Capacitance Sensors for Mason Bee Activity Measurement

Jyotsna Joshi(jyotsna3), Piyush Sud(psud2), Keerat Singh (keerats2)

ECE 445 - Senior Design Laboratory

1. Introduction

1.1 Objective and Background

The well-known loss of pollinators around the world has been a concern for ecologists, agriculturalists, farmers, and everyday citizens for several years now. While the exact reason for the infamous Colony Collapse Disorder affecting honeybees is unknown, there is work being done on boosting their populations so that honeybees can be the thriving pollinators they were once. But what if we are focusing too squarely on the honey bees? What if there is a more effective way to pollinate crops and native plants with a bee population that is native to North America? That would be the mason bees, *megachilidae osmia*. Mason bees, solitary bees that don't live in hives, don't make honey, and usually don't sting, are a species of bee that can pollinate an area almost 100 times more efficiently than the western honeybee. They are a good species for even amateur apiarists to keep near their homes to boost local native bee populations and participate in solving global ecological issues.

1.2 Problem

There are some key hurdles to keeping mason bees. Mason bees live in "tunnels"; in nature, this means they live in dark crevices found in trees, rocks, or in the ground, but kept bees live in tunnel homes. Please refer to Figure 1 to see examples of these tunnel nests.

Additionally, female bees will populate these tunnels with eggs for next year, and seal tunnels when they are done laying their eggs. Beekeepers must clean these tunnels, especially at the end of every season, and harvest the bee cocoons for the next year. It can be challenging to know when to clean a tunnel, especially if one is unable to tell if the tunnel is occupied by an alive adult bee. This difficulty arises from the fact that these tunnels are long and dark, and so bee activity deep inside the tunnels is hard to gauge.

1.3 Solution

What our solution is: Our solution adds sensors to a mason bee house so that beekeepers can be confident their bees are active and healthy, and the house is clean. If they are alerted when unwanted visitors like parasites are entering the bee home, they can be proactive about preventing their spread. Additionally, by alerting the beekeeper when a tunnel is full of mason bee eggs, that tunnel can be removed and kept somewhere safe, away from mold and parasites.

How it will be implemented: At the core of our solution are capacitive sensors that non-intrusively detect bee behavior in tunnels. These sensor readings will be interpreted to determine when bees are entering and exiting, how much of the tunnels are being actively used, and when unwanted intrusions occur. This data will be stored on an SD card so beekeepers can view collected data at their leisure.

Figure 1: Wood block with holes drilled in to make tunnels for mason bee nesting

Our solution prototype:

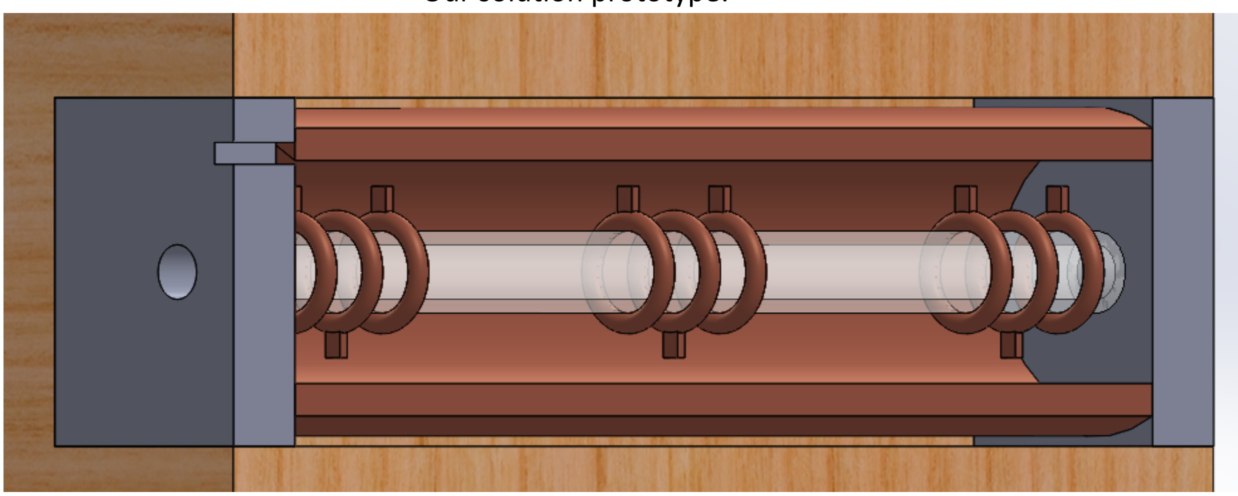


Figure 2: Cutaway of bee tunnel to show capacitor rings. Note the hole on the top of the left endplate for the connector.

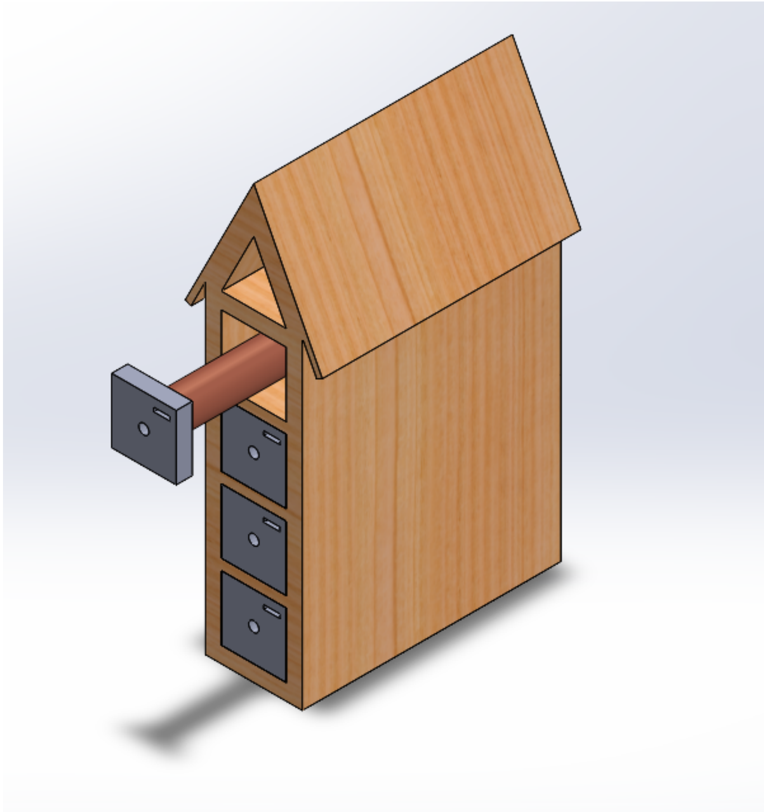


Figure 3: Mason bee house with one tunnel extended to show interior

1.4 High Level Requirements List

1. Capacitor sensor setup shall differentiate between entering and exiting simulated bees (6mm metal ball) in each tunnel.
2. Sensor setup shall differentiate between simulated bee and simulated parasite (3mm metal ball to approximate the size of the Houdini fruit fly, a troublesome parasite that eats mason bee larvae).
3. An integrated SD card shall store data about how much of each tunnel is populated with simulated eggs (6mm metal ball temporarily stuck to the tunnel).

1.5 Demo Expectations

Our current demo plan is to simulate the behavior of bees using metal balls that are similar in size to mason bees. Previous research on bee sensors has used this testing method and shown it to be successful. To test whether the sensors can detect the presence and direction of bees, we will roll a 6mm ball in and out of the tunnel.

To test whether the device can detect how much of a tunnel is filled with eggs, we will fill the tunnel to varying degrees of fullness with 6mm balls (to simulate the cocoons) , and roll a ball up and down the length of the tunnel (to simulate bee behavior in a partially filled tunnel). Our Analysis and Storage subsystem should be able to tell how full a tunnel is based on this simulation.

To test whether the device can differentiate between parasites and bees entering and exiting, we will roll a 6mm ball in and out of the tunnel, and roll a 3mm ball in and out of the tunnel. The data recorded on the SD card should reflect a bee for the 6mm ball and an unwanted intruder for the 3mm ball.

2. Design

2.1 Block diagram

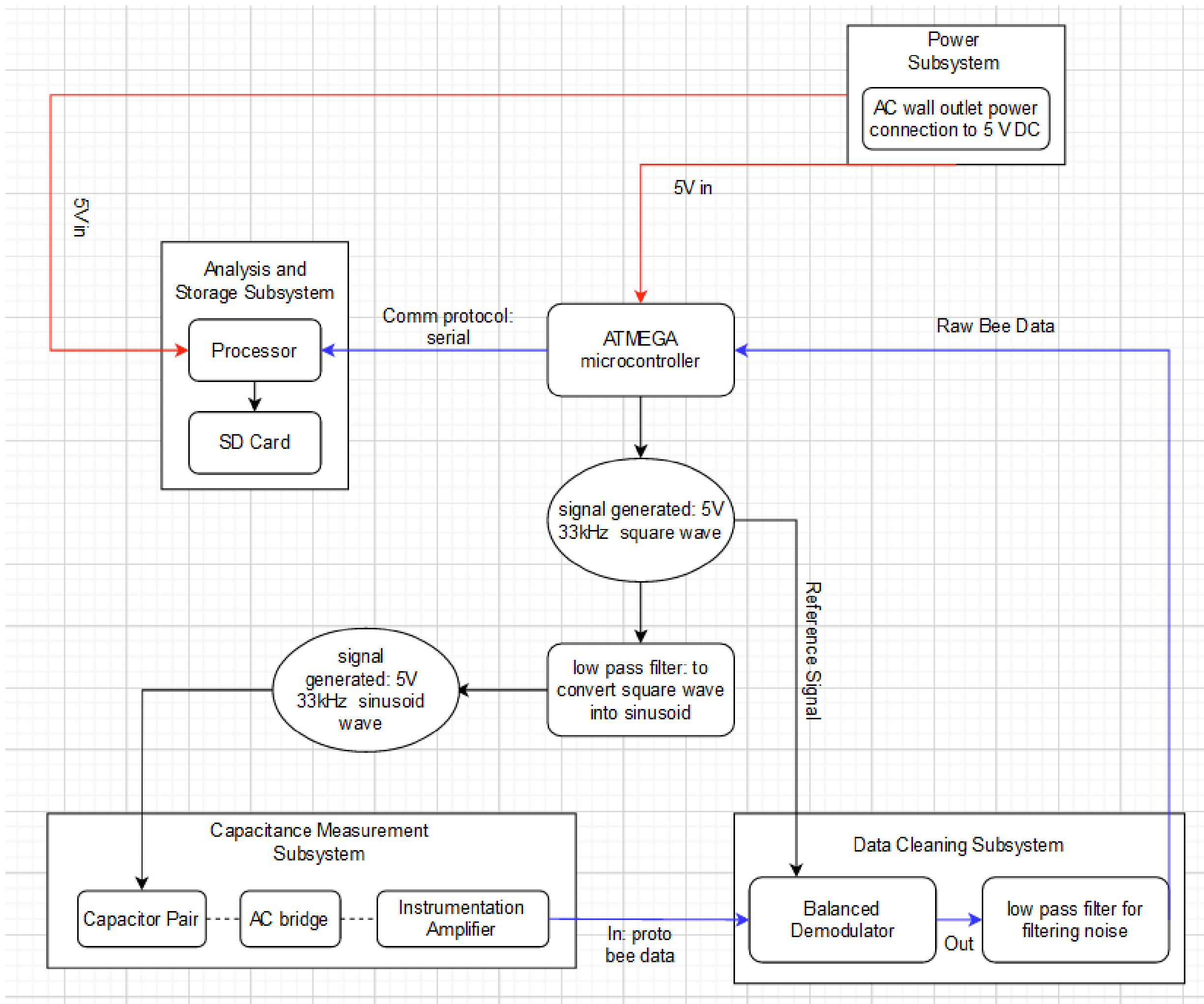


Figure 4: Block diagram of Circuit Design. See Figure 2 for Capacitor Pair set up.

2.21 Mason Bee Housing Subsystem

Subsystem Overview:
For our mason bee house, we will be using a hollow wooden structure with holes drilled into it. Inserted into these holes we will have PVC or acrylic pipes which will function as the mason bee tunnels. The structure will have 4 tunnels, and each tunnel will have multiple pairs of capacitors [see Figure 2 above for capacitor set up, Figure 3 for house structure]. Each tunnel will have a connector for the sensor wires to be sent to the processor for analysis.

Subsystem Requirements:
1. Create a structure to hold the tunnels
2. Provide mounts for the electronics and connectors

2.22 Capacitance Measurement Subsystem

Subsystem Overview:
The capacitor sensors that form the heart of our project are based on research done at the University of Prince Edward Island in 2005. In their paper “Capacitance-based sensor for monitoring bees passing through a tunnel”, they describe a setup where they forced bumblebees to enter their hives through tunnels. In these tunnels they had set up a “two-capacitor set-up along with an ac bridge and phase-sensitive detection” which “produce an asymmetric double pulse for each bee passage”. They then used this double pulse to estimate velocity, size, and direction of travel of the bumblebee.

We plan to adapt this sensor setup for use in mason bee tunnels, with a two-capacitor setup at the mouth of the tunnel for entry and exit, along with more capacitors along the length of the tunnel to determine how far into the tunnel the activity goes. Each of the four tunnels will have this sensor setup. The sensor data will go to a microcontroller for processing so that we can identify which tunnels are occupied, how much of the tunnel is filled with eggs, and whether it is a mason bee or an unwelcome intruder entering the nest.

Subsystem Requirements:
1. Sensors can record a bee’s crossing and direction of travel.
1. Sensors can collect data that can be analyzed to tell how full each tunnel is with eggs.
2. Sensors can differentiate between different sizes of simulated insects.

2.23 Analysis and Storage Subsystem

Subsystem Overview:

We would like for the identified bee behavior (which tunnels are occupied, entry and exit times recorded in different tunnels, any intruders detected) to be stored on an SD card that the beekeeper could remove from the mason bee house and look at on a personal computer.

Subsystem Requirements:

1. Data is transferred from microcontroller to processor so that data can be analyzed.
2. Data and analysis are stored in a file that is easy to read without specialized software (eg. txt file, .csv file, etc).

2.24 Power Subsystem

Subsystem Overview:

Many mason bee keepers install mason bee houses on the outside walls of their own home. We plan to take advantage of exterior outlets that may exist on the home by using a commonly available 5V DC wall adapter.

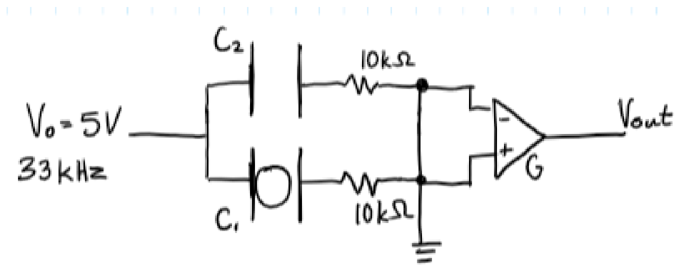
Subsystem Requirements:

1. Provide power to the processor that will analyze and record the data.
2. Provide power to the integrated circuits in the capacitive sensor setup.
3. Provide power to the microcontroller.

Tolerance Analysis

One risk to the successful completion of our project is whether we can generate the necessary waveform for driving the AC bridge in the capacitance sensor setup, and the balanced demodulator, from our microcontroller. We will need a sine wave and a square wave of 5V and 33kHz frequency. The ATMEGA 168/368 generates PWM signals using three separate timers; it has a system clock of 16MHz and the timer clock frequency for PWM generation will be the system clock frequency divided by a prescale factor accepted by the ATMEGA. These prescale factors will let us subdivide clock steps into smaller increments and generate higher frequency signals as needed.

Another item of concern to consider is whether the generated output will be within the measuring capabilities of our microcontroller. The diameter of the tunnel entrance is 8 mm, and our testing plan involves using a 6mm ball bearing. With this in mind, we performed calculations to determine what the change in voltage in that scenario would be. The core of the sensor is an AC bridge, which can identify imbalance in the impedance of its legs. With plates with 8mm of separation, we would expect the capacitance to increase at most by a factor of 4 if metal 6mm in diameter is passed between the plates. We expect the data most immediately generated by the sensor is small, but to get some concrete expectations we did calculations to see the voltage for the proto-bee data (see Figure 4). As you can see in the circuit diagram, the voltage value is dependent on the gain of the instrumentation amplifier. We can adjust that gain, along with the gain involved in the data cleaning subsystem in the block diagram, to be confident that that data is in the range of what is measurable by the microcontroller (between 0.5 and 5 V).



$$V_{out_{max}} = \frac{G \cdot V_0 \cdot (C_1 - C_2)}{C_1 \sqrt{\left(\frac{1}{2\pi f \cdot RC_2} - 2\pi f \cdot RC_1\right)^2 + 4}} =$$

$$C_2: \frac{\varepsilon_0 A}{d} = \frac{\varepsilon_0 \times (\pi r^2)}{d} = \frac{16\pi\varepsilon_0}{8} \frac{mm^2}{mm}$$

$$\approx 0.05 \text{ pF}$$

$$C_1: \frac{\varepsilon_0 A}{d} = \frac{\varepsilon_0 \times (\pi r^2)}{d} = \frac{16\pi\varepsilon_0}{2} \frac{mm^2}{mm}$$

$$\approx 0.20 \text{ pF}$$

$$2\pi f \cdot RC_2 \approx 1.04 \times 10^{8} \text{ Hz}\,\Omega$$

$$V_{out_{max}} = \frac{G \cdot 5 \cdot 0.15\,pF}{0.2\,pF \cdot \sqrt{\left(\frac{1}{1.04 \times 10^{-8}\ Hz\,\Omega} - 1.04 \times 10^{-8}\ Hz\,\Omega\right)^2 + 4}}$$

$$\approx G \cdot 8.56 \times 10^{-5} \text{ V}$$

Figure 4. Calculations regarding the proto-bee data voltage

An important point that came up in the above calculation is that the instrumentation amplifier used in the AC bridge with the capacitor pair is susceptible to a non-ideal common mode gain caused by a mismatch in the resistances of the internal resistors that make up the instrumentation amplifier. The signal we expect to receive is quite small, so this additional inaccuracy could cause the expected signal to be lost in noise. So we must make sure to use an instrumentation amplifier IC, since those are checked to make sure they meet ideal specifications, and they use precision resistors.

Ethics and Safety

The primary motivation of this project is to help boost native wild bee populations, which in turn will aid both agricultural and eco-conservation efforts.

For this project, we are not using real, live bees; we will be using metal balls to simulate bees going through the tunnels. Since no live bees will be used in the demo of this project, it will be safe and poses no obvious risks to bees. Additionally, we will not be using batteries, so this product is not likely to do damage to the environment or the user.

We will also do our utmost to prevent accidental harm done to mason bees that would eventually inhabit the device. This aligns with section 1.2 of the ACM Code of Ethics: avoid harm. We did research to investigate whether living among electric fields affects the bees. While we did not find any relevant research on the effects of an electrical field on mason bees, we have found that leafcutter bees, which are in the same family as mason bees, were unperturbed by the electric field produced by a similar sensor's operation. We have also sized the mason bee tunnels in a way that reflects current research on healthy mason bee populations. Research published in the journal *Apidologie* in 2013 concluded that tunnels of at least 15 cm produce the healthiest offspring and a suitable male-female larva ratio.

We also gave thought to whether this device would disenfranchise beekeepers, because it introduces technology that the layperson is not familiar with. If usage of this device became widespread, however, a layperson would still be able to keep mason bees easily. Even though the technology is complex, the portions that the beekeeper is asked to interact with are familiar. This lines up with ACM Code of Ethics section 1.4, where it is noted that technology should be as accessible as possible. Most personal computers on the market can read SD cards, and we plan to store the data in an easily understandable and usable format like a .csv or .txt file. This keeps usage of the device within the skills of the typical beekeeper.

References

"ACM Code of Ethics and Professional Conduct." ACM.org. [Online]. Available: https://www.acm.org/code-of-ethics. [Accessed: Feb 10, 2022].

Bee Built. (2017). How to Keep Solitary Bees. Youtube. Retrieved January 31, 2022, from https://www.youtube.com/watch?v=QGEpJ7F_ZuU.

Bee Built. (2017). *Introduction to Solitary Bees*. Retrieved January 31, 2022, from https://www.youtube.com/watch?v=vf8QyIF3eoY. [Figure 2 from here]

Campbell, J. M., Dahn, D. C., & Ryan, D. A. (2005). Capacitance-based sensor for monitoring bees passing through a tunnel. *Measurement Science and Technology*, *16*(12), 2503–2510. https://doi.org/10.1088/0957-0233/16/12/015 [Figure 3 from here]

Mader, E., Shepard, M., Vaughan, M., & Guisse, J. (2018, May). *Tunnel Nests for Native Bees*. https://xerces.org. Retrieved January 25, 2022, from https://xerces.org/sites/default/files/2018-05/13-054_02_XercesSoc_Tunnel-Nests-for-Native-Bees_web.pdf [Figure 1.1 and 1.2 from here]

Paul Wheaton. (2014). *Mason Bee Micro Documentary*. *Youtube*. Retrieved January 31, 2022, from https://www.youtube.com/watch?v=V8vAQ1B5Zj4.

Sedivy, C., Dorn, S. Towards a sustainable management of bees of the subgenus ***Osmia*** (Megachilidae; ***Osmia***) as fruit tree pollinators. *Apidologie* **45,** 88–105 (2014). https://doi.org/10.1007/s13592-013-0231-8