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Sensor-based Behavior Analysis and Modeling for the Honeybee Superorganism: a Platform

Sebastien Druon

LIRMM

U. Montpellier - CNRS

Montpellier, France

sebastien.druon@umontpellier.fr

Baptiste Magnier

EuroMov Digital Health in Motion,

U. Montpellier, IMT Mines Ales,

Ales, France

baptiste.magnier@mines-ales.fr

Jonathan Bares

LMGC

U. Montpellier - CNRS

Montpellier, France

jonathan.bares@umontpellier.fr

Jean Triboulet

LIRMM

U. Nimes - U. Montpellier - CNRS

Montpellier, France

jean.triboulet@umontpellier.fr

Jean-Luc Oms

LIRMM

U. Montpellier - CNRS

Montpellier, France

jean-luc.oms@umontpellier.fr

Matthieu Rousset

IBMM

U. Montpellier - CNRS

Montpellier, France

matthieu.rousset@inserm.fr

Abstract—For the last twenty years, the mortality of honeybee colonies has been increasing and is now a major concern for biologists. There have been a number of hypotheses put forth in the literature, including hives' infestation with parasites like Varroa destructor, the appearance of new predators like Asian hornets (*Vespa Velutina*) or small hive beetles and widespread use of pesticides. In addition, climate and environmental changes are modifying the honeybee's interaction with its ecosystem. Last works suggest that this mortality could be due not to a single reason, but to a convergence of stress factors.

This article presents the development of an experimental platform dedicated to track the honeybee colony (*Apis mellifera*) health in parallel with the quantification of the main environmental stressors. Our main objective is to provide biologists with a paraphernalia that is primarily based on motion analyses with different sensors inside and outside the hive for the study of bees' behavior at both individual (the bee) as well as a colony (the superorganism) scales. The aim is to create a reference dataset of behaviors associated with environmental factors in both normal and stressful environments.

Index Terms—Honeybee, Instrumented hive, Multimodal sensing, Multimodal measurement, Movement, Platform.

I. INTRODUCTION

A. Motivations

For two decades, an alarming increase in honeybee colony mortality worldwide and a drop in honey production in our developed countries is described [13]. Bees, which suffer from the major global environmental changes and anthropogenic activities [3], are constantly subjected to several environmental stressors that act synergistically [11]. In a natural environment, numerous significant threats can emerge to bee colony resulting in a deterioration of their diet and the development of chronic diseases:

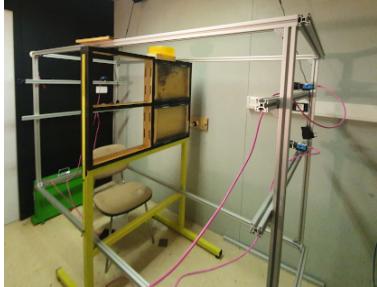
- alteration of their ancestral mutualism with plants,
- poisoning of their ecosystems with persistent pesticides,
- infestation by the disease-spreading Varroa mite,
- predation by the invasive Asian hornet in Western Europe.

The honeybee is an eusocial insect with a dual biological aspect. It can be observed as a single individual, or as a member of a global entity: the colony. Hence, this opens a parallel between a bee in a colony and a somatic cell in a multicellular organism. The colony is then considered as a superorganism where different cohorts of bees cooperate with each other to perform its vital functions as cells organize themselves into organs to perform a physiological function.

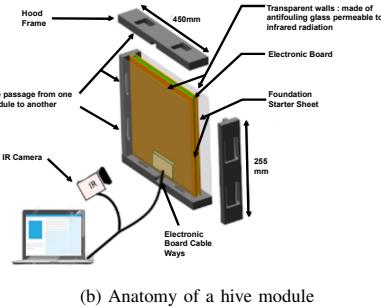
The global aim of our project is to decipher the mechanisms of actions leading to bee and colony disorders. On the one hand, it is based on the development of an instrumented hive dedicated to real-time monitoring of a colony life from its birth to its death. On the other hand, the purpose is to quantify the level of several stressors of the beehive in parallel. Our innovation lies in the implementation of dedicated methods and sensors to the systematic, automatic and non-invasive collection of multidimensional data. These measures range from the detection of individual behaviors (at the scale of each single bee) to the monitoring of sociometric and mechanistic parameters of the superorganism (at the hive scale). Correlation of all these data will allow to establish which stress levels and which combinations of stressors induce disruption of key physiological functions of the superorganism. Here is an overview of a description of the overall organization of the instrumented hive, as well as the main methods and sensors selected to analyze the various forms of movement, collective and individual, within the hive.

B. Previous works

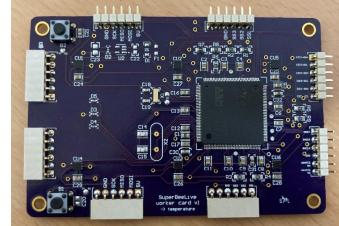
Honeybee hives have already been the subject of several studies and experimental setups; many contributions can be found in the literature such as for example in [5], [19] and [2]. In most of the studies, the monitoring consists in analyzing physical data recorded from various sensors located at specific points within the hive and even outside. In the Electronic Bee



(a) The hive is composed of upto 4 rectangular modules



(b) Anatomy of a hive module



(c) A homemade sensor board for temperature recording.

Fig. 1. Description of the experimental hive and its visual representation.

Hive project [25], for instance, the sensors are installed at designated locations inside the hive: temperature, humidity, carbon dioxide concentration and global weight of the hive are recorded. In [9], temperature, humidity, air quality and accelerations were chosen as indicators of the colony health and monitored throughout a cloud architecture.

Contrary to the previous ones, some works focus on data transmission (mostly in the case of wireless technologies), such as [20], [10], [16] and [21]. However, the sensors used are most often dedicated to environmental measurements (oxygen, carbon dioxide, pollutant levels, temperature, and humidity) because of the transmission restrictions due to available bandwidth. Data processing has also been studied, as in [4], where supervised machine learning is applied (on temperature, weather, apiary inspections and hive weight) to forecast the health status of the colony.

Obviously, some platforms including computer vision approaches have also been proposed. Indeed, cameras can be used to observe and quantify the population of bees, giving an insight on their biological status. One example of such an approach is [6], where an image recognition algorithm is used to measure the degree of infestation with Varroa mites. The in and out activities of honey bees being considered by biologists as a good indicator for the colony health, special attention have also been paid to monitor them as in [22] and [7]. In both studies, the entrance of the hive has been recorded. While the first relies on the use of a Kalman Filter, the latter proposes a monitoring system which relies on infrared (IR) vision and tags attached to the torso of each bee worker to identify them individually with an SVM (Support Vector Machine) classifier approach (see also [26]). In [27], the bees are observed in flight, on a close view of the entrance. Using a 50 fps (frames per seconds) acquisition video, the proposed method achieves a tracking of 99% of single flying bees based on blob segmentation. This work, which initially suffered from limitations due to the hypothesis of constant velocity flight has been further developed in [28], [29] and [18].

Usually, as stated by biologists, social interactions between the bees is a key to a better understanding of the superorganism status and health. In [15], digital video cameras were used to track such social interactions on a small quantity of bees (16 subjects) walking on a flat surface. In this work, the processing

is performed offline, on prerecorded videos, and consists in the localization and tracing of bee positions. Due to the limited working area, and the needed lab conditions, it is not suitable for the inside monitoring of the hive.

As illustrated in the aforementioned works, existing platforms for measuring and monitoring the biological observables of a bee colony are highly specialized in terms of sensor selection and methodology. While global parameters for long-term monitoring of the hive (temperature, humidity, *etc.*) are based on sensors, the recording of behaviors and movements at a finer scale typically requires video data. These videos present challenges in terms of transmission, storage, and real-time processing. Still, they represent a key tool to understand the behaviour of a beehive and a slight destabilisation of its balance. A promising method to evidence and characterize this behaviour consists in using active matter tools. This latter have shown to be very powerful to understand the collective behavior of other animals like a school of fish and flock of birds to name a few [23]. This approach, as it has been done for model active systems [24] would permit to evidence state variables characterizing the beehive state, whether it is healthy, perturbed or sick, and to monitor carefully its wellness.

By utilizing the platform presented in this article, we will be able to design a fully instrumental beehive as well as its associated computer and electronic architecture.

II. THE INSTRUMENTED HIVE

The measurement platform presented in this paper is an observation beehive that enables both physical measurements at specific points from sensors and video recording, along with the computer infrastructure for data storage and processing.

In this context, the beehive has been restructured to accommodate the installation of cameras and their manipulation without disturbing the colony. Instead of being cubic in shape and containing frames to support the honeycombs, our beehive, located in a dark room, is 2-dimensional, just like an observation hive. It consists of 4 (up to 6) rectangular modules assembled together with pathways for bees to move between them (Fig. 1(a)).

Each module has two visible faces where bees can settle on foundation starter sheets, protected by glass windows. Openings are located on the left, right, upper and lower sides of each module. They allow bees to access the other side of

the module, the neighboring modules and entrance/exit. Two IP (Internet Protocol) video cameras are associated with each module: one for each side of the module. These cameras have been chosen to work in the infrared portion of the spectrum in order to minimize the lighting perturbations of the honeybees. Indeed, they are blind to red and infrared wavelengths (see acquisitions in the next Section).

As outlined in Fig. 1(b), an electronic board can be installed between the two honeycomb sheets where the bees settle. This electronic board supports sensors. Their positions can be identified in the reference frame of the images captured by the video cameras and the board provides us with the possibility to get spatially sampled measurements (of temperature for example). The sensors installed on the prototype of electronic board include (Table II):

- temperature,
- relative humidity,
- dew point,
- structure vibrations,
- sounds.

The electronic board inserted inside each module consists in the assembly of up to 6 different sensor boards, each one carrying its sensors and a microcontroller (STM32 type). These boards are specialized depending on the type of sensors needed (vibration, temperature...) and are linked together by the connectors located on their edge (see Fig. 1(c)). Since a hive is not homogeneous, this modular architecture brings some flexibility to the systems. Indeed, different living zones have different purposes, and thus can require different sensing capabilities.

Furthermore, measures are also performed at the entrance of the hive. A pair of 60 fps color cameras are located in a close range of the landing board. They record both in and out activities of the bees, as well as predator activities (Asian hornet), as illustrated in Fig. 2.

In addition to these permanent devices, temporary measurement devices have been implemented in a shorter amount of time. For instance, we developed other specialized sensors: one that enables us to identify the pollen carried by foragers upon their return to the hive, and another one for ultrasound measurements of the honeycomb contents.

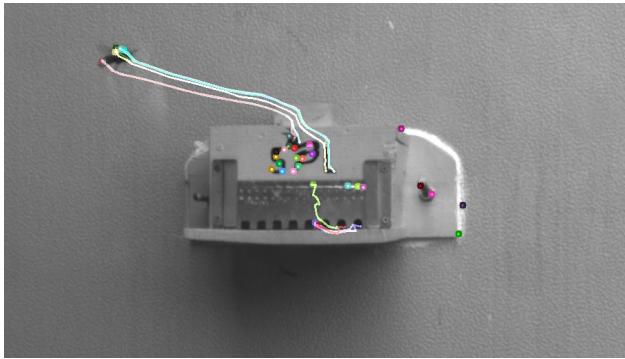


Fig. 2. Tracking of an Asian Hornet at the entrance of the hive.

TABLE I
STRUCTURE OF A GIGEVISION NETWORK PACKET

Header	Size (Bytes)	Notes
Preamble	8	
Ethernet header	14	Ethernet Time sync.
IP header	20	
UDP header	8	
GVSP header	8	
Payload	1450	
CRC	4	
Interframe GAP	12	Wait time (equiv. Bytes)
Total	1524	

A. Data recording and processing

As stated in the introduction, the main goal of this platform is not only to measure observable in real time but also to record them for subsequent analysis of the behaviors corresponding to specific events. This implies to focus on both storing large quantities of data and defining metadata to maintain a metrological approach. Within the scope of this project, we have chosen a centralized approach in which each sensor is treated as an autonomous device that transmits its own data to a single storage server. The required bandwidth necessitated the installation of a dedicated infrastructure (optical fiber network) as well as substantial storage capabilities. As a consequence, the platform is not mobile, unlike the work of [20] or [10].

All the considered sensors communicate with the central server through an Ethernet network using the UDP (User Datagram Protocol) network. In the case of sensors providing scalar data (temperature, humidity...) or vector data (vibrations, sounds), these data are automatically labeled with a header that includes a timestamp, the serial number of the card or sensor that performed the measurement, and location information (module position in the beehive and sensor position within the module). The objective is to maintain traceability of the measurements, enabling retroactive weighting of confidence in certain readings when a sensor proves to be faulty.

Regarding the cameras, two different models are utilized. The cameras capturing the motions of the bees inside the colony are Imaging Source 33GX174 cameras. They are IR sensitive, and their frames are sent uncompressed at a 1920×1200 resolution, MONO8 format, at 30 fps, using the GigeVision protocol. The camera pair located on the outside uses 33GX273 cameras, with similar characteristics but using a resolution of 1920×1200 , RGB24 video format, at 50fps.

Considering a network MTU (Maximum Transfer Unit) of 1500 Bytes, one packet transmitted by a camera can be decomposed as illustrated by table I. A total of 1524 Bytes are sent on the network for a payload of 1450 Bytes, leading to an overhead of 4.86% for the transmission of video streams.

Given the chosen resolution and pixel encoding, each video camera inside the hive requires an additional 0.58Gbps (Giga-Bits per seconds) bandwidth. The outside camera pair being based on higher framerate color cameras, it requires another 3Gbps bandwidth. This adds up to a total of 10Gbps to be transferred and stored at any time.

The network bandwidth problem has been addressed by

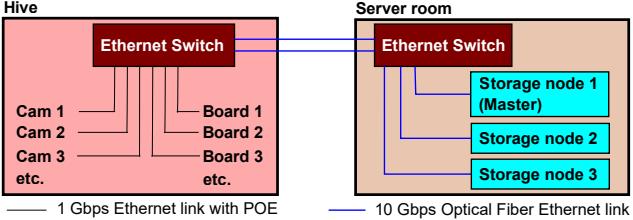


Fig. 3. Hive network architecture

installing a dedicated 10Gbps optical fiber between the hive and the main storage server. The architecture of the network is illustrated on Fig.3: on the hive building, a POE (Power Over Ethernet) switch has been installed. It provides each camera and electronic board with both 1Gbps connectivity and electrical power supply. The up-link to the server room is made with the 10Gbps dedicated optical fiber aforementioned.

In the server room, data storage is performed based on a BeeGfs¹ cluster file system. It is a distributed and open source file system: the storage is distributed transparently by software between disk servers (the nodes) through a 10Gbps optical fiber switch. This storage solution is usually used in HPC (High Performance Computation) systems for scratch file-systems. This performance is compatible with our needs for high bandwidth storage and offers the possibility of extending our storage space by adding new nodes to the cluster.

The master node of this cluster is in charge of network basic services (DHCP, DNS, Firewalling, etc.) and of running the acquisition daemon services for data collection and storage, both from cameras and from electronic boards. We run data processing algorithms on the slave nodes, since the storage operations are not CPU intensive, or from other workstations. The whole storage space (88 TB at the time of writing) represents 14 full days of storage with the current configuration of the hive because the bee colony is still young and not all the modules are used².

B. Software tools

This experimental setup aims not only at recording and referencing the activities of the honeybees for researchers, but also at centralizing the results and annotations generated by the community. To achieve this goal, two software tools have been developed for the users of this data. The first one consists of a metadata management format and an annotation format. This JavaScript library allows you to annotate directed oriented bounded boxes³. Furthermore, since it uses the file system, it needs to be hosted on a server, whether local or remote.

The file format we developed for this hive platform is based on the AVI file format. One file is generated every minute for each module and is a container embedding several tracks. One given track has corresponding metadata and can be:

- **Video streams:** for video camera sensors,
- **Sound streams:** for audio and vibration data streams,

- **Data streams:** for annotations and data with lower time granularity such as temperature, humidity, dew point, etc.

Using a unified file format is a guarantee to avoid any risk of data desynchronization from different sensors tied to the hive. It also allows for the incorporation of annotations made on this data, like specifying a behaviour of a bee at a certain position at a certain time. This will enable tasks such as training a convolutional neural network.

Additionally, a software player reads these files and adds annotations in a simple and intuitive manner. This software allows accessing the data on the storage server, enables querying capabilities, and facilitates working on the recordings by adding annotations associated with tags for differentiation.

As mentioned above, the instrumented beehive also serves as a platform for new sensor designs or installing temporary experimental devices that complement the permanent setup. So far, this has been the case for two devices: a pollen analyzer located in the access corridor to the beehive and an ultrasound system for measuring the content of the honeycomb cells.

III. PRELIMINARY RESULTS

The experimental setup and the various tools presented in this work have recently been completed, allowing us to start exploring different avenues for data analysis. In this Section, we will highlight some preliminary results to illustrate the collaborations currently in place around this project, as well as the initial findings.

A. Movement and tracking

To track individual bees inside the beehive, we have chosen to test two approaches. (i) The first approach is based on finding a visual feature vector that can distinguish one single bee in the different images obtained from our camera video streams. We tested it on a few bee workers inside the hive. This is a classical approach, relying on techniques like Scale Invariant Feature Tracking (SIFT) commonly found in the state-of-the-art literature [17]. While this method yields good results, it is not very robust to occlusion and tends to drift when tracking over a long period. Our implementation, based

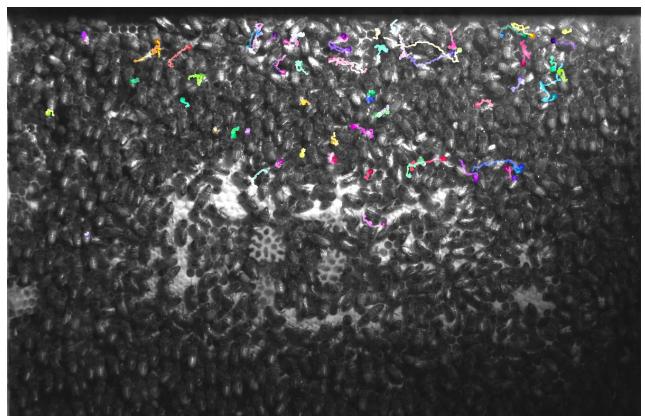


Fig. 4. Tracking of a few individuals inside the hive (IR camera).

¹<https://www.beevfs.io/c/>

²<https://videos.superbeelive.net>

³<https://github.com/BenoitFaureIMT/DOBBA>

on OpenCV, has confirmed the limitations of this method (see Fig. 4 and 5 –left–) on long term tracking. We therefore reserve these approaches for the tracking of individual difficult to differentiate from others. (ii) The second approach we explored is based on Convolutional Neural Networks (CNN), often referred to as “Deep Learning”. Specifically, we used the YOLOv5 algorithm [14], a network dedicated to detection tasks. An application to Queen Bee detection and tracking is illustrated in Fig. 5 (right).

In our case, the size of the images makes it challenging to directly use CNN on the entire pixel space due to the number of inputs it would require (1920×1080) and the size of the network to handle. Therefore, our detector is based on a smaller-sized network, operating on a sub-image of size 100×100 . Multiple sub-images are extracted from each video frame, and the network helps us locate the queen bee and provides a tracking certainty score.

This work has led to a Python implementation that performs well on a camera stream. The ongoing work involves porting it to C to integrate it into the existing tool library for the project. An extension of this development could involve enhancing its robustness to occlusions by providing the last known position of the queen bee as an input or limiting the research on the sub-images around the last known position. Others type of specifics bees could be tracked by these approaches like for example foragers, which can be distinguished from other bees by the pollen balls attached to their legs.

Elsewhere, we have also explored the detection of behaviors based on a frequency description of the image using Fast Fourier Transform (FFT). Indeed, some specific behaviors exhibit periodic characteristics, such as the waggle dances made by bees (see [26]). This behaviour stands out when working on the frequency space, and can indeed be easily detected, as illustrated in Fig. 6.

B. Vibrations

As stated in [12], [8] and [1], bees are capable of detecting various types of vibrations:

- Airborne vibrations are detected by the Johnston’s organ located in a part of the antenna. This organ appears to interpret signals between 250 and 300 Hz (Hertz). However, it does not distinguish between continuous vibrations and pulsed vibrations.
- Vibrations in materials are likely detected by several organs/structures within the bee’s body. As an example,

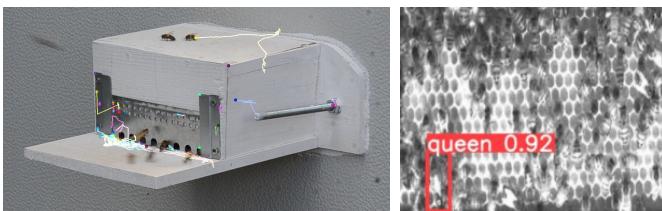


Fig. 5. Detection and tracking outside and inside the hive: (left) Tracking of a few individuals on hive entrance, (right) CNN results on Queen Tracking.

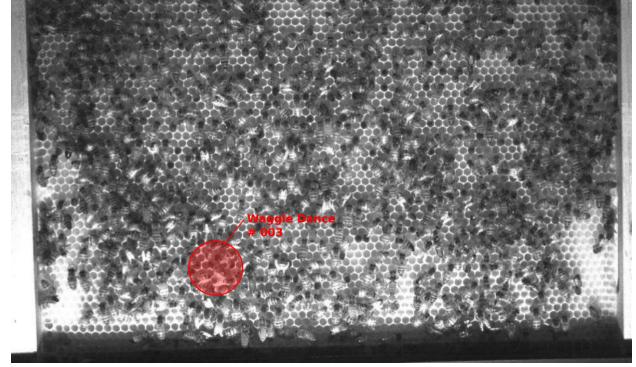


Fig. 6. FFT based Waggle dance detection

the subgenual organ located in the leg is sensitive to vibrations between 200 and 1000 Hz.

Several behaviors in the bee colony involve vibrations. Some examples include:

- Waggle dance, which produces airborne vibrations from wing beats between 250–300 Hz, as well as airborne vibrations around 15 Hz (10 to 30 Hz) caused by oscillatory movements of the abdomen.
- Ventilation, which involves wing beats at around 300 Hz.
- Flight produces airborne vibrations around 250 Hz.
- The “phase reversal phenomenon” produces vibrations in the range of 200 to 1000 Hz within the framework.
- The DVAV (Discontinuous Vibration-Amplitude Vibration), which consists of small rhythmic movements of the abdomen on the comb, produces vibrations.

Airborne vibrations are of course out of this scope of this project, but the detection of DVAV and behaviours such as waggle dances and ventilation can be related to observable patterns in the data recorded by cameras and can help with their detection. A simple vibration detection system, displayed on Fig. 7, has been proposed. It is based on a piezoelectric sensor which will generate a very small signal when the comb structure is subject to vibrations, in a way very similar to how audio microphones work. This tiny signal is fed to an amplifier stage and to an ADC (Analog to Digital Converter).

As can be seen on the vibration signal captured inside the hive after the amplification stage (see Fig. 8), amplitude is now above a few volts, allowing for sampling and recording.

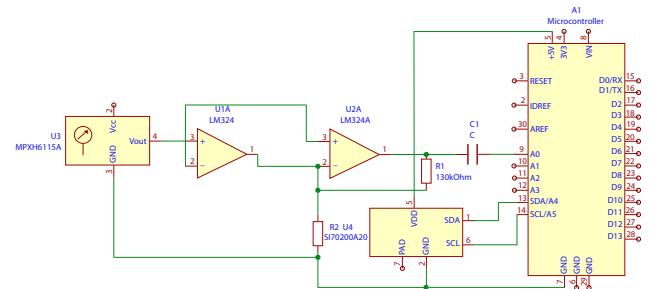


Fig. 7. Sensor and signal amplification stage



Fig. 8. Measured vibration signal example (volts).

IV. CONCLUSION AND PERSPECTIVES

Beside chemical communications, different classes of motion compose the basis of the bee colony's communication. These classes go from the individual scale to the superorganism scale. Our work is a first tentative to detect in parallel and integrate most of these motions and their results to gain a global view of the superorganism's organization and health. Vibration sensors produced by an individual bee or a group of bees and which range from 10Hz to 1KHz are detected with a set of sensors located on the electronic card and attached to wood or directly on wax. Microphones enhance these tools dedicated to the detection of vibrations. In addition, dances and stereotypical motions of individual bees corresponding to specific developmental tasks are detected using camera lying in front of the hive. Global analysis of the pictures obtained allows to capture global motions of numerous bees on the same frame. Finally, two additional cameras in front of the hive enable to monitor and quantify predation (Asian hornet). The sensor clustering proposed in this instrumented hive, recapitulated in Table II, is unprecedented to our knowledges.

From its conception this connected object was designed with a double purpose. The first is an educational objective where the challenge is to train our students from the School of Mines and the University of Montpellier to learn how to adapt published algorithms to real-time data. The second is to propose to the computer vision community specialized in movement analysis to think new modes of analysis to extract movements within the population of individuals in constant dynamic. As such, our project is sufficiently flexible so that our instrumentation can be adapted to their specific needs.

TABLE II
SENSORS INSTALLED ON THE HIVE (4 MODULES CONFIGURATION)

Sensor type	Reference	Qty	Localization
IR Cameras	33GX174	8	2 per module
Color Cameras	33GX273	2	Hive entrance
Temperature	TSYSO1	512	128 per module
Dew point	SI7021	8	1 measure per module
Relative Humidity	SHT3x-DIS	4	1 per module
Sound	DMM-4326-T-R	24	6 per module
Vibrations	MPXH6115A	8	2 per module

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