/src/modules/src/log.c” file, where it was used to modify a secondary parameter in the “logStartBlock()” function. In practice, the value defined in “period_in_ms” was divided by ten during transmission and then multiplied by ten in “log.c”, thus preventing the period from falling below 10 ms. While this straightforward modification theoretically enabled a temporal discretization of 1 ms and thus a frequency of 1000 Hz, practical instability was encountered in the message content containing acceleration data when a period below 7 ms (corresponding to approximately 142 Hz) was set. Regarding point ii), at the current research stage, no new commands have been implemented for modifying accelerometer settings (e.g., Output Data Ready – Sampling rate, Full Scale, etc.). Instead, manual adjustments were made through the modification of the “crazyflie-firmware/src/hal/src/sensors_bmi088_bmp388.c” and “crazyflie-firmware/src/hal/src/sensors_bosch.c” files. For point iii), further details are provided in the subsequent Section.

3. Experimental validation

3.1 Materials and methods

Experiments have been conducted on a pinned-pinned steel beam in laboratory conditions under ground motion excitation. Beside the Crazyflie drone, two other conventional sensors have been installed in proximal positions (see installation plan in Figure 3) to serve as competitors from commercial and academic alternatives: a G-Link-200 rugged wireless accelerometer [7] from MicroStrain and a custom sensor node designed within the Intelligent Sensor Systems Lab of the University of Bologna [8] and equipped with the LSM6DSL IMU. Sensors have been configured as reported in Table 2, which corresponds to the best compromise between the settings available for each acquisition system. Along with tests in nominal conditions, damages have been simulated by hanging a dead mass of various weight (100 g, 500 g, and 1 kg) to the beam at 28 cm from the left support.

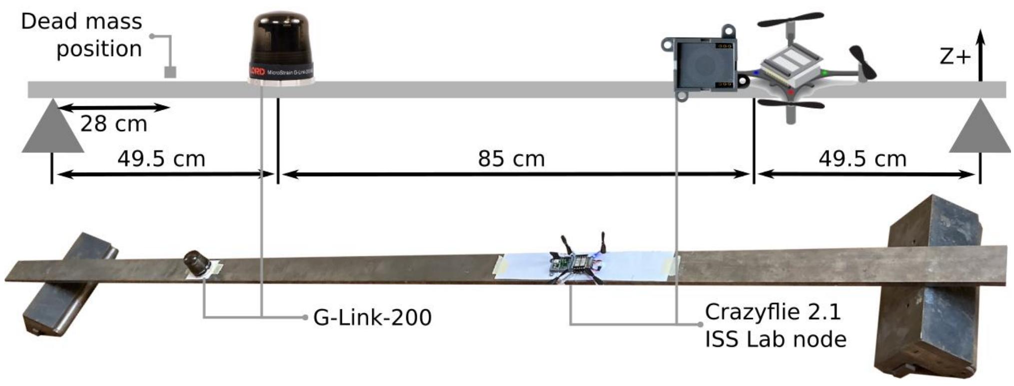

Fig. 3. Sensor installation plan.

Table 2. Sensor settings.

	Sampling Frequency	Full Scale Accelerometer	Full Scale Gyroscope
G-Link-200	256 Hz	2 G	---
ISS Lab node	208 Hz	2 G	125 deg/s
Crazyflie 2.1	142 Hz	3 G	1000 deg/s

3.2 Spectral analysis and damage detection

The level of spectral fitting between the three sensors has been analysed first by computation of the amplitude of the Power Spectral Density (PSD) of vertical accelerations. The latter have been considered over in-plane accelerations given the bending and exciting conditions which force the beam to vibrate along the z-axis. Spectra are depicted in Figure 4 focusing on the frequency band 0-70 Hz in which the three dominant modes of the structure are concentrated. As can be seen, three well-defined peaks appear at frequencies of 6.8 Hz, 26.3 Hz, and 58.3 Hz, with the spectral responses of the three systems clearly aligned. The only difference relates to the lower amplitude of the signal recorded by the drone, as testified by the fact that its profile is averagely 10 dB lower than the one retrieved by the other two platforms, the ISS Lab node being the most energetic.

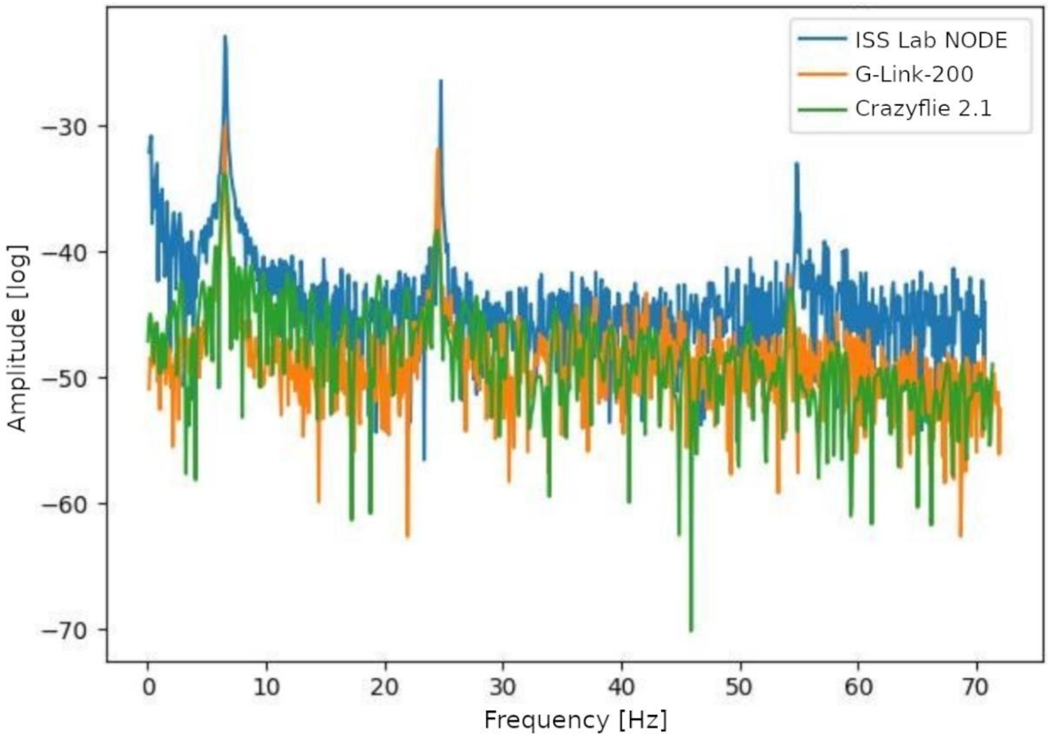

Fig. 4. Normalized acceleration spectra comparison along the Z-axis with a 1 kg load.

Then, the damage detection capability of the drone mounted IMU have been assessed by tracking the shifts in the frequency peak location of the three dominant modes above. Results have been collected in Figure 5, which reports a sharp reduction in all the modes even in presence of minor modifications (first mode) due to the lower mass. This proves the applicability of the Crazyflie internal IMU for the purpose of acceleration data sensing and characterisation beyond the mere navigation functionalities.

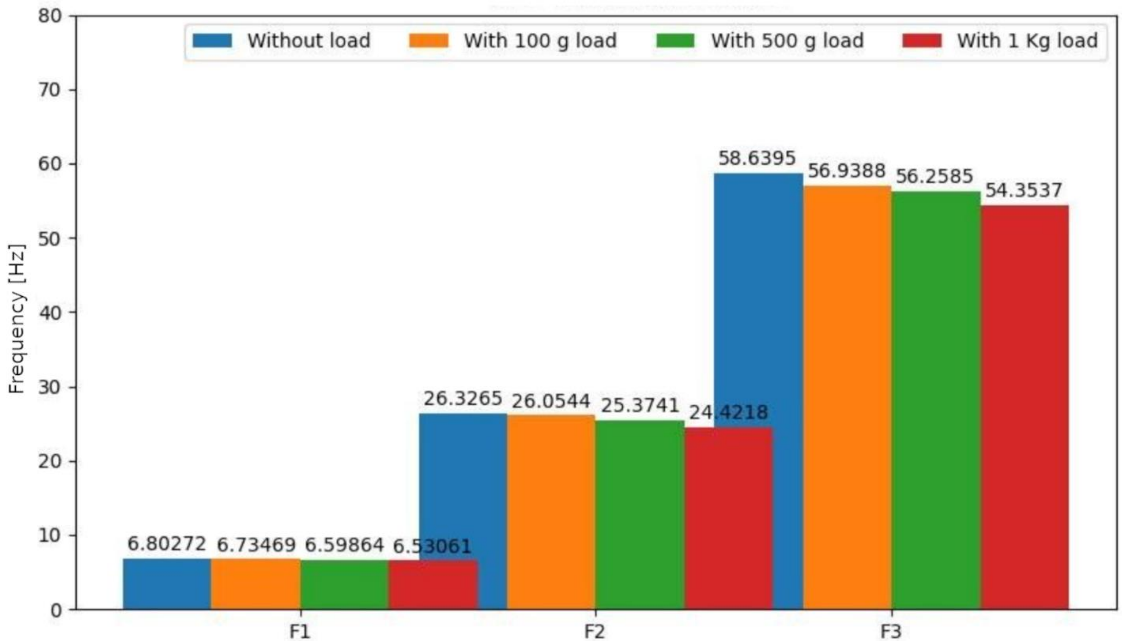

Fig. 5. Maximum acceleration frequencies for the drone across different payloads.

Conclusion

This study suggests that the nano-drone **"**Crazyflie 2.1**"** shows promise as a platform for vibration monitoring and potential for integration into WSN. The ability to detect even minor changes in structural dynamics has been demonstrated, with a maximum deviation of 1% compared to reference sensors. Further research could focus on optimizing the drone's performance and developing more accurate data acquisition methods, as well as exploring hardware expansions for improved battery management. Overall, the **"**Crazyflie 2.1**"** offers advantages in terms of flexibility and cost-effectiveness compared to traditional sensors.

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