Biodegradable Sensors, Attachments, and Power Sources for Agricultural Monitoring *(Faculty Mentor: Mark G. Allen, Alfred Fitler Moore Professor of Electrical and Systems Engineering)* *http://mems.seas.upenn.edu*

A key technology enabler for widespread monitoring of agricultural fields is the ability to make sensors and associated elements that are biodegradable; i.e., that will not contribute to pollution or contamination of the agricultural environment once their functional lifetime and utility is completed. The Allen group is working on fabrication technologies for the realization of sensors, power sources, and packages based on all-biodegradable and biocompatible materials. Micromechanical structures with barbs and piercing structures for position stability[20], pressure sensors capable of RF interrogation[21], and biodegradable batteries and power sources[22] have all been fabricated from biodegradable/biocompatible materials and large- area fabrication methods such as micromolding and lamination (**Fig. 1**).

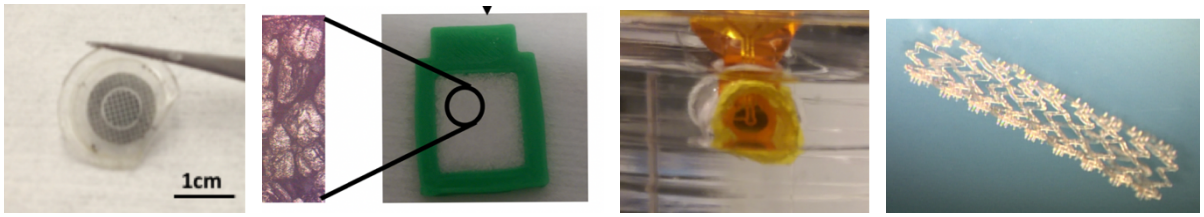


Figure 1. Structures and sensors fabricated from biodegradable/biocompatible materials. (Left) Wireless pressure sensor from biodegradable polymers and metals; (Center left with inset) biodegradable battery based on Mg and NaCl; (Center right) electrochemical sensor for ion and oxygen concentration measurement based on Au and silicone;(Right) Barbed cylindrical package structure from biodegradable polymers for chaff packaging. All structures were fabricated based on large area techniques such as molding and lamination.

REU students will work to expand this technology suite to (1) encompass new biodegradable substrates; and (2) integrate new nano-based sensing materials so as to realize smart chaff suitable for crop monitoring using additional sensing schemes such as water, heat, ions, and pH. Students will not only gain appreciation for the microfabrication technologies needed to produce biologically-degradable MEMS structures and sensors, but will also gain understanding of transduction principles and measurement science in this important application realm.

Data Pipeline Engineering and Integration with models. *(Faculty Mentor: Dennis R. Buckmaster, Agricultural & Biological Engineering, Purdue University)* *https://engineering.purdue.edu/ABE/people/ptProfile?resource_id=42205*

Digital Agriculture, at its best, builds upon decades of discipline research with some integration of new IoT sensors and communication pathways as well as public resource data such as weather, soil, and topography. One challenge to be addressed is to more fully document the backstory or fuller context of situations so that artificial intelligence and machine learning can be more complete and robust. Another is the integration of mechanistic (descriptive of the fundamental science) models that might be biological, physical, chemical, logistical, economic, etc. in origin. The better parameterization of these models and even auto-population of initial conditions can stem from data sets and data streams. In this project, the student will assist in the work to "serve up/present" and curate as much data as we possibly can for part of the cropping system testbed. This data will then meld with biophysical model(s). It will require interoperability focus and that involves wise choices of data architecture and an integration with data pipelines (often based on open-source tools). The end game is to provide better insight (including probabilities, when applicable) for tactical and strategic cropping decisions while preserving security and privacy.

Design of an IoT4Ag Robotic Sensor Deployment System *(Faculty Mentor: David J. Cappelleri, School of Mechanical Engineering, Purdue University)* www.multiscalerobotics.org
The goal of this project is to design an IoT4Ag sensor deployment system for autonomous agricultural ground robot. Two types of IoT sensors must be deployed by the robotic platform. Chaff sensors need to be distributed on the surface of soil at locations with designated spacing to ensure appropriate spatial coverage for the field of interest. The second type of sensors similarly need to be spread about the field but require them to be inserted into the soil at a depth of approximately 6" deep. Thus, the developed sensor deployment system should be able to 1. Store the sensors that need to be deployed; 2. Distribute sensors at a designated spacing above the soil; and 3. Insert the sensors into the ground at a designated spacing in the soil; and 4. Log the type of sensor that has been distributed, its sensor ID, and its placement location. This project will require the mechanical design of the deployment systems, mechatronic system design for operating and controlling the systems, and integration and interfacing with the agricultural ground robot for execution and tracking of sensor deployment locations. Field tests will be conducted at the Purdue University Agronomy Center for Research and Education (ACRE) facility.

Design of a Mobile Robot Deployment System *(Faculty Mentor: David J. Cappelleri, School of Mechanical Engineering, Purdue University)* www.multiscalerobotics.org
The goal of this project is to design and prototype and mobile robot deployment system for transporting a team of agricultural robots to a field of interest. It must also house a charging station for the robots and serve as a communication base station for the team. The platform must be designed to be integrated with an autonomous Polaris Ranger utility task vehicle (UTV). The fleet of robots must be secure when being transported to the field of interest and then be automatically deployed once there. This project will require the mechanical design of the deployment system, mechatronic system design for the charging station and communication system, and integration and interfacing with the Polaris Ranger UTV. Field tests will be conducted at the Purdue University Agronomy Center for Research and Education (ACRE) facility.

Integrated remote sensing systems for high resolution monitoring in agriculture (*Faculty Mentor: Prof. Melba M. Crawford, Agronomy Department, Purdue University)*
https://engineering.purdue.edu/CE/People/ptProfile?resource_id=12521
With the advances in science and technology, it has become possible to generate thousands of genotypes of a plant and produce the seeds at low cost. To evaluate the performance of the plant varieties, numerous physical and agronomic traits are measured in the field during the growing season (phenotyping), and the varieties with the most desirable traits are selected. High-throughput phenotyping using non-invasive remote sensing (RS) technologies in combination with machine learning based analytics has become a critical part of the plant breeding chain focused on reducing the time and cost of the selection process for the "best" genotypes with respect to the trait(s) of interest. In this interdisciplinary project, we will investigate the use of RGB and multi/hyperspectral cameras and LiDAR integrated with ground-based and aerial robotics platforms to measure and monitor variables of interest (e.g. plant count, plant height, leaf area, and spectral response) throughout the growing season to evaluate varieties and management practices. Undergraduate students will work with teams of graduate students in engineering, agronomy, and aviation technology to develop and calibrate robotic systems, acquire and process the remote sensing data, and collect field reference data for predictive models.

Development of AI and Communications for a Drone Base Station Module: *(Faculty Mentor: William R. Eisenstadt, Electrical and Computer Engineering, University of Florida)* https://www.ece.ufl.edu/people/faculty/william-eisenstadt/
The engineering and agricultural researchers at UF and IFAS have been successfully developing systems and AI for precision agriculture including sensors, stationary and roving cameras, powerful computers, communications, and AI analyses to evaluate the crop condition and disease activity. There are great opportunities and challenges in applying these techniques in the field. A prototype being developed that is

a drone base station communications and data module that receives communication and data from a drone, supports AI analysis of the drone data and also receives data from field sensor devices near the drone base station. In this project, the student will look at the new Nordic DECT NR+ technology for long range and MESH communications to support this module. The DECT NR+ technology has a possible communications range of 2 miles. One or more of the following tasks are expected to be accomplished.

- Develop node-to-node data communications between sensors and the data module
- Develop node-to-node communications between the a drone and the data module
- Work on moving image data files from a sensor and storing them on the data module
- Measure the communication distance for on the ground and from a drone to ground.
- Work on image recognition of drone images of crop disease.
- Work on developing the DECT NR+ MESH technology for the field.

See https://www.nordicsemi.com/Products/Wireless/DECT-NR

Co-design of Optical Sensor – Detector Systems *(Faculty Mentor: Cherie Kagan - Penn)* Current remote sensing techniques utilized in precision agriculture involve RGB, multi/hyperspectral, and LiDAR imaging using aerial and ground robot systems. These systems cannot directly measure plant stress indicators such as transpiration rate and leaf temperature. Low-cost, biodegradable colorimetric sensors are being developed in IoT4Ag to directly measure plant stress indicators and communicate this information through optical signals detectable with current imaging systems. We propose an REU project to define specifications for, and co-design optical sensor-detector systems. These sensor-detector systems are composed of highly-reflective optical sensors consisting of nanostructured metasurfaces embedded in adaptive polymers deployed on soil and leaf surfaces, and optical detectors mounted on ground and aerial robots for sensor readout. Metasurface resonances shift as the adaptive polymer responds to environmental stimuli, yielding a change in color to be read by cameras. We aim to design high quality-factor (Q) metasurfaces by engineering the size, shape, composition, and arrangement of constituent nanostructures, such that the signal-to-noise ratio is maximized. The project also involves developing a testbed to assess the detector sensitivity to camera orientation and distance from the sensor, sensor reflectivity, camera resolution, natural/artificial illumination etc. to inform metasurface sensor design criteria. Image analysis will be conducted to derive quantitative metrics of sensor-detector performance and to select cameras with suitable size, weight, and operating spectral range for deployment.

Development of ISOBlue: An Open Source Platform for Edge Computing and Communications to Enable At-Scale Data Collection from Novel Agricultural Sensors (*Faculty Mentor: Prof. James V. Krogmeier, Electrical & Computer Engineering, Purdue University)* https://engineering.purdue.edu/~jvk/ This project focuses on leveraging existing ag machines (tractors, combines, sprayers, etc.) as mobile platforms for sensor data collection, processing, and cloud connection. Because these sorts of machines travel widely over a farm and have ample power and space for communications and edge computing they are ideal for early deployment of IoT4Ag sensors. This work builds on the existing ISOBlue project[1] to extend its influence beyond simple logging of a machine's controller area network (CAN) bus to general purpose edge computing that can also support a host of radios, software defined radios (SDRs), and backhauls. Over several development cycles the ISOBlue project has evolved to be a software stack, called Avena, that provides open source developers a telematics and edge computing base for creation of farm machine software applications. In order to provide abstraction and a predicatable software-machine interface, a collection of open source tools is used in its implementation including Docker, for consistent software-runtime and easy distribution, Wireguard, for secure and flexible network access, NATS.io, for message queue supporting inter-process communication and micro-service style pipelines, and Ansible, for consistent deployments. An REU student will work on the ISOBlue project to add the capability to perform as a LoRaWAN gateway and/or to incorporate CBRS/TVWS and SDR style radios as a backhaul for machine and other nearby sensor data and run machine-to-machine communication experiments.

Precision Agriculture in Orchards *(Faculty Mentor: Prof. Vijay Kumar, Professor of Mechanical Engineering and Applied Mechanics, Computer and Information Systems, and Electrical and Systems Engineering, University of Pennsylvania)* https://www.kumarrobotics.org
Precision agriculture, namely continuous, high spatial resolution monitoring of the acreage of a field and the crops thereon, promises better management of irrigation, energy intensive fertilizers, and other plant nutrients, as well as identification of crop stress. Remote sensing satellites and airborne sensing with winged aircraft have allowed scientists and farmers to map large farmlands and forests through acquisition of multispectral imagery and 3-D structural data. However, data from these platforms are costly and typically lack the spatio- temporal (e.g., cm-scale, day-to-day) resolution necessary for precision agriculture. A REU student will work with doctoral students in Kumar's group to develop the integrated hardware and software to enable the automated acquisition of data and the translation to actionable information for farming of high-value crops.

UAV Trajectory Optimization for Communications Coverage *(Faculty Mentor: David Love, Purdue)*
Precision agricultural systems depend on high-rate communications for controlling the myriad of agricultural control and sensing applications. To provide this connectivity, new network deployment approaches are needed. In this project, we look at how a UAV can be used to offer connectivity over a large coverage area. We optimize the UAV trajectory subject to aerodynamic, power, and rate constraints. Our focus is primarily on fixed-wing UAVs which can be used for other precision agriculture applications in addition to communications.

Wireless Communication with Subsurface Agricultural Sensors (*Faculty Mentor: Prof. Troy Olsson, Electrical and Systems Engineering, University of Pennsylvania)* https://olssonlab.seas.upenn.edu/
To massively deploy agricultural sensors key breakthroughs are needed in the cost, volume, biodegradability, and subsurface operation of wireless sensor interfaces. The objective of this project is to develop radio frequency (RF) hardware and waveforms for remotely and passively interrogating buried agricultural sensors. The Olsson lab is exploring passive wireless sensor architectures that minimize the number and size of the wireless components, are amenable to interfacing with a broad range of sensors, and are constructed entirely from biodegradable and/or benign materials. In particular, we are exploiting the recent breakthroughs in the performance of RF microelectromechanical systems (MEMS) devices developed in our lab to miniaturize and extend the range of passive wireless sensors. In this REU project, the student will participate in the design of passive wireless sensors, their components, and interrogation waveforms. The RUE student will also characterize the passive wireless sensors in both a laboratory and subsurface field environment, providing valuable feedback to improve the designs.

Spraying-based deployment of biodegradable agricultural sensors (*Faculty Mentor: Prof. Kevin T. Turner, Mechanical Engineering and Applied Mechanics, University of Pennsylvania)*
http://turner.seas.upenn.edu/
IoT4Ag has developed a new class of passive biodegradable agricultural sensors that adhere directly to the leaves of plants and provide data on plant health. Deploying these sensors in large numbers in the field is challenging, and new sensor deployment approaches are needed. We are currently developing spraying-based approaches where sensors are encapsulated in liquid or gel droplets and sprayed onto plants. This REU project will investigate different materials and spraying conditions to realize the successful sensor deployment and attachment. The student will experimentally evaluate different liquids, gels, and spraying conditions using a custom spraying setup and also demonstrate sensor attachment on plants. If the student is interested, there is an opportunity to augment the experimental studies with computational modeling of the droplet impact and drying process. This project is well-suited for a student interested in applying fluid mechanics and/or knowledge of soft materials to a novel application.

Autonomous Interactive Plant Root Phenotyping Applications *(Faculty Mentor: Alina Zare, Professor of Electrical and Computer Engineering, University of Florida)* https://faculty.eng.ufl.edu/machine-learning/

In order to understand how to increase crop yields, breed drought tolerant plants, investigate relationships between root architecture and soil organic matter, and explore how roots can play in a role in greenhouse gas mitigation, we need to be able to study plant root systems effectively. However, we are lacking high-throughput, high-quality sensors, instruments and techniques for plant root analysis. Techniques available for analyzing root systems in field conditions are generally very labor intensive, allow for the collection of only a limited amount of data and are often destructive to the plant. Once root data and imagery have been collected using current root imaging technology, analysis is often further hampered by the challenges associated with generating accurate training data. Most supervised machine learning algorithms assume that each training data point is paired with an accurate training label. Obtaining accurate training label information is often time consuming and expensive, making it infeasible for large plant root image data sets. Furthermore, human annotators may be inconsistent when labeling a data set, providing inherently imprecise label information. Given this, often one has access only to inaccurately labeled training data. To overcome the lack of accurately labeled training, an approach that can learn from uncertain training labels, such as Multiple Instance Learning (MIL) methods, is required. In this REU project, we will investigate and advance approaches for characterizing and understanding plant roots using methods that focus on alleviating the labor intensive, expensive and time-consuming aspects of algorithm training and testing.

Digital twining for agricultural system and sensor design *(Faculty Mentor: Charlie Messina Professor of Horticultural Sciences, University of Florida, Director of UF/IFAS Crop Transformation Center)* https://croptransformation.ifas.ufl.edu/people/ The development of affordable and scalable sensing and communication technologies by the NSF IoT4Ag ERC enables reimagining agriculture to increase food production while reducing greenhouse gas emissions. To realize this opportunity, these technologies need to be integrated within decision support systems from farm to small catchment scales. Digital twining is an emerging approach that could be applied to the design of agricultural systems including sensor types and deployment. The SWAT model simulates water and nutrients surface and subsurface flows, and how water and nutrient availability affects crop growth and development. This 3D spatio-temporal model can be used to assess the environmental impact of land use and crop management practices on food production. In this REU project, the student will work with the digital twin SWAT to design agricultural systems comprising crop genetics, agronomic management and sensor type and networks that can increase system outputs while reducing inputs and environmental externalities including greenhouse gas emissions. The student is expected to interact with other students engaged in sensor design.