École Polytechnique Fédérale de Lausanne

MICRO-581

Robotics Project 2

Mechanical and electronic subsystem for an integrated observation system of in-hive honeybee traffic

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1 Introduction

Honey bees (*Apis mellifera*) are key to ensure the wellness of our terrestrial ecosystem. Besides producing honey, they contribute to pollination, which ensures the success of reproduction in plants. However, due to many causes [1, 2], the number of pollinators, including bees, is declining. Therefore, it is essential to come with solutions to preserve the honey bees' survival. In that context, a European project called Hiveopolis aims at creating a "modern society of honey bee colonies". Their most ambitious goal is to integrate a dancing robot within the hive to direct forager bees to precise nectar and pollen locations. Another goal of Hiveopolis is to design a modern beehive equipped with a various number of sensors. MOBOTS from EPFL is part of Hiveopolis and helps in growing the project. We, Tristan Bonato and Victor Casas, under the supervision of MOBOTS designed a Flow Monitoring device integrated inside the hive. The objective was to measure the bees' traffic within the beehive. Tristan Bonato and Victor Casas were responsible for the electronics and mechanical part respectively. At the early stages of the project, we validated the mechanical structure, sensor type, and electrical architecture. After designing and manufacturing the PCBs and mechanical structures, the module was assembled and tested inside a modified hive, which had particularly a camera that could confirm the success of our device.

2 Related work

Past works on monitoring systems have been investigated. To increase the efficiency of beekeepers and to study bees' behaviours, numerous studies have been focusing on designing monitoring devices that record information about humidity, temperature, CO2, weight and sound [3, 4, 5]. Moreover, some studies were dedicated to analyzing the flow of bees at the entrance of hives. These researches mainly differ from each other by the type of sensor used to count the bees which are: imaging systems [6, 7] and infrared sensors [8, 9]. Moreover, the previous steps of this current semester project were handled by Claire Meyer [10] and tried various types of sensor and concluded in the end that the infrared sensor was certainly the most valuable in terms of reliability and low power consumption.

Our module takes inspiration from some of the studies presented above. However, our main contribution comes from the fact that we integrated our module inside the hive, which is revolutionary in studying the bees' flow within a hive.

3 Flow monitoring module: Requirements and constraints

3.1 Introducing the module

Here we introduce the idea of our module to monitor the bee's traffic inside the hive. Firstly, the structure of the channels (figure 1-A) is made of holes through which the bees will go through. Moreover, each channel includes two sensors in order to sense whether the bee is entering or leaving the device (Figure 1-B). Finally, a structure protects the electric components that are around the structure of the channels (Figure 1-C).

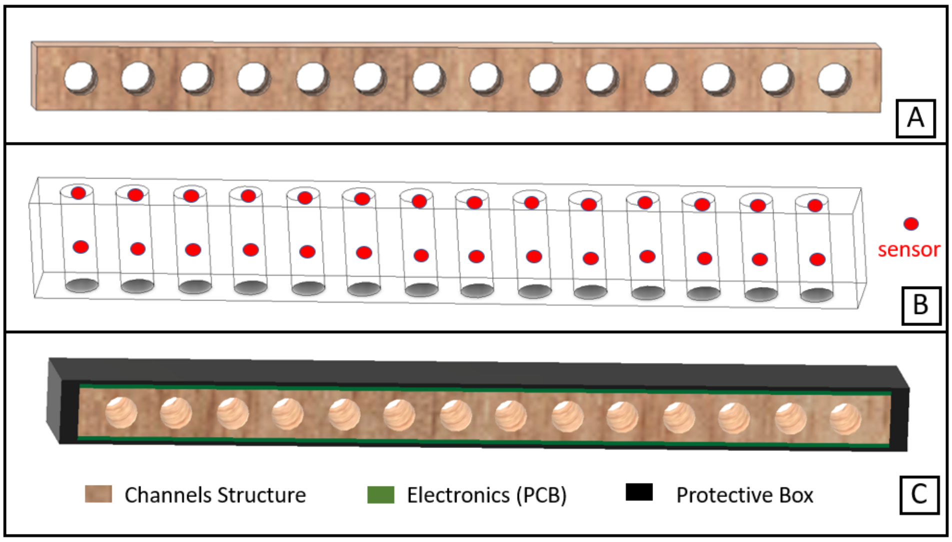


Figure 1 – *(A): Channels structure where the bees cross through the holes (B): Each channel is equipped with two sensors (C): The electronic components that are around the channels' structure are enclosed with a protective box.*

3.2 Mechanical requirements and constraints

Module dimensioning: The module has to be implemented in a hive, in which the frames can be disposed next to each other (parallel), like in a box hive, or on top of each other (planar), like an observation hive. The first configuration (parallel) is shown in a Hiveopolis hive of EPFL (Figure 2-A top). At the bottom of Figure 2-A, we propose to add 6 modules around the frame in order to detect if a bee is going from one frame to another. The second configuration (planar) can bee seen in an observation hive at the Artificial Life Lab, in Graz, Austria (figure 2 -B top). At the bottom of figure 2-B, we propose to add two modules between the frames.

These examples demonstrate that the dimensions of the frame constrain the module's dimensions. Figure 2-C shows that the short and long edge of the frame is 209 and 419 millimeters, respectively. Thus, the width W of the module has to be of maximum of 209 millimeters. It is then possible to have one module on the short edge of the frame and two modules on the long edge of the frame. In addition, the thickness of the frame is 25 millimeters; hence, the deepness D of the module has to be 25 millimeters. Finally, the height h of the module is not directly constrained. However, the larger the module is, the more space the bees could take. Therefore, one goal is to minimise the height of the module, subject to the functional objectives.

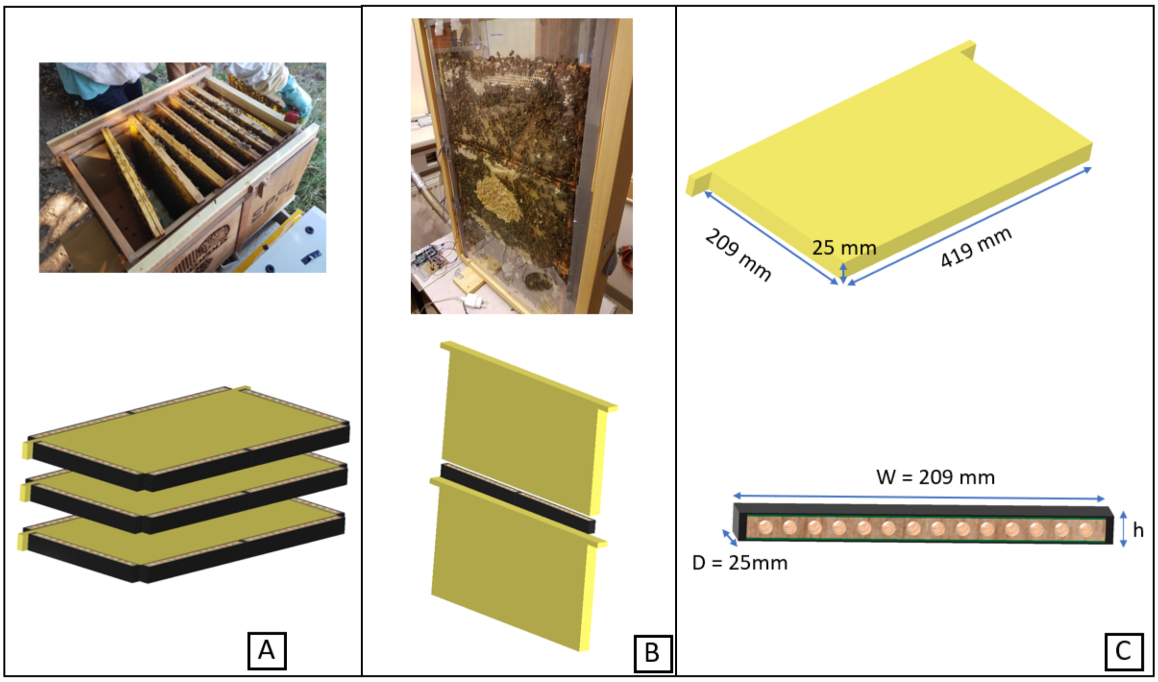


Figure 2 – *Location constraints, for the following images, the black part is our modules, and the yellow one is the frame (A): This image shows where we put our modules with parallel frames configuration. We can put six modules per frame all around (B): This image shows where we put our modules with planar frames configuration. We can put two modules between two frames (C): This image shows the details of the Dimension of the module. We are constraint in* $W = 209$ *and* $D = 25$ *mm but not in h. Moreover, we should keep the space around the channel small as possible.*

Channels diameter: The first unknown that came to our mind while designing the channels was their diameter. On the one hand, a small channel can prevent the bees from crossing, and the colony may die. On the other hand, a big channel may seduce the bees to fill the channels with resin. By looking at previous studies and experiments [9, 6, 10], we decided that the diameter of the channel should be 8 millimeters. All the inhabitants (workers, drones and queen) can pass through the channel with this size. We know that the queen can pass because the beekeepers use "queen extruder" to isolate the queen. Furthermore, the size of the slot is around 4.1 mm. [11]

Materials: Each material used in the module has to be bee-friendly, which wood and some plastics are. Wood can be worked with a CNC machine and thermo-plastics with 3D printing at SKIL (EPFL). The wood should be less invasive to bees, but its manufacturing (CNC) is less precise (1 millimeter) than printed plastics(0.1-0.6 millimeters). To compromise precision and bio-compatibility, we bought and tested a 3D printing PLA filament reinforced with wood fibers from Extrudr. However, its nozzle and layer thickness are bigger than the filaments already at our disposal at SKIL (e.g., ABS, PLA, PETG) and, thus, less precise. At SKIL, PETG is more attractive to print than ABS and PLA since its 3D printing machine is more reliable, which is essential when printing a piece taking 10 hours.

To conclude, the material we chose to manufacture our mechanical structure depended on the desired precision. If the accuracy desired was about 1 millimeter CNC machining fits well to manufacture a module made of wood. 3D printing wood filament could fit well for precision around 0.6 millimeters, but for maximal accuracy (around 0.1 mm) conventional plastics filament suited better. For example, in the early stages of the project, we used the CNC machine to manufacture wood channels that went at the hive entrance. At last, the final modules were made of PETG with the 3D printing machine since the size of the electronic components required great precision (0.2 millimeters). We are afraid that if we leave too much space next to the electronics, it will disturb the bees.

3.3 Electronic requirements and constraints

The project imposed many constraints on electronics. The most important one is to be bio-compatible. The components and the technology used have to avoid being invasive as far as possible: not harming the bees and not affecting their behaviours (e.g., having a low thermal footprint). The electronic design has to fit in the hive; the space is tight and dark. The consumption needs to be as low as possible for saving energy on the intelligent hive. Finally, the design and the components need to be robust. The detection mechanism has to measure precisely the traffic. In the hive, there is dust; thus, the quality of the sensors is likely to decrease over time.

4 First round prototyping

4.1 Channel morphology

While designing the channels, J. Abbott inspired us with the study he made on V-shaped channels [12]. Indeed, he proved that the bees chose wider channels over smaller ones. Moreover, that idea appeals to us because we wanted to avoid a bee entering a channel that does not collide with a bee exiting the same channel. So another dimension to the project is to compare two types of channels. Firstly, constant shaped channels (Figure 3-A) where each channel has the same dimension at its entrance and exit. Secondly, V-shaped channels (Figure 3-B) where the channel's dimension goes from 8 $\times$ 14 millimeters to 8 $\times$ 8 millimeters. Our V-shaped channel design alternates between broader and narrower entrances, which keeps the distance a bee has to move before finding a wide entrance small. With the constraints of the side of channels, we can have a total of 14 channels per modules.

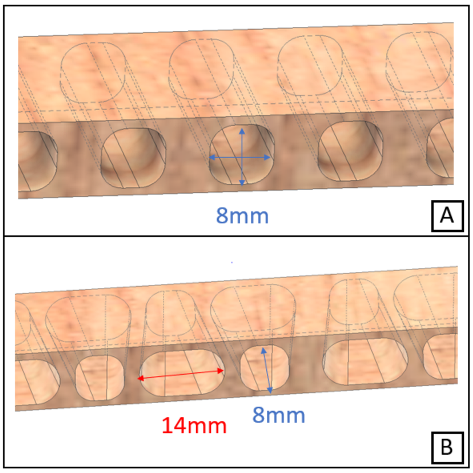


Figure 3 – *(A): 8 millimeters bi-directional channels (B): V-shape mono-directional channels*

We tried both configurations (Constant shaped and V-shaped) at the entrance of a hive. The channel structure was set in front of the entrance and the flow of the bees was recorded using a GoPro camera (Figure 4-A) for a duration of 60 minutes. The modules were left at the entrance for 30 minutes each and the recording analysed for the last 5 minutes. This procedure allowed the bees some time to become familiar with the modification to their hive. Later, the recorded videos were manually analysed to account for the number of insects that crossed the module, and to which direction.

The results of each type of structure are shown in Figure 4 (B and C). The constant shaped channels had approximately the same number of bees going in (38 bees) and going out (40 bees), during the period of 5 min. Then, concerning the V-shaped channels, the bees preferred to take the wider holes than the smaller holes and mostly when they were entering the hive (maybe because of foraging honey bees' attraction to light). In addition, the flow was bigger for the V-shaped structure. To conclude, the idea of using V-shaped channels was positive. Since the lighting conditions are not the same at the entrance and within the the hive, the increase in traffic with V-shaped holes may not hold inside the hive.

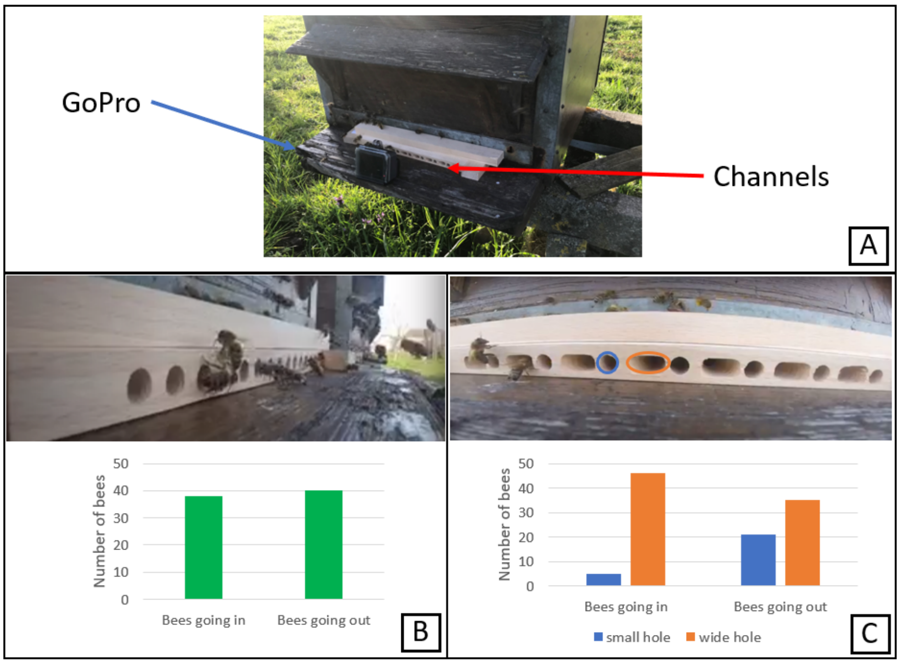


Figure 4 – *Testing the channels design at the entrance of a hive (A): Setup. The channels were placed in front of the entry and the a Go pro was taking movies of the experiment. (B): Constant shaped channels result. We recorded 38 bees going inside and 40 outside (C): V-shaped channels result. We recorded 59 bees going inside and 55 outside. On the plot, The wider side is with respect to the side they start from. We can clearly see that the bees prefer the wide entry.*

4.2 Validating sensor type and configuration

Inspired by the work of [10] and [13], the direction to take is the detection of bee traffic using infrared light. The device could be small, robust and with low power consumption. Furthermore, it is entirely bio-compatible ("bee-friendly"). The bees are sensitive to wavelengths smaller than 650 nm. Figure 5 shows representative sensitivity of the three photoreceptors of honeybees and bumblebees ([11], and [14]). The infrared light has a range between (λ = 700 nm to 1 mm). Thus, with an infrared device, we do not disturb the bees.

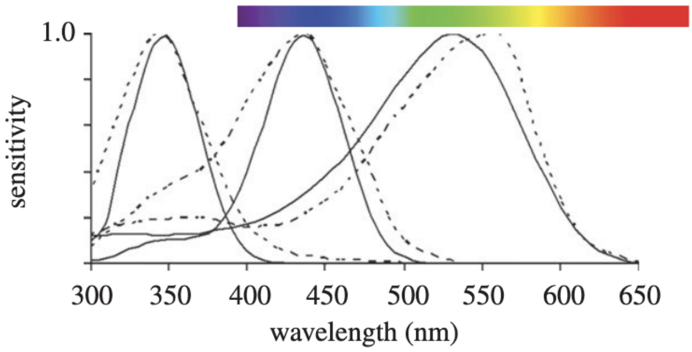


Figure 5 – *The plot shows representative sensitivity of the three photoreceptors of honeybees(dotted line) and bumblebees (solid lined). The color bar above shows human vision. Extracted from Dyer et al [12]. We can observe honeybee activity within their hives using light above 650-700 nm without disturbing their behaviours.*

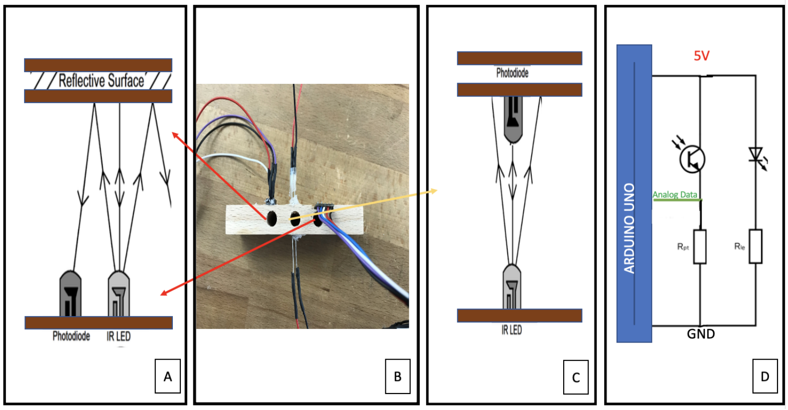


Figure 6 – *Testing two Infrared device configuration (A): Opto-reflective configuration. (B): Mechanical structure (C): Barrier configuration (D) Electric schema for infrared components. The analog data is collect under the phototransistor. If receivers full illuminated it implied the maximum current. The current create a drop; the signal is low.*

The infrared detection is composed of an emitter and a receiver. The emitter sends an infrared signal, and the photo receiver converts the optical signal to the electrical domain. Two infrared detection configurations were approached: reflective mode and barrier mode. The first configuration uses the principle of reflectivity. The emitters and receivers are in the same plane (Figure 6 - A). The light arriving in the receivers increases when a bee is passing. In the barrier configuration, the emitter is positioned in front of the receiver (Figure 6 - C). When the bee is passing through, the light arriving on the receiver is partially or entirely cut. In both modes, based on the variation of light arriving at the receivers, we are able to detect if bees are on the sensor or not.

We used three components to test these two configurations: two opto-reflective sensors (Vishay CNY70 and ON QRE113) for the reflective mode and one pair of led/phototransistor (Vishay TSHA440 and OSRAM SFH309) for the barrier mode. We disposed of the components in a structure with channels (Figure 6-B). After made all the electronic setup, we collected dead bees from a hive vicinity and passed them through the channels to observe the signal levels. We thought it was essential to test with real (dead) bees because our devices are sensitive to albedo, and we want to have data close as possible to reality.

To collect data, we have a resistor after the phototransistor (Figure 6 - D). When the phototransistor has whole light, it let it pass much current; the drop on the resistor creates a low signal.

Table 1 – Comparing the signal intensity of the two photo-emitter/receiver configurations

Configuration	Signal without bee	Signal with bee
Barrier	100	500
Reflective	35	50

the circuit was able to detect if a the dead bee was passing on the channel for each configuration. But, even if the opto-reflective is interesting because of the one plane geometry, it is not enough robust. The Table 3 shows the difference of the signal intensity with or without bee. The difference with or without bee for the reflective mode is really small. Thus, in the hive, the dust can decrease drastically the efficacy of the sensors. For this reason, we decided to go on with a pair of infrared/phototransitor disposed on barrier configuration.

4.3 Electrical architecture validation

4.3.1 Electronic strategy

Before talking about the strategy and electrical architecture, let us do a quick reminder. Each complete structure has 14 channels, with two infrared sensors per channel (Figure 1). To preserve energy, we choose to light it up only one channel per time. For this, we scan each channel one by one; we light it up the two infrared led in the channel. The first parameter to define is the switching frequency between channel. Dr. Pickard [15] measured the speed of bees, through a channel. He found that the median speed is 45 mm/s, and the maximum speed is 60 mm/s. The length of a bee is in a range of 10–17 mm [11]. In order to estimate the sampling frequency of our system in order to not miss any passing bees, let's take the worst case: a fast and small bee (10 mm long walking at 60 mm/s). To be able to detect the bee, we need a frequency bigger than 6 Hz (see Eqn 3). However, we have 14 channels; thus, the minimum scan frequency is equal to 98 Hz (14 channels × 7 Hz).

$$Frequency_{min} = \frac{Velocity_{max}}{Size_{min}} = \frac{60mm/s}{10mm} < 7Hz \tag{1}$$

$$Frequency_{min} * 14 < 98HZ \tag{2}$$

$$Frequency_{final} = Frequency_{min} * 2.5 < 250Hz \tag{3}$$

Finally, we choose safety; we take 250 Hz. That lets each channel light up 4 ms one by one for a total scanning time for each module equal to 56 ms. With this high frequency, we suppose that we will see if two bee are closely following each other.

Let's look Figure 7 - A to understand how the scanning is done. We have two different phases; active phase and dead phase. Each phase last 4 ms for a total time of scanning equal to 56 ms. During the active phase, we light up the LED 1 ms, collect analogs data, and the shut for 3 ms; for a total of 4 ms. Thus, instead of active the every LED for 56 ms we active one LED for 14 ms. We decrease the consumption of the LED on the scanning time by a factor 14*4 = 56.

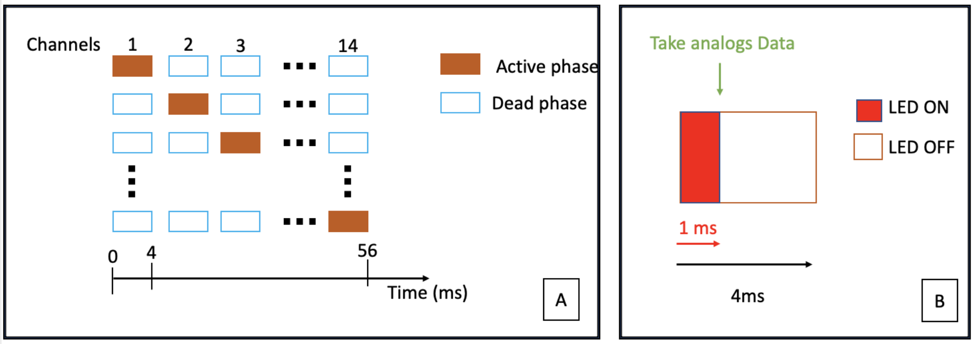


Figure 7 – *(A):Scanning diagram. We have two phases; active and dead phases. Only one channel is on active phase per time. The active phase last 4 ms for a total scanning time equal to 56 ms. (B) The image shows a the active phase in detail. We light up the led for 1 ms, collect analogs data from phototransistors and turn off the led for the end of the phase.*

Contrary to the LEDs, we decided to let the receivers to be active all the time. The current when the phototransistor is fully illuminated is tiny ($I_{max} \sim 1$ mA). The loss of energy is negligible, and it simplifies the electronic architecture.

4.3.2 Implementation of the strategy

To implement the strategy we use analog multiplexers. The multiplexer (Mux) is a device that selects between several input signals and forwards the selected input to a single output line. We choose a particular Mux, ADG1606BRUZ, that is fast, with low internal resistance and with analog or digital input/output. Furthermore, this Mux can be used as a multiplexer and a demultiplexer: All the lines are usable in both directions. The channel selection is controlled with four digital lines plus one for the enable.

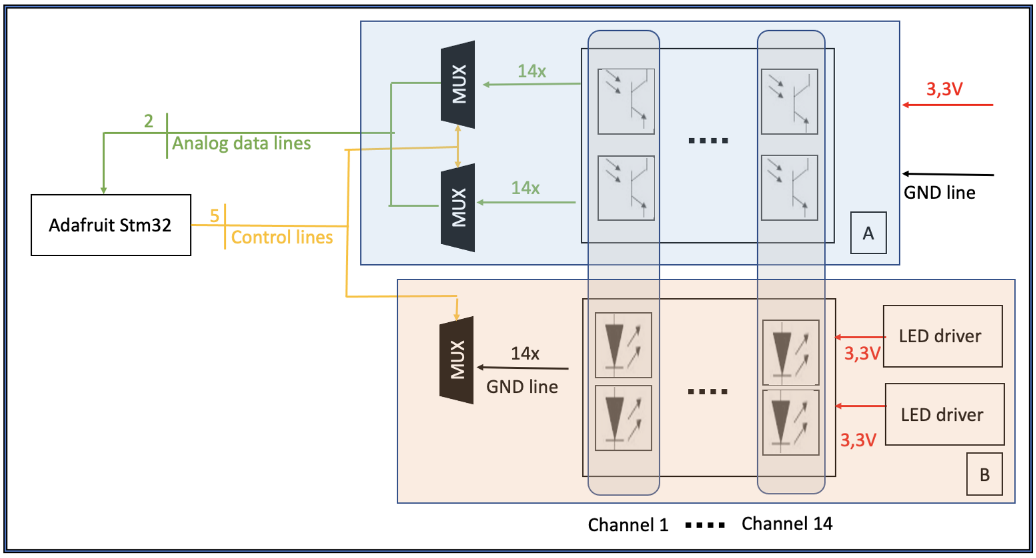


Figure 8 – *This image shows the block diagram of our system. The system is controlled by Adafruit stm32 mictrocontroller. It sends 5 digital control lines to active on channel. It receives as well two analog data at 250 Hz. (A) Block of the receivers: This block is always connect to power supply. On each channel they have two phototransistors. The two Muxs take data from each phototransistors and send it to the mictrocontroller. (B) Block diagram of the emitters. Here we use only one Mux. When the channel is chosen, both LEDs are connect to the ground. On the other side each led (one for each side of the module) is connected independently to a led driver. The goal of the led driver is to deliver at maximum 10 mA.*

IR light emitters Let us focus on the light emitters' architecture (Figure8 - B). We have two groups of LED, each one on the side of the channel. Each group is connected to 3,3V regulated power rails with a LED current driver in between to deliver at maximum 10 mA. Then, the two LEDs from the same channel are connected to one of the 14 inputs of the multiplexer. The output the Mux is connect to the ground. of With this strategy, we can light up the two LEDs sitting on one channel depending on the control lines.

IR light receivers The phototransistor circuit is a bit different (Figure8 - A). We have two groups of the phototransistor, each one on the side of the channel. All the phototransistor are connected to +3,3V on one emitter side and ground with a 10 kΩ resistor on the other collector side. The resistor is here to do a potential drop. Each point between the resistor and the phototransistor is connected independently to the multiplexer. The configuration phototransistor, resistance and analog line is the same as Figure6 - D. We underline that for this system we have two Muxs, because we need to collect two data per channel. The phototransistors from the same group are all connected on the same multiplexer. And each multiplexer has its analog output connected to a microcontroller. With this strategy, the control lines select the two phototransistors in channel c, and we can thus measure their voltages.

4.3.3 Test of the strategy

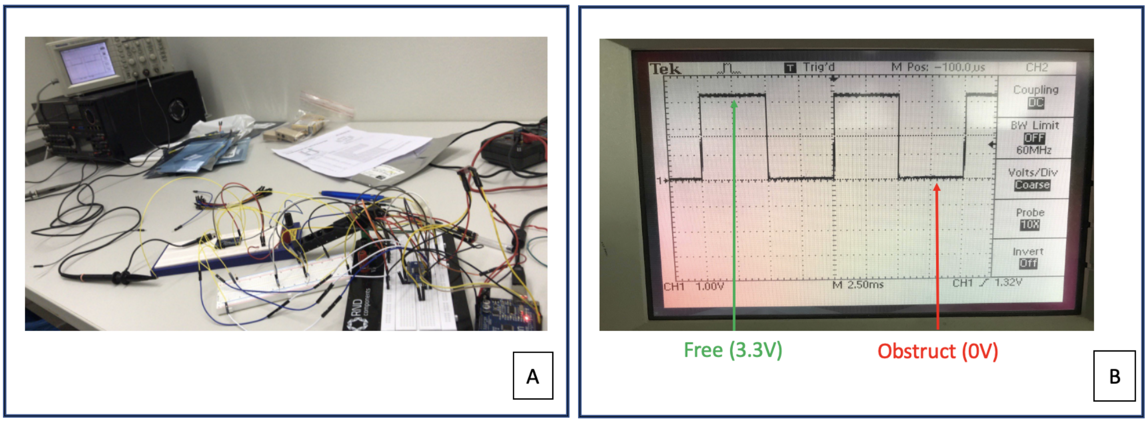


Figure 9 – *Testing all devices and strategy. Two channels are test alternatively during 5 ms with the scanning procedure.(A): Electronic configuration. We test the different compontnes with wire and a bread board. We use an osciloscope tu analyze the signal (B): Oscilloscope signal between two channels. When nothing obstruct (Free) the channel we read a signal equal to 3.3V, when we obstruct with a dead bee, the signal drop to 0V.*

Now that we have the strategy, we need to find appropriate components and test the architecture. We ordered several LEDs, phototransistors, LED current drivers and multiplexers. We used an Arduino UNO to control the Mux address lines. And, we checked the analogs waveforms (that shows if something is in the channel or not) with an oscilloscope (Tektronics tdx 210). The Figure 9 shows the configuration and an oscilloscope signal. Then, we passed dead bees through the channel to test the detection.

We tested each combination and selected the component with the best compatibility, smallest consumption and most robust. The final chosen components are on the Table 2

Table 2 – Components chosen with characteristic

Function	**Part**	**Characteristic**
LED	VSMY1940X01	λ_p = 940 nm emitting diode, 10 mA consumption
Phototransistor	IN-S126BTNPT	λ_p = 940 nm max sensibility, max current 1 mA
Analog multiplexer	ADG1606BRUZ	16:1 multiplexer (analog or digital)
Current driver	BCR401UE6327HTSA1	Deliver precisely 10 mA (+/- 2%)

The maximum functional frequency tested is 714 Hz, with each channel light up during 1 ms. Thus, our system can perfectly works with 250 Hz.

5 Final module

5.1 PCB design and manufacturing

We used Altium Designer 21.4 to design the PCBs. We design two different PCBs; one for the emitter system and one for the receiver system. We used a four-layer FR-4 PCB for both PCBs with dimensions equal to 0.8×202.0×25.0 mm (±10% for the thickness). We want something as thin as possible but robust enough to prevent damage during manipulation. We did not choose four layer configuration to allow extra room for easier routing; we want to improve the signal integrity. Thus, two fully dedicated ground layers (L2 and L3) offers betters signal integrity comparing to routed ground [16]. On the Figure 11, we can see the tracks and the 3D views from Altium. The tracks in red are in the first layer (L1), and the tracks in blue are in the last layer (L4).

The schematics that we used to do the PCBs are the ones exposed in Figure10. A point to underline, is that we add one extra LED on the other side of the PCB to synchronize data with infrared Camera (Figure 11.E and Figure 10 - B) The schematic is the first step to design a PCB in Altium. Then you need to have the foot print and the 3d models of all components and place them on the PCB in the desired disposition. Finally, you need to connect components with track on different layer.

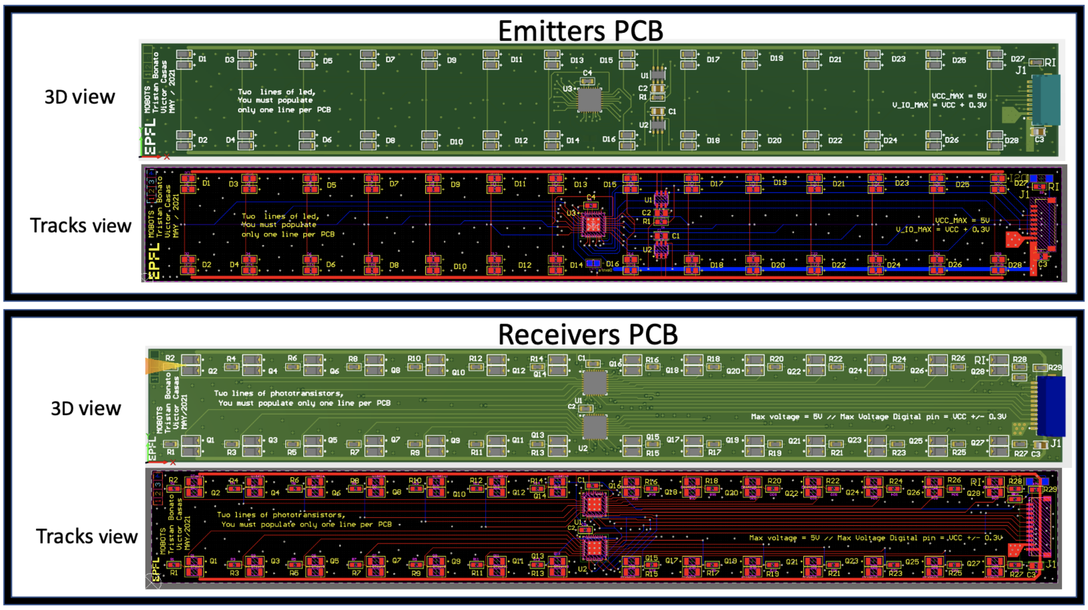
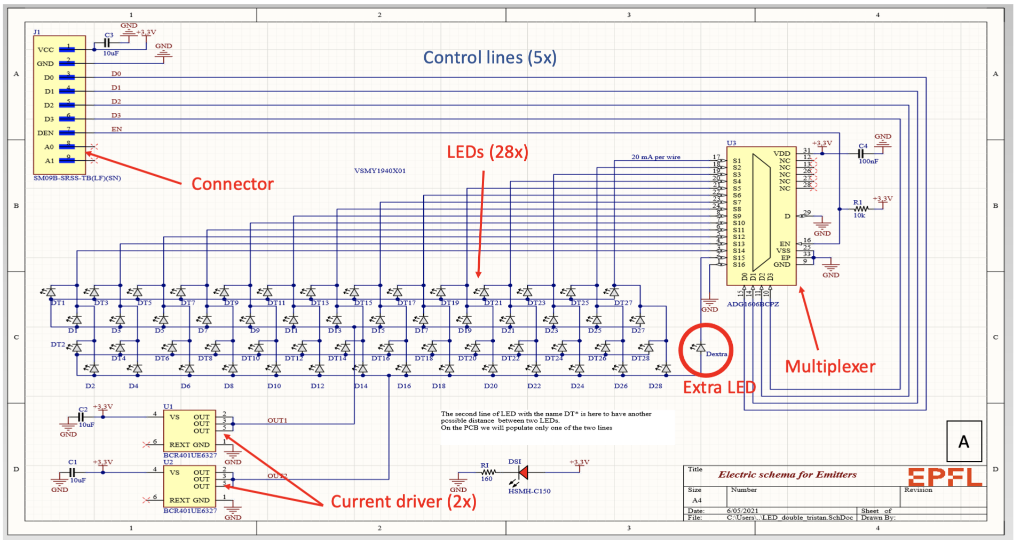
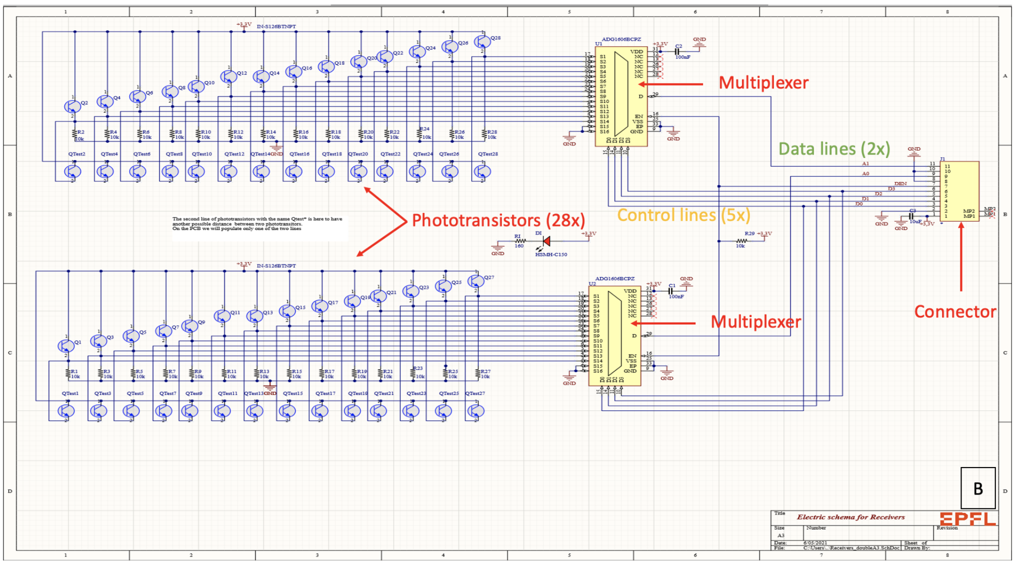


Figure 11 – *PCB view from Altium. In green is the 3d view, and in black is the 2d view of the tracks and components. For the tracks view, the color red shows the first layer (L1) and the tracks in blue the fourth layer (L4). In between we have two ground layer (L2 and L3). The first block shows the emitters PCB and second block shows the receivers PCB.*

When we received the boards, they were without components. So, with the help of Daniel Burnier, we fused the components in a BL SV260 Vapor Phase Batch Soldering Oven. We take this opportunity to test two different solder paste; SAC305 and SN100C Figure 12 - B.



(a) Schematics for the emitters.



(b) Schematics for the receivers.

Figure 10 – *This images are here to see the real implementation instead of the block diagram. The important part on these schematics are: (A) The 28 LEDs, the two led driver, the multiplexer, the extra LED (for communication with camera) and the connector.(B) the 28 phototransistors, the 2 multiplexers and the connector.*

After assembling everything (Figure 12), we test the board. Firstly, we test every component if shortcuts occur. Thus, we check, one by one every channel, on both side, if the LED emits and the phototransistor receives. Moreover, finally, we measure the current consumption, 18.7 mA, on scanning mode. The theoretical values should be a bit more than 20 mA.

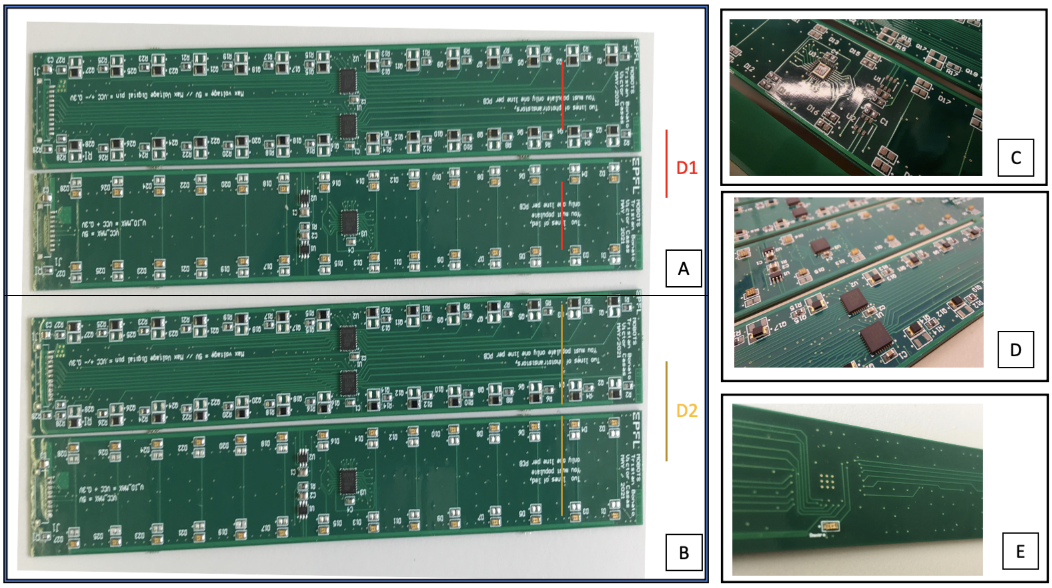


Figure 12 – *Populated PCBs. Two different populations. (A) PCB with the distance between middle of the LEDs/phototransistors (D1) equal to 16 mm. (B) PCB with the distance between middle of the LEDs/phototransistors (D2) equal to 20 mm. (C) Details of one PCB with the solder paste before oven. (D) details of PCBs populated.(E) Extra led for camera communication. This LED is placed in the other side of the PCB just under the Mux.*

5.2 Channels structure design and manufacturing

We designed two type of channels: V-shaped (example in Figure 13) and constant shaped (circular). At this stage of the project, we had to integrate the PCBs to the channel structure. The majority of the electronic components on the PCB were facing the channel structure. Therefore, some slots had to be designed in the channel structure. The electronic components are sometimes smaller than 1 millimeter and the precision required is about 0.2 millimeters. Hence, the channel structure was manufactured with PETG which offers a great amount of precision and great reliability.

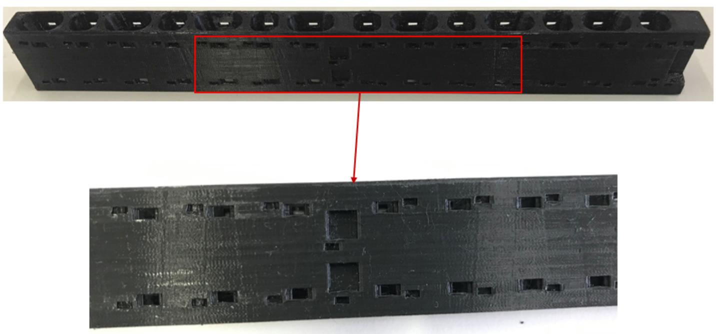


Figure 13 – *Example of V-shaped channel structure with 14 channels and made of PETG. Each side of this structure has slots to accept the electronic components from the PCB.*

5.3 Assembling the module

Figure 15 - A shows the parts from the module: two PCBs (receivers' side, emitters' side), the channels structure and the protective box(brown part). The protective box has been made to fit exactly in the test setup that we will discuss next section. We made the protection with the wood filament (3D printing) since precision was not required for this part. Figure 15 - B shows the module assembled. Each PCB was inserted on the faces of the channels' structure and then these parts were slit inside the protective box.

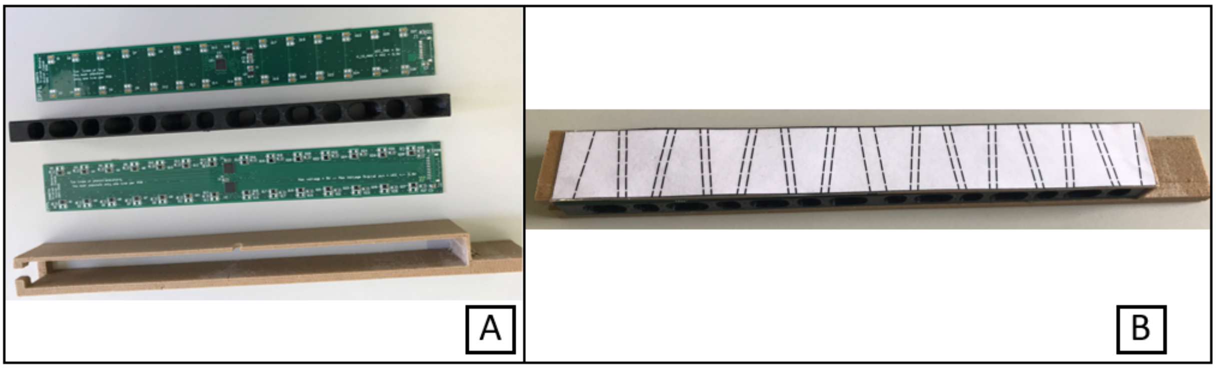


Figure 14 – *(A): From top to bottom: Emitters' PCB, Channels' structure, Receivers' PCB and Protective box (B): Module assembled*

6 Simulating in hive experiment

At this point, we had a complete module (mechanic plus electronics) and a software that scan and collect data. We needed to simulate the experiment in our lab before going in the field. The experiment in the hive had the goal of verifying three main points; the observation in-hive, the choice of the mechanical structure and the electronics.

6.1 Integration of the module in the test hive

To confirm the reliability of our module, we had to check the behaviors of the bees around our structure in real condition. Thus, we filmed in dark condition inside the hive, with infrared led. With this system the bees would not be affected (Figure15 - C).

We set up the controller and the camera to have visibility on all the frame without having objects in the field of vision.(figure15 - B).

To confirm the modules we needed to have bees passing through. We tried to encourage them by separating the hive in two parts and blocking one entry (Figure 15 - A). With this configuration, the bees would have to pass through our modules if they wanted to exit the hive.

Finally to protect our set up we put a Plexiglas on the top of the frame to keep the bees into the hive (Figure 15 - B).

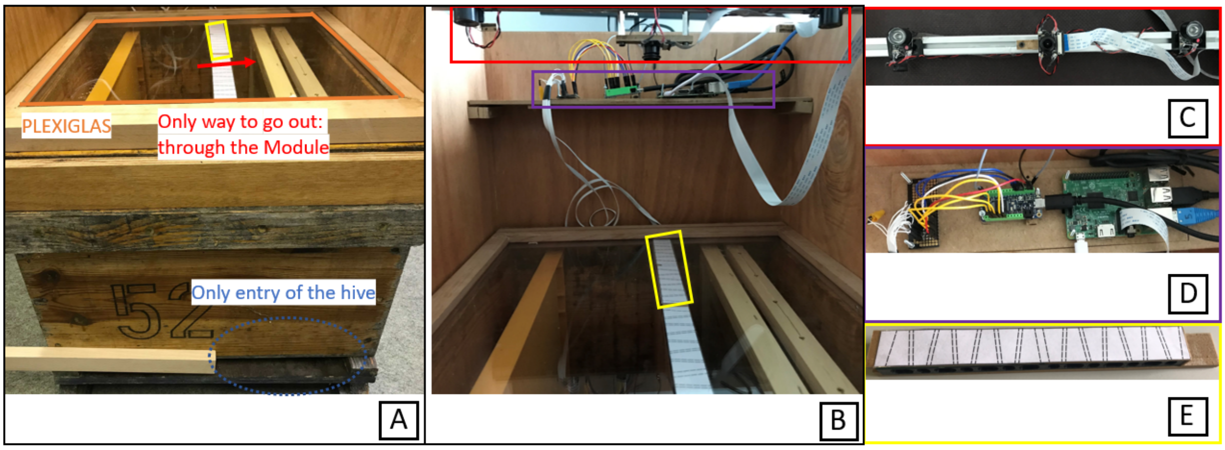


Figure 15 – *(A): Mechanical structure disposed on the top of the inferior part of the hive (where are the frames). We separate the hive in two part, with a barrier mounted by our modules in between and a part of the exit block. Thus, the bees on the left part have to pass through our module to exit the hive. (B): This images shows the different part of the experiment. We have a camera with LED on the top (C), the control electronics (D) and the complete module (E).*

6.2 Electronic control

The electronics that controls the system is composed by an Adafruit stm32 and a raspberry pi (Figure 15 - D). The Adafruit runs the Arduino code to scan the modules and collect data. The Raspberry is the master computer that manages everything; it runs the camera and collects data, runs the scanning code, and reads and saves the analogs data. Figure 16 shows in detail the architecture. To synchronize the log data and the camera, we blink the extra Led 5 times and each time we rerun the entire code.

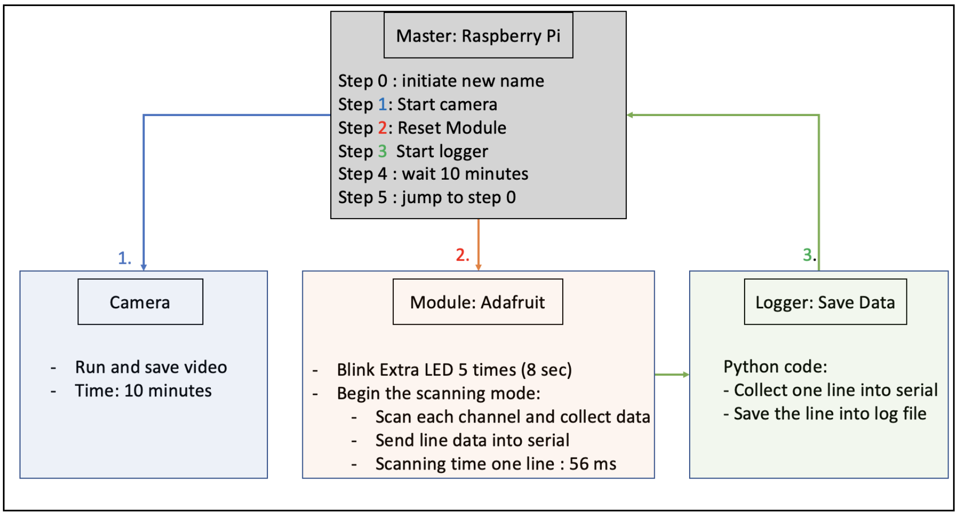


Figure 16 – *This image explain the software architecture. Firstly we have a Raspberry pi with the role of the master. Then we have a camera to record data, an Adadruit module to perform the scanning and collect data, and the Logger python file that reads the serial data from the module and saves it in a Log file. These blocks are controlled by the Raspberry which initiates the camera before resetting the module. Then it runs a python code to log the data. And finally, after 10 minutes it runs everything again.*

7 Installing set up in the field

After verifying that everything worked well in the lab, we went to the field to install our setup. Maxime Balandret helped us during all the setup. Before each manipulation, we put a small among of smoke to force the bees goings inside the hive. They have an instinct when smoke appears; get some food in case of evacuation. We assure the reader that we took care of the bees, and almost none were harm.

Firstly, we reordered the frames and check the health of the colony (Figure 17 - A). When we arrived, the barrier frame was located at the extreme right of the hive. Therefore, we relocated our barrier frame close to the middle. Afterwards, we smoothly placed the upper part of the module with the camera and electronics (Figure 17 - B). This manipulation was a bit laborious because we had a module connected to the electronics. Then, we put the module on the barrier frame (Figure 17 - C). We only connected one module, the other one was complete would no be connected to the electronics. Then, we placed the Plexiglas protection to observe the bees safely and to protect our electronics (Figure 17 - D). Finally, when everything was powered, we closed the box to be in dark conditions, and we controlled the raspberry with the help of an Ethernet cable (Figure 17 - E).

Figure 17 – *This image explains how we installed the set up in the field. (A) Reordering the frames and the barrier. (B) Put the upper part containing the electronics and the wired module. (C) Place the modules correctly on the barrier frame. (D) Put the Plexiglas protection and connect everything. (E) Close the hive with the roof and control the Raspberry with our computer by an Ethernet cable*

8 Results

The goal was to leave the module for 6 days in the hive. The submission of the report (11/06/2021) will occur the third day of experiments. Hence, this report does not include all the results. On the contrary, the presentation (15/06/2021) will contain all the results and discussion of the experiments.

8.1 In-hive observation

The observation inside the hive was a real challenge because of the illumination, camera position, and geometry of the frames.

The first problem was the lighting because of the reflection of infrared light on Plexiglas (figure 18 - A). We tried to add some LEDs, vary their orientation, put black papers (figure 18 - B (bottom image)) to suppress their reflection on the Plexiglas. Finally, we made an improvised diffuser with a plastic box and white paper that improved the lighting conditions (figure 18 - C).

Secondly, between the two frames, there was a gap (figure 18 - A). This gap appeared as a dark line from the camera. Furthermore, it was difficult to have an idea of depth perception: we couldn't distinguish if a bee was at the same height of a channel or deeper in the barrier frame. To solve this problem, we made a bridge under our structure between two frames with white

Plexiglas.(figure 18 - B) With this mechanism, the gap appeared full, and the bees' direction was easier to record.

We used different camera positions, depending on what we were interested in focusing. The first configuration needed to place the camera in the middle of two modules, close to the hive's roof, to observe the flow or the difference between the two modules (figure 18 - A). In the second configuration we placed the camera in the middle of one module and closer to the Plexiglas (figure 18 - C).

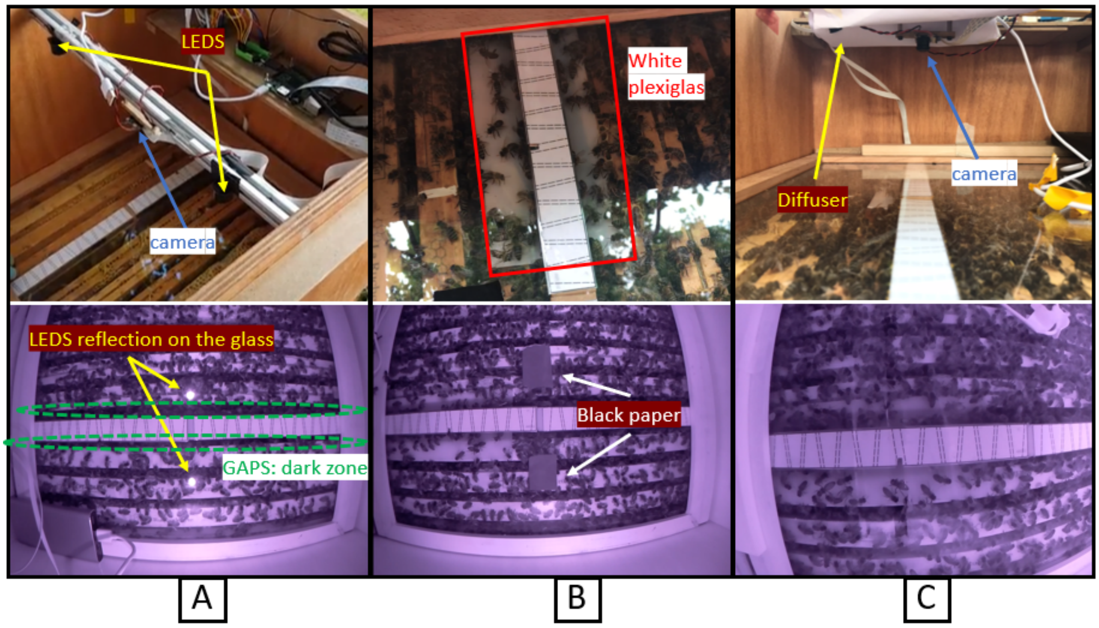


Figure 18 – Different setups inside the hive*(A): The camera is placed above the modules at maximal height. The two LED's from the camera are reflecting their light on the Plexiglas which is not ideal. The gaps between the frames are problematic since they are perceived by the camera as dark zones. Moreover, it is really difficult to have any idea of depth perception. (B): A white Plexiglas is placed below the modules and above the frames. It grants better lightning conditions around the modules and suppresses the problem of depth perception. Black papers were placed above the Plexiglas to suppress the LED's reflection. (C): In order to have better results in comparing the data from the sensors and the camera, we placed the camera above only one module. Moreover the lightning conditions, were improved by placing the LED's behind the diffusers.*

8.2 Bees passing through the channels

Figure 19 - C shows example of plots where bees are crossing the channels. These results are verified with the videos from the camera where we actually see the bee crossing the channel (example Figure 19 - A and B). Each plot shows intensities of both phototransistors from one channel (blue and orange lines). A low intensity means that the bee is detected. The intensity when a bee is detected varies from 500 to 20 bits.

We clearly see in each plot that both sensors are triggered one after another which indicates a channel's crossing. Most of those plots show a small overlap of both sensors triggered. It means that the tail and the head of the bee are detected by both sensors at the same time and that the bees may measure around 15 mm which is the sensor spacing used in the module.

The time spent by the bees that cross the channel varies. The fastest one can cross the channel in less than one second and the slowest one in 6 seconds. In average, a bee crosses the channel in 4 seconds.

Ideally, it would have been nice to identify the body parts of the bee from these plots (Figure 19 - C). However, these plots do not seem to repeat a regular pattern every time.

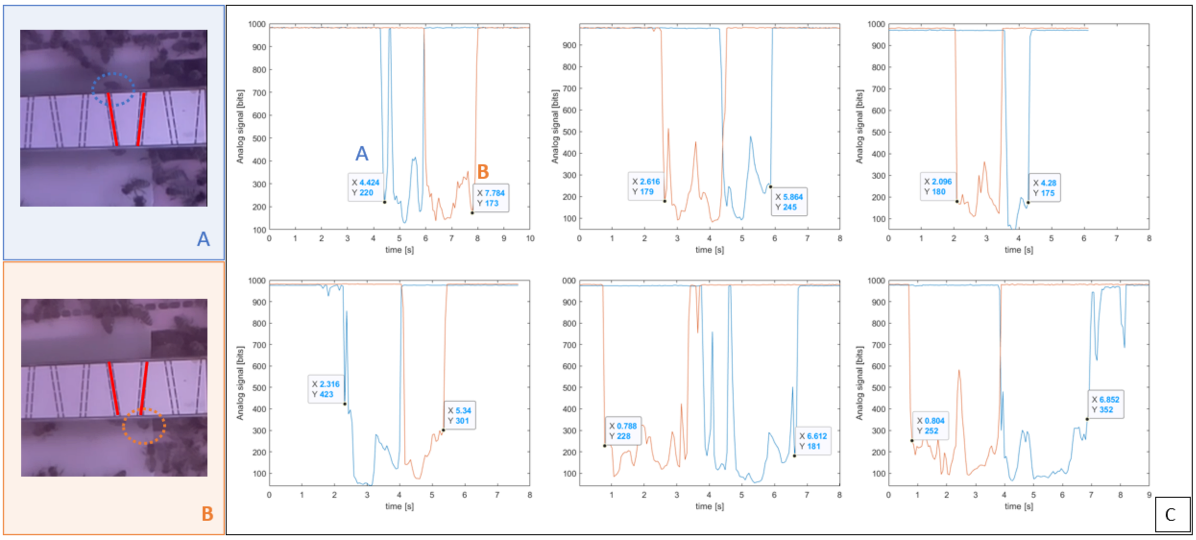


Figure 19 – Bees' detection *(A): Bee entering the channel. (B): Bee exiting the channel. (C): Plots showing the intensities of both phototransistors from one channel. Each plot is an example of a bee crossing through the channel. When the intensity of the phototransistor is low, it means that the bee is detected. Events A (bee entering the channel) and B (bee exiting the channel) are related to the first plot (top-left).*

8.3 Bees' accommodation

The first three days of experiments, the bees were filling the imperfections of the modules with propolis. Propolis is a kind of natural plastic. They combed small spaces around the barrier protection in plexiglas, the PCB and the channels (Figure 20 - A,B,D), and they combed small spaces around electronics as well (Figure 20 - C). It is essential to underline that they did not comb the channel itself but made all the structure more polished and perhaps more smelly "like home" as well. On the conditions mentioned before, it was challenging to analyse the data relevantly. The bees were close to the channel's entry; thus, many bees were triggering the sensors without crossing the channel itself ((Figure 20 - E,F)). Thus, at this stage of the experiments, it was really difficult to analyze the data from the log files.

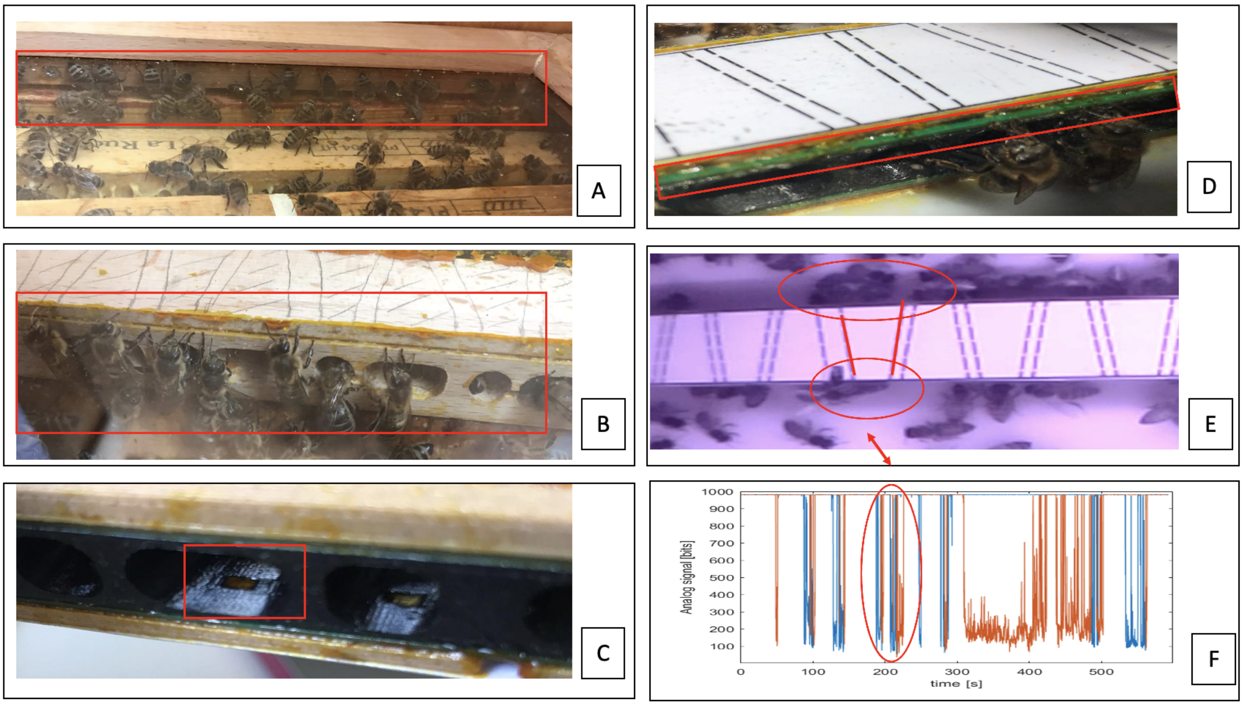


Figure 20 – *Theses images are here to shown the retouching of the bees. They fill all the small hole on new part into the hive to isolate the hive. The name of this material is propolis; it's a kind of natural mastic (A): Image of bees put some propolis on the corner of the new plexiglas (barrier protection under the hive). (B): Bees filling the irregularity of the wood. (C): LED entirely covered by propolis. (D): Space between PCB and pla structure recover. (E): Image of bees clumped together at the entry/exit of a channel. (F): Plot of both sensors' analogs outputs (orange and blue) from one channel. The red circle illustrates the event from image E where we have both sensors triggered by the bees at the same time (both output values are below 500). Between 320 seconds and 500 seconds one sensor (orange) is triggered by bees all the time.*

8.4 traffic inside the hive

To have comparable values, we observe the traffic between two different frames and between one side to the other of the same frame (Figure 21). It is laborious to count each bee and see their path. But we can clearly see that the bees slightly move between two frames (2-3 time per minutes) and move significantly between two side of the same frame (20-25 per minute).

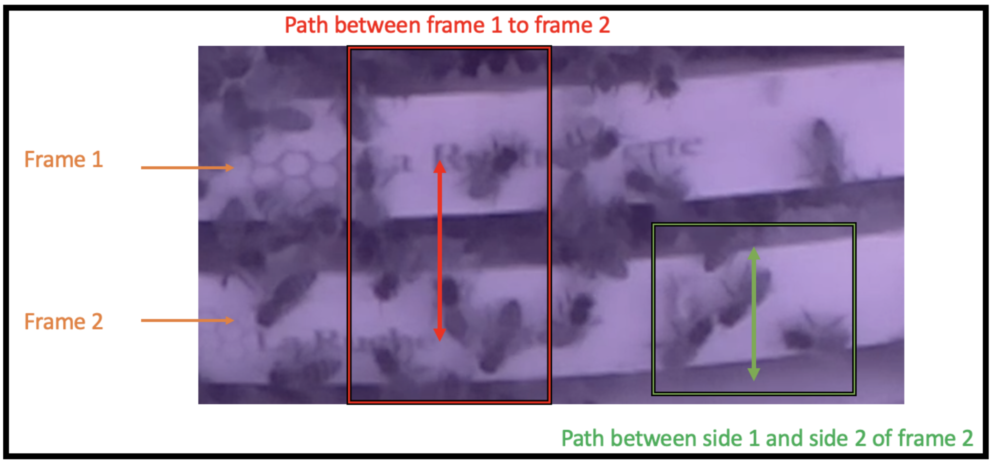


Figure 21 – *This images shows the two different paths we observe. The first one is when the bees is passing trough one frame to a different one (in red). and the second path is when the bees are passing trough one side to another side of the same frame (in green). The bees do not move a lot between different frame (2-3 times per minutes) but they love to move between on frame to another (20-25 per minutes).*

8.5 V-shape success

By looking at the first videos and log files collected the first days, we noticed that the idea of V-shaped channels was not working as expected. Indeed, it was not clear that the bees were choosing every time the wide channel over the small one. In order, to confirm these results we did a small experience: we recorded 10 minutes without the roof (light conditions) of the hive so the bees were able to see and ten minutes with the roof (dark conditions) so the bees were plunged into darkness. The results are shown in the table below:

Table 3 – Comparing whether the bee is choosing the small or wide channel in light or dark conditions (20 minutes experience)

Conditions	**Small entry [%]**	**Wide entry [%]**
Light	69	31
Dark	46	54

This table shows that in light conditions the bees tend to choose the wide channels over the small ones and in dark conditions they don't seem to have any preference. Hence, these results give the impression that the V-shape channels do not work in in-hive conditions (dark) but we should carry out longer experiments to validate this hypothesis.

8.6 Material

At the beginning of the experiments we put two modules in the hive. As explained before, the protective box was made of PLA-wood and the channel structure was made of PETG. Moreover, the module contained two PCBs. When we realized that the bees were spending most of their time filling the imperfections around the modules (Figure 20 - C to F), we wondered whether it was because of the material (plastics). Hence, we changed one of the current modules by one module made of wood without any electronic components and figured out that the bees were combing the holes as well (Figure 20 - B).

8.7 Obstructed led consequence

After few days, the bees covered some LEDs and phototransistors with propolis (Figure 20 - C). Nevertheless, the pair of emitter-receivers could still detect if a bee was detected or not. Moreover, we did not notice any difference of signal intensity between the first and third day of experiment.

9 Discussion

Unfortunately, we were ready too late for the experiments. To have relevant results, we would have to leave the modules in the hive for more than a week to give the bees more time to adapt. Perhaps, after that, they would have used the channels for the purpose we thought. We could have decreased the time spent by the bees to adapt by creating a more polished structure or filling the structure with some propolis from the hive before putting it inside. In addition, the materials we chose for our final module (PETG, PLA-wood) did not seem to be less accepted by the bees than wood.

Imprisoning the bees to force them to pass through our channel was unfortunately not effective. The bees seemed satisfied to stay in their place since they had enough supply.

To improve the flow, we think that we should put the module in other places. The bees do not seem to move a lot between frames from the top. However, they seem to move significantly more between one side to another of the same frame. Our modules are placed above a barrier frame and the only interest for a bee to cross the barrier is to move to another frame. Then, if we put the modules around a functional frame (with honey or larva), we should have more flow.

The bees' detection is working well. We can detect if a bee passes through the channel by observing both sensors triggered consecutively. The distance spacing that we choose let the overlapping time of both sensors narrow. Supposing that the bees will pass fluently through the channels, we could detect where the queen is. The overlap between two triggered sensors from the same channel will be bigger because the queen is significantly bigger than the other bees. Unfortunately, the fact that two bees can make entry simultaneously and then trigger both sensors at the same time can falsify this result.

Unfortunately, the V-shape has not the regulating flow we thought. J. Abbott [12] experimented the V-shape channels in light conditions but we tried the V-shape channels in the hive which means no light. Under these circumstances, the bees do not tend to choose the wide entry over the small entry. This problem is not a big deal to have the direction of a bee crossing the channel because each channel is equipped with two pair of sensors. However, we did not solve the problem of two bees passing through the same channel in opposite directions. However, we confirmed the study of Abbott by observing that the bees preferred V-shape in full light environment by testing it at the entrance of the hive and in the hive without its roof. If we confirm the theory that the V-shaped channels do not work inside the hive, constant shaped channels which are already designed, should be manufactured.

We need to recollect data when they accept the modules in a modified functional frame to confirm our impressions. With these data, we should perform data analysis to observe the flows and their respective signal.

10 Conclusion

This project begins by studying bees characteristic and behaviours. Our modules are designed and tested at the entrance of a hive with two types of shapes: constant shaped and V-shaped. Infrared sensors are chosen to measure the passage of the bees. Throughout the project, we experiment with various materials and manufacturing methods to have a bee-compatibly mechanical structure with high precision. We also design an electronic architecture that exploits the same digital line to control emitters and receivers without a synchronization problem. This architecture is robust and energy-efficient. Finally, we develop a fully functional module for in hive flow monitoring.

An observation setup including two modules, a camera and the electronics is then built in order to integrate it in the hive. We improve the setup inside the hive by finding good lightning settings and we collect actual data from the camera and the flow-monitoring device designed and manufactured previously. Our module is able to detect a bee and sometimes its passage. However, the bees are not accommodated to the modules and are spending time combing small imperfections in front of the channels, sometimes triggering the sensors.

We should let the bees more time to adapt to our modules and collect better data. With these data, we shall measure the flow between two sides of an active frame. This point would be a real achievement for us. We hope other students will go on with this works and upgrade it.

We find this project extremely stimulating. The combination between engineering and nature was a real challenge. Furthermore, the lack of certainty about the bees' behaviours regarding a new structure into the hive forced us to be creative. The fact that we designed a fully functional module was motivating as well. Finally, to be in contact with hives, bees and beekeepers gave us an unforgivable experience.

11 Acknowledgments

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