# DRPD-ROF2017:

# Wireless Sensor System for Beehive Health Monitoring

- Co-PIs:

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- Start Date: June 1, 2017
- Budget request: $85088

# Abstract

Pollinators, such as honey bees, bumble bees, hummingbirds, wasps, and butterflies, serve an important ecological function. They provide pollination services to many plants, thus facilitating plant reproduction. Honey bees (*Apis mellifera*) in particular pollinate many of the food crops used by humans and are responsible for billions of dollars of added crop value.The population of managed honey bees has been under constant threat the last decade, with many parts of the world experiencing colony loss rates exceeding 30% yearly. The stressors impacting managed colonies result in physically detectable changes to the beesáppearance, foraging behavior, colony strength parameters, etc. Determining the causes of and solutions for this phenomenon are still active areas of research. Elevated colony losses are a multifactorial problem, with several potential causes working in concert, including diseases (viruses, bacteria and fungi), pests (the most notable of which is *Varroa destructor*, a parasitic mite), pesticides, poor nutrition, and loss of habitat.

To address this concern, the US government established a set of research goals and recovery actions in the Pollinator Research Action Plan. Research goals included establishing pollinator health baselines, assessing environmental stressors, restoring habitat, supporting land managers and beekeepers (including the development of best management practices), and pollinator monitoring and study. Part of our overall goal is to establish a baseline for the existing state of honey bee health. Currently, there exists no good system for monitoring the health of managed colonies in the US. Our projects aim is to design, build, and test a noninvasive, wireless, multimodal beehive monitor that could be used to monitor colony health nationally. Such a system, if widely adopted, would allow stakeholders to monitor their own hives, and allow researchers to collect data easily and remotely. Combined with additional geographical, and land management data (i.e., pesticide use, proximity to crops, etc.), this data network would aid in highlighting causes of, and developing BMPs to mitigate the elevated colony losses.

An inexpensive, wirelessly connected beehive monitor could achieve widespread acceptance in the beekeeping industry. Several easily measured variables include: bee traffic at the hive entrance and the general shape of foraging beesb́odies (a proxy for their health - measured through a camera mounted at the hive entrance; presence of a queen in the hive, general hive activity (measured as audio frequencies produced by the hive); and honey content (measured through the electromagnetic characteristics of the hive body). These metrics provide data on bee diseases (worker bee shape changes under certain disease stresses), colony propensity to swarm, and availability of food in- and outside the nest. Such sensors may be devised by repurposing existing, off-the-shelf sensors, and integrating them into a single system that transmits its data to a server wirelessly. This research aims to develop and test such a system, with hope of commercialization and widespread acceptance.

# Project Description

## 1 Specific Aims/Objectives

The short term goal of this project is to collect baseline data on the current state of honey bee heath using monitoring technologies, with a long term goal of reducing the loss rate of managed colonies. Specifically, we hope to develop a system that can be used to alert beekeepers to health problems with their hives using visual, audio, and electromagnetic sensors, and to network the sensors to permit aggregation of data on hive health for future analysis. We have developed three objectives to address these goals.

1. We will develop and test a multimodal, noninvasive, networked beehive health monitor, that would be distributed among apiculturists to aggregate data on beehive health in real-time.
2. We will perform controlled experiments, with a set of sensor-equipped beehives, to evaluate the effectiveness of the system in determining hive stressors.
3. We will publish our results and use them to pursue further funding from government agencies. With more widespread usage and increased funding, we can conduct studies collecting data state- and nationwide.

These objectives meet the USDAs priority of elucidation of individual or interacting factors that affect pollinator populations that will lead to the development of novel tools and technologies to mitigate their losses. The proposal largely depends on established techniques, but this seed grant will allow us to establish a program focused around beehive sensor research. Potential future outcomes include novel sensing modalities, such as electromagnetic honey content and pesticide concentration monitoring.

## 2 Background and Significance

Pollinators perform an important ecological service in the reproduction of 70% of plant species. Of pollinators, honey bees (*Apis mellifera*) are unique in that they must gather large amounts of pollen for food. While doing that, they transfer pollen between flowers, resulting in the pollination of those flowers and many of the fruits, nuts, berries, and vegetables humans consume. The population of managed honey bees has been under constant threat the last decade, with many parts of the world experiencing colony loss rates exceeding 30% yearly [23]. Elevated colony losses are a multifactorial problem, with several potential causes working in concert, including diseases (viruses, bacteria and fungi), pests (the most notable of which is *Varroa destructor*, a parasitic mite), pesticides, poor nutrition, and the loss of habitat. Elevated colony losses are of particular concern as agricultural production of pollinator dependent crops is increasing to meet the food needs of a growing human population. The USDA's Report on the National Stakeholders Conference on Honey Bee Health provides a basis for understanding the root causes of these population declines [6]. Several causes have worked in concert to weaken or kill colonies. Invasive Varroa destructor mites are the primary concern. It is detrimental to bees on its own and is known to transmit deadly bee viruses, including Deformed Wing Virus (DWV). Furthermore, the lack of forage for bees leads to decreased food stores, and suppression of bee gut microbiota. Bees also are impacted by chronic exposure to sublethal doses of pesticides. The stressors impacting managed colonies result in physically detectable changes to the beesáppearance, foraging behavior, colony strength parameters, etc.

According to the Pollinator Research Action Plan goals [11], the aim of US government-sponsored research is to reduce honey bee overwintering losses to no more than 15%. Part of this overall goal is to establish a baseline for the current state of honeybee health. While there are honeybee censuses [26], there exists no monitoring system for the health status of managed hives in the US. Such a network of standardized beehive monitors would enable researchers to mine data associated with crop and apiary management practices with measures of colony fitness. Here lies what we plan to accomplish.

We aim to design, build, and test a noninvasive, wireless, multimodal beehive monitor that can be used in apiaries (places where managed hives are kept) nationwide. In particular, our system would implement visual, audio, and weight sensors to monitor bee health and behavior, as well as hive food content, without having to disturb the hive. As such, apiculturists could install the station easily. With 3G connection, these stations could upload data to a centralized database, enabling real-time monitoring of trends in hive health. This could form the basis for a network similar to the weather station network of WeatherUnderground. In this way, researchers could understand variation in colony loss rates over space, time, weather, and management practices. Sensors have been used to monitor hives in previous work. In a similar vein, researchers in Ireland have combined visual, infrared, load cells, particulate monitors, and gas analyzers in the b+WSN and 3b projects [16, 17]. Beelab is an open source Canadian project, providing apiculturists with a highly simplified kit for hive data collection [19]. Thus far, there is no US-based project with these goals. Furthermore, previous work centers on using technologies that are invasive to hives. We aim to avoid this problem using non-invasive technologies.

It is clear that several sensing modalities can be useful for monitoring hive health, and be non invasive. Researchers have implemented video and computer vision systems to monitor bees outside of the hive with success [1, 24]. Such technologies might be able to detect pesticide impacts as pesticides are known to lead to abnormal adult bee morphologies [22]. We also believe they can be used to detect bee infection with DWV given that the virus produces symptoms in bees that can be detected visually [8]. Sound is an indicator of hive status as well. The queen emits a particular sound prior to a swarm (piping), and this has been detected in previous works using microphones [9, 10]. Hive weight can indicate activity and food stores, and efforts to monitor hive weight have been made in the past [15], requiring load cells. Such a measurement system would allow noninvasive monitoring of the colony's food. However, load cells are cumbersome to install, so an alternative will be developed. We will try an alternative technique known as time-domain reflectometry (TDR), typically used for measurement of soil water content. In TDR, a pair of electrodes on the surface of the hive propagate a pulse, whose travel time serves as an indication of the hive's dielectric constant [7]. The higher the dielectric constant, the longer the travel time. The dielectric constant of honey is significantly different than that of air or wood [12], so hive honey content can be monitored in this way.

By combining computer vision, audio monitoring, and weight/honey measurement, a hive's health status can be well described. Further, with access to wireless networks and solar power, and meta-data regarding management practices, this information can be monitored remotely and aggregated for analysis and prediction. Keeping the system simple, inexpensive, and noninvasive will increase acceptance among stakeholders.

# 3 Innovation/Potential Impact of Research

The goal of this project is to develop and test a multimodal, noninvasive, networked beehive health monitor, that would be distributed among apiculturists to aggregate data on beehive health in real-time. The novel CV algorithms and and audio spectral analysis methods offer room for innovation, as these techniques have not been applied very thoroughly to studying bees in the past. Further, there have been no studies looking at electromagnetic sensors for honey content monitoring.

Potential impacts are significant. High loss rates of managed colonies is a real and pressing issue, affecting the human food supply significantly. The success of this project would enable researchers to study the disorder with greater scrutiny and develop best management practices to stop it. On a small scale, individual farmers could better care for their own hives.

# 4 Approach/Research Design

The planned research is comprised of five main tasks: computer vision algorithm development, audio sensor design, electromagnetic sensor design, sensor integration and programming, and field implementation.

## 4.1 Computer Vision Algorithm Development

In order to provide targeted data, images of the hive entrance need to meet certain requirements. Images must only be acquired when workers are present, and workers' features need to be extracted. Thus, a program will be developed that takes a video stream and captures images when bees are present, as in [4]. The first part of the computer vision (CV) algorithm must simply detect the presence of bees at the hive entrance, through simple thresholding (dark bees are easily distinguished against the white paint of the hive entrance) or more advanced techniques such as Support Vector Machines trained on bee features [1]. Then the individual bees will be tracked frame-to-frame using a method such as optical flow [13] or nodal analysis as in [4]. Finally, the individual bees shapes must be determined and reduced to a set of shape parameters, as with Hough circle fitting [28], for example. Additional machine learning algorithms will be implemented and trained using human experts to distinguish healthy from diseased bees. The computer vision algorithm will be developed using test images and existing video on a desktop computer.

## 4.2 Audio Processor Design

A microphone on the side of the hive will pick up audio and amplify sounds produced by the bees, after which it will be digitized and processed. The microphone/amplifier/digitization circuit will be designed and constructed. Audio frequencies below 1 kHz are sufficient for detection of swarms. A software algorithm that analyzes the spectral content will be developed that pinpoints swarming events following the techniques described in [10]. Evidence also suggests that queens can be detected; even though their sound is similar to workers, they generate a stronger tone between 400 and 550 Hz [9]. Potentially, there is a link between hive sounds and exposure to airborne toxins [3]

### 4.3 Honey Content Sensor Design

Monitoring the honey content will be done in two ways: first, through measurement of the hive weight [15], a standard technique, and second, through time domain reflectometry, a novel technique in this application. TDR has been applied extensively in measurement of soil water content, such as with the commercially available soil probes from Acclima [2, 20], due to the high dielectric of water relative to dry soil. Such a commercial sensor could be easily repurposed and attached to the exterior of the hive for purpose of hive monitoring, and calibrated against the weight of the hive. A hive weight monitor will be designed to support the high weights (over 200lb) of a full hive, and measure small changes with time. This can be done using off-the-shelf load cells and amplifiers. The signal will be digitized and logged and used as a reference against the electromagnetic sensor.

### 4.4 Sensor Integration

The three sensing systems will be integrated into one datalogging system using a low-power embedded computer, such as the Raspberry Pi [25], which would also implement the CV algorithm. This computer would perform the image processing and log all data. In addition, it would serve the data to a web interface and central database that will be designed and programmed for this task.

### 4.5 Field Implementation and Controlled Experiments

Finally, the sensors and embedded computer will be installed on a test hive. A weatherproof housing will be designed and fabricated. The system will be powered by solar cells. A 3G connection will allow wireless data upload. The system will be monitored and debugged during the following 3 months. At least 10 hives will be divided into different treatment groups. Several relevant treatment variables could be controlled artificially to evaluate the systems efficacy, including presence of a queen, and Varroa and small hive beetle infestations, etc. Sensor measurements (honey content, bee morphological measurements, audio spectra) can be tested statistically for significance with regard to these explanatory variables indicative of hive health.

### 4.6 Timeline

The project will be completed over 18 months. Tasks 1-4 will be performed during June 2017 through August 2017. Task 4 will be completed in the 3 months following 1-3. Task 5, field implementation and testing, will follow, for a duration of 3 months. Finally, the system should be ready for a field experiment in Spring of 2018, for nine months, after which data will be analyzed and papers written for 3 months.

### 4.7 Pitfalls

There are several potential difficulties with this project. First, computer vision algorithm development is challenging, and depends largely on the quality of the test dataset. Gathering enough extant test video of beehive entrances, and formulating an effective feature extraction and analysis algorithm, may prove more time-consuming than anticipated. If we are unable to develop and effective algorithm before field implementation, we could do so during the experimental trial, simply by using images collected the experiment. Second, the required sensitivity of the microphone and load cells are as yet unknown, and method of dynamically adjusting both for environmental factors (ie, loud noises and hive shifts due to maintenance) will need to be developed. A likely solution would be to use autonmatic gain control to prevent saturation, or to flag times when periodic hive maintenance disturbs measurements and ignore this data. Third, the field implementation will need to be kept highly power efficient to support such processor-intensive activities, such as computer vision, as well as wireless networking. At worst it may require supplemental power, perhaps instead relying on power-over-ethernet, or by off-loading power-consumptive analyses to a centrally located server. Finally, the system cost should be kept low enough that it would be readily accepted by apiculturists, so that data could be aggregated. There are several inexpensive candidates for each part of the system, and additionally, TDR manufacturers are generally amenable to supplying reduced-cost sensors for experimnets, which can help boost a manufacturerś profile.

## 5 Preliminary Data

Not applicable

# References Cited


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[17] Fiona Edwards Murphy, Michele Magno, Pádraig Whelan, and Emanuel Popo Vici. b+wsn: Smart beehive for agriculture, environmental, and honey bee health monitoringpreliminary results and analysis. In *Sensors Applications Symposium (SAS), 2015 IEEE*, pages 1–6. IEEE, 2015.

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# Key personnel and roles

- Joaquin J. Casanova

  **Expertise:** Agricultural sensors, computer vision, machine learning

  **Role:** lead for system design and development

- James D. Ellis

  **Expertise:** honey bee pathology, ecology, toxicology and behavior

  **Role:** lead for beehive controlled experiments

# Budget

Total :

1. **Salaries**

   **Dr. Casanova** at 5%

   **Dr. Ellis** at 5%

   **Undergraduate student, salary** 18 months – $31500

   **Undergraduate student, fringe** 18 months – $788

   **OPS Hive Manager, salary (10 hours/week, $15/hour)** 18 months – $12000

   **OPS Hive Manager, fringe** 18 months – $300

2. **Materials**

   **Sensors** – $500 per hive for at least 30 hives, and backup systems – $17500

   **Test equipment** – $5000

   **Apicultural supplies** – $5000

   **Hives** – 30 hives at $500/hive – $9000

3. **Additional costs**

   **Publication and travel** – $4000

4. **Total: $85088**

## Continued Support and Commercial Potential

This project may be viewed as a preliminary study - significant advancements could be made as we increase the scale and advance then sensors. Once apiculturists are widely using such a sensor platform, this bacomes a very useful tool. Aggregating hive data, along with weather condition, location, and nearb pesticide and herbicide usage, can elucidate unknown correlations that will highlight causes of CCD. Additionally, further advances in sensors may be developed and implemented, such as bee tracking in the field with lasers [5] or infra-red monitoring of bee population [21]. Potential future sources of funding include:

- USDA NIFA – AFRI Food Security Challenge Area
- Fresh From Florida – Specialty Crop Grant
- DOI – Competitive State Wildlife Grant Program

These types of sensor systems would become inexpensive on a large scale so it is a good candidate for commercialization, and there is certainly a market for it among apiculturists and apicultural researchers. According to the Florida Department of Agriculture and Cnsumer Services, Apiary Inspection Section [18], in Florida alone there were over 450,000 managed hives, with a total honey value over $20 million. Popularizing the wireless hive monitors could start at the level of IFAS extension offices setting them up for free; when enough are in place, stakeholders may be more apt to purchase them. Eventually, the data network could function like WeatherUnderground [27], where users purchase weather stations and contribute data in a citizen-science program [14]. Future funds from NIFA or other grants, along with commercial proceeds, could fund refinement and advancements in the technology.

# Biographical Sketch: Joaquin Casanova

## (a) Professional Preparation

**Phd, Electrical Engineering** University of Florida, Gainesville, FL, May 2010

**ME, Agricultural and Biological Engineering** University of Florida, Gainesville, FL, December 2007

**BS, Agricultural and Biological Engineering** University of Florida, Gainesville, FL, December 2006

## (b) Appointments

**Research Assistant Professor,** University of Florida, August 2016

**Senior Engineer,** University of Florida, November 2013

**Research Engineer,** USDA, May 2010

## (c) Products

30 technical publications in peer-reviewed journals and conference proceedings. 2 patents awarded. Most closely related to the proposed project:


1. Schwartz, R. C., **Casanova, J. J.**, Bell, J. M., & Evett, S. R. (2014). A reevaluation of time domain reflectometry propagation time determination in soils. Vadose Zone Journal, 13(1).

2. **Casanova, J. J.**, Schwartz, R. C., & Evett, S. R. (2014). Design and field tests of a directly coupled waveguide-on-access-tube soil water sensor.Applied Engineering in Agriculture, 30(1), 105-112.

3. **Casanova, J. J.**, O'Shaughnessy, S. A., Evett, S. R., & Rush, C. M. (2014). Development of a wireless computer vision instrument to detect biotic stress in wheat. Sensors, 14(9), 17753-17769.

4. **Casanova, J. J.**, OShaughnessy, S., & Evett, S. (2013, November). Wireless computer vision system for crop stress detection. In ASA-CSSA-SSSA Annual Meeting Abstracts (p. 123). ASA-CSSA-SSSA Annual Meeting Abstracts. Session 196-7.

5. **Casanova, J. J.**, Evett, S. R., & Schwartz, R. C. (2012). Design and field tests of an access-tube soil water sensor. Applied Engineering in Agriculture,28(4), 603-610.

6. **Casanova, J. J.**, Evett, S. R., & Schwartz, R. C. (2012). Design of access-tube TDR sensor for soil water content: Testing. Sensors Journal, IEEE,12(6), 2064-2070.

7. **Casanova, J. J.**, Evett, S. R., & Schwartz, R. C. (2012). Design of access-tube TDR sensor for soil water content: Theory. Sensors Journal, IEEE,12(6), 1979-1986.

8. Garnica, J., **Casanova, J. J.**, & Lin, J. (2011, May). High efficiency midrange wireless power transfer system. In Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (IMWS), 2011 IEEE MTT-S International (pp. 73-76). IEEE.

9. **Casanova, J. J.**, Taylor, J. A., & Lin, J. (2010). Design of a 3-D fractal heatsink antenna. Antennas and Wireless Propagation Letters, IEEE, 9, 1061-1064.

10. Low, Z. N., **Casanova, J. J.**, Maier, P. H., Taylor, J. A., Chinga, R. A., & Lin, J. (2010). Method of load/fault detection for loosely coupled planar wireless power transfer system with power delivery tracking. Industrial Electronics, IEEE Transactions on, 57(4), 1478-1486.

11. **Casanova, J. J.**, Low, Z. N., & Lin, J. (2009). Design and optimization of a class-E amplifier for a loosely coupled planar wireless power system.Circuits and Systems II: Express Briefs, IEEE Transactions on, 56(11), 830-834.

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13. **Casanova, J. J.**, Judge, J., & Jang, M. (2007). Modeling transmission of microwaves through dynamic vegetation. Geoscience and Remote Sensing, IEEE Transactions on, 45(10), 3145-3149.

## (d) Synergistic Activities

1. **Main Activities** Dr. Casanova is a research assistant professor in the Department of Electrical and Computer Engineering at the University of Florida. His main research activities are electromagnetic sensors, instrumentation design, and machine intelligence applications. Previously he did research with the USDA in these areas and developed chemistry instrumentation for UFs Chemistry Department.

2. **Professional Membership**
   - 2004-present Member American Society of Agricultural and Biological Engineers (ASABE)
   - 2006-present Member Institute of Electrical and Electronics Engineers (IEEE)

# Biographical Sketch: Jamie Ellis

## (a) Professional Preparation

**Postdoc, Entomology** University of Georgia, Athens, GA 2006

**PhD, Entomology** Rhodes University, Grahamstown, South Africa, 2004

**BS, Biology** University of Georgia, Athens, GA 2000

## (b) Appointments

**Gahan Endowed Associate Professor of Entomology,** University of Florida, October 2013

**Associate Professor of Entomology,** University of Florida, July 2012

**Assistant Professor of Entomology,** University of Florida, August 2006

## (c) Products

Most closely related to the proposed project:

1. Seitz, N., Traynor, K.S., Steinhauer, N., Rennich, K., Wilson, M.E., **Ellis, J.D.**, Rose, R., Tarpy, D.R., Sagili, R.R., Caron, D.M., Delaplane, K.S., Rangel, J., Lee, K., Baylis, K., Wilkes, J.T., Skinner, J.A., Pettis, J.S., vanEngelsdorp, D. 2015. A national survey of managed honey bee 2014 - 2015 annual losses in the USA. Journal of Apicultural Research 54(4): 292-304. http://dx.doi.org/10.1080/00218839.2016.1153294.

2. Schmehl, D.R., Tom, H.V.V., Mortensen, A.N., Martins, G.F., **Ellis, J.D.** 2016. Improved protocol for the in vitro rearing of Apis mellifera workers. Journal of Apicultural Research, 55(2): 113-129. http://dx.doi.org/10.1080/00218839.2016.1203530.

3. Gregorc, A., Evans, J.D., Scharf, M., **Ellis, J.D.** 2012. Gene expression in honey bee (Apis mellifera) larvae exposed to pesticides and Varroa mites (Varroa destructor). Journal of Insect Physiology, 58: 1042-1049. http://dx.doi.org/10.1016/j.jinsphys.2012.03.015.

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5. **Ellis, J.D.**, Evans, J.D., Pettis, J. 2010. Colony losses, managed colony population decline, and Colony Collapse Disorder in the United States. Journal of Apicultural Research 49(1): 134-136. doi: 10.3896/IBRA.1.49.1.30.

Other significant products:

1. V. Dietemann; **J.D. Ellis**, P. Neumann (Eds). 2013. The COLOSS BEEBOOK, Volume I: standard methods for Apis mellifera research. International Bee Research Association, Cardiff, Wales, UK, 640 pp.

2. V. Dietemann; **J.D. Ellis**, P. Neumann (Eds). 2013. The COLOSS BEEBOOK, Volume II: standard methods for Apis mellifera pest and pathogen research. International Bee Research Association, Cardiff, Wales, UK, 352 pp.

3. Graham, J.R., Tan, Q., Jones, L.C., **Ellis, J.D.** 2014. Native Buzz: citizen scientists creating nesting habitat for solitary bees and wasps. Florida Scientist, 77(4): 204-218.

4. **Ellis, J.D.**, Hepburn, H.R. 2006. An ecological digest of the small hive beetle (Aethina tumida), a symbiont in honey bee colonies (Apis mellifera). Insectes Sociaux 53: 8-19. doi: 10.1007/s00040-005-0851-8.

5. **Ellis, J.D.**, Munn, P.A. 2005. The worldwide health status of honey bees. Bee World 86(4): 88-101.

## (d) Synergistic Activities

1. 2015: Hosted an international workshop for government and research agencies to learn techniques for in vitro rearing worker honey bee larvae.

2. 2006 Present: Created over 250 extension publications, including chapters in extension books, curriculum guides and handbooks, instructional multimedia presentations, peer-reviewed extension publications, websites, fact sheets, newsletters, etc.

3. 2006 Present: Supervised or served on the committee of 25+ graduate students and supervised over 15 undergraduate students conducting independent research projects.

4. 1996 Present: Delivered over 550 extension presentations on bee related topics in over 30 countries on six continents.

5. 2011 Present: Teach a distance education, 3-credit course on Apiculture. The entire course is distance based, using innovative technologies to teach students about beekeeping.