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INVESTIGATOR: Gu, Y.

PERFORMING INSTITUTION:
WEST VIRGINIA UNIVERSITY
886 CHESTNUT RIDGE RD RM 202
MORGANTOWN, WEST VIRGINIA 26505-2742

PRECISION POLLINATION ROBOT

NON-TECHNICAL SUMMARY: One of the major issues concerning current agricultural production is crop pollination. Approximately $24 billion per year worth of crops in the U.S. rely on pollination by various pollinators. However, the recent decline of honey bees (i.e. colony collapse disorder) has greatly threatened productivity. Declines of other native pollinators, such as different insect types and animals, have also been reported. Such shortages of pollinators in the U.S. have significantly increased the cost of farmers' renting them for pollination services. From both economic and food sustainability points of view, there is an urgent need to seek alternative pollination systems.In this project, a multi-disciplinary team of researchers will develop a prototype of precision pollination robot for bramble (i.e., blackberry and raspberry) pollination in a greenhouse environment. The project team will use a robotic arm carried by a ground rover for precise flower manipulation. Computer vision algorithms will be used to estimate the flower position, size, orientation, and physical condition, and to guide the robotic arm to capture and interact with flowers. A set of soft brush tips, mimicking bee's hairs and motion, will then be used to pollinate flowers. The precision rover navigation, mapping, and localization of individual flowers within complex greenhouse environments will be provided through a fusion of multiple types of sensor measurements. A database will be automatically generated and updated by the robot, recording the history of flower development and pollination status. A human operator will collaborate with the robot through supplying agriculture domain knowledge, providing high-level decisions, and correcting mistakes made by the robot. The efficiency and throughput of the prototype pollinator robot will be evaluated through a comprehensive set of experiments comparing multiple pollination methods.The successful completion of this research project will significantly impact the field of precision agriculture. First, robotic pollinator bypasses many current issues with natural pollinators in agriculture, such as honeybee colony collapse disorder, pollinator parasites and diseases, predators, pesticide spray, adverse weather, and the availability of pollinators in a timely manner. Second, robotic pollinators will improve fruit quality and production. Such applications include selective pollination, selective abortion of flowers, and digital cataloging, condition tracking, and yield prediction for fruit productions. Finally, the precision localization, evaluation, and manipulation of small and delicate plant parts provides fundamental capabilities for enabling a variety of other precision agriculture applications such as automated irrigation, fertilization and harvest, monitoring plant damages, as well as weed and pest control.The outcomes of this research project will be broadly disseminated to the research community, the growers, and the general public. This project will also

enhance regional educational and outreach activities and broaden the participation of students from underrepresented groups.

OBJECTIVES: The goal of this research project is to develop a prototype pollinator robot, and perform proof-of-concept demonstrations of its effectiveness for brambles pollination in a greenhouse environment. In supporting of this goal, the project involves the following four main research objectives:1. Investigate the detailed mechanisms of pollination between bees and flowers in order to provide the knowledge and bio-inspiration for the pollination robot design.2. Develop autonomous capabilities to precisely locate, evaluate, interact, and manipulate small and delicate plant structures within unstructured, low-dynamic, and GPS-challenged greenhouse environments.3. Perform system integration and proof-of-concept demonstrations of precision robotic pollination.4. Perform detailed evaluation of the prototype pollinator robot efficiency and throughput as compared to existing pollination methods.

APPROACH: We will use a robotic arm mounted on an existing ground rover for precision flower access and manipulation. Computer vision algorithms, using images captured in both visual and UV spectra, will be used to estimate the position, orientation, size, and condition of the flowers. A set of soft brush tips, mimicking bee's hairs (i.e. scopa) and motion, will then be used to pollinate flowers. The design parameters of the delicate robot-flower interface will be driven by a series of insect pollination experiments. The precision rover navigation, mapping, and localization of individual flowers within complex greenhouse environments will be provided through a fusion of GPS, Lidar, camera, inertial sensor, and wheel encoder measurements. A database will be automatically generated and updated by the robot, recording the history of flower development and pollination status. A human operator will collaborate with the robot through supplying agriculture domain knowledge, providing high-level decisions, and correcting mistakes made by the robot. This intelligent system will allow more selective, consistent, and uniform pollination, which has the potential of leading to better fruit set and production at a large scale. The evaluation of the project will be based on a study that compares the yield and fruit quality with several different conditions such as no pollination (i.e. control), natural insect pollination, manual pollination, robotic pollination, and collaborations between human and robot pollination. The effectiveness of pollination will be evaluated by determining the fruit yield per plant, fruit size, fruit weight, harvest time and overall distribution of fruit across a plant.

PROGRESS: 2019/11 TO 2020/11
Target Audience:Findings from this project were presented at an annual national conference, American Society of Horticultural Sciences, which is attended by students, faculty, and industry scientists, and a department seminar at West Virginia University. Due to COVID-19, other outreach activities have been limited during this period. We have been given virtual lab tours to other researchers, undergraduate students, and high school students. Changes/Problems:Due to the COVID-19 pandemic, complex robot experiments that require multiple participants become very difficult to perform. To partially mitigate this issue, we have developed a robotic pollination simulation to continue develop and test the precision robotic pollination technology. What opportunities for training and professional development has the project provided?During this project year, a total of eight graduate students, four undergraduate students, and one postdoc research fellow were involved on the project. The team members received hands-on training through the participation of this multidisciplinary research project. They also learned team-working and leadership skills when interacting with other project members. How have the results been disseminated to communities of interest?During this project year, the results of this project have been disseminated to science community through a conference paper, a Ph.D. dissertation, and one seminar talk. The outcome from the research was used in developing curriculum material for an Introduction to Digital Image Processing class and a Mobile Robotics class. The WVU greenhouse hosted a tour for undergraduate horticulture students. At the tour, the summary of the project and the importance of the research were explained. The team members have also given several robotics lab tours (either physical or virtual), and presentations to high school students. What do you plan to do during the next reporting period to accomplish the goals?We will continue to develop the pollination robotics simulation, leading to the

open release of the code. We will also write manuscripts on robotics technology and bee hair structure and foraging behavior.

IMPACT: 2019/11 TO 2020/11
What was accomplished under these goals? Entomology To develop an effective end effector of the BrambleBee robot, we examined detailed hair structure and pollen adhesion to bee hairs using scanning electron microscope. Through examination of bee hairs on the body of Osmia cornifrons, the Japanese hornfaced bee, we were able to group and categorize seven different types of bee hairs: branched hair, side-branched hair, abdominal scopal hair, brush hair, basitarsal brush hair, chisel-tip brush hair, and enlarged-tip brush hair. The seven hair types could be grouped further into simple, compound, and complex hair. Branched hair and side-branched hair (mostly responsible for pollination) were compound hairs while enlarged-tip and chisel-tip hairs (mostly for cleaning body) were complex hairs. Branches on compound hairs (about 10 μm in length) help increase a chance to collect pollen. We found that the role of branched hair was to collect pollen by providing a large surface for pollen acquisition and heat conservation; we observed a considerable amount pollen grains adhered to or trapped by branched hairs. Abdominal scopal hairs were elongated stiff setae and slanted backward. Compared with branched hairs, they were thicker and spirally twisted. The length of most scopal hairs were 1.2 mm and hair stand about 40 ~ 60 μm apart from each other, which can pack the collected pollen to carry to their nests for pollen provision. All the brushed hairs on trochanter, femur, and tibia were short (about 0.3 mm) and twisted form with point tip. Enlarged-tip brush hair had spatula-like tips and they were found in tibia and basitarsus. Chisel-tip brush hairs whose tip were located in tibia and femur of hind leg. These brushes were used to groom mostly but we also found many pollen grains. BrambleBee Robot System Pollination End-Effector Design: a new iteration of robotic pollination end effector was designed in order to mimic methods that natural pollinators use when pollinating flowers. The manipulator consists of three linear servos attached to a flexible 3D printed plate outfitted with a soft membrane that collects and distributes pollen onto the flowers. It is controlled using a lookup table that was constructed using known positions of the flexible plate given motor outputs. Robot Localization: the localization algorithm has two improvements. First, since our localization system is set up based on Robot Operator System (ROS) and time delay occurs during message transferring, a time synchronization module is implemented after receiving messages from sensors. With the assistant of the synchronization module, the motion estimates show to be more stable than our previous results. Second, the raw point cloud scan from the Lidar sensor has been de-distorted utilizing the initial measurements from the INS system. This step improves the performance of the point cloud matching algorithm. Computer Vision for Flower Detection and Localization: the improved computer vision system includes 1) a new set of data collected in the greenhouse, 2) a new classifier trained on the collected dataset, and 3) a new method for localizing the flowers with increased precision using a combination of depth and color images. The flower identification system replaces the segmentation and classification steps of the previous system with a single step using Mask R-CNN. This method provides both a bounding box containing the segmented flowers as well as a mask (or binary image) identifying the segmented flowers. The depth images corresponding to each flower are now used for localizing the flowers and improve the pose estimation resolution. The flower localization algorithm works by loosely modeling each flower as a plane. Using the point clouds computed from the depth images, the best fit plane is computed. The normal to the plane is used to represent the orientation of each flower and the centroid of the point cloud is used for representing the position of each flower. Each plane normal is converted to a transformation that can be used for moving the end-effector to the center of each flower for pollination. Robust Pollination under Uncertainty: one of the key objectives of a precision pollination robot is robust pollination under a variety of sources of uncertainty. Computed flower pose is often inaccurate due to noisy sensors and estimation errors. Our experiments have shown that the primary mode of failure is due to the poor estimation of the flower pose. The goal of this effort is to arrive at a principled approach for the pollination robot that improves the success rate of the pollination task. To achieve that goal the research team is actively investigating two approaches namely 1) combined planning and learning approach, where we model the problem as a Partially Observable Markov decision process (POMDP) and 2) frame the pollination task as a hard exploration problem, where a single positive reward is

given only when the robot successfully pollinates the flower. Simulator Development: given the COVID-19 pandemic, physical testing of robots has been limited. A pollination simulator is being developed using Gazebo in conjunction with ROS. This provided a high-fidelity environment that could run the same code as the physical robots, using simulated hardware interfaces. The Gazebo environment uses Universal Robot Description Format (URDF) files as simulation models for the robots. The robot's sensors, such as IMU, lidar and encoders are also modeled in the simulation environment, with uncertainty and noise factored in. The greenhouse testing facility, plants, and flowers were modeled in Blender, then exported with texture images as COLLADA files that are readily able to be used with Gazebo. This design with textures allows for the future use and testing of different flowers. All the previously developed algorithms such as localization, mapping, robot motion planning, control, and the flower classifier can be ported over to the simulated environment with minimal changes to the algorithms that consisted of the differences between the physical sensors and the modeled sensors. Horticulture To determine the optimal time for pollination, pollen production, and viability tests were conducted using pollen collected at different stages of flower development. Pollen was collected by shaking the flower and placed on germination media. Pollen was incubated for three hours at the same temperature as the plants were grown (23.9 ± 1.8/ 20.2 ± 1.6 °C, day/night ± st. dev.). Pollen production was evaluated by counting the number of pollen grains at 4X magnification using an Olympus microscope BX53 and digital camera DP26 (Olympus America, Inc., Center Valley, PA). The pollen was considered viable if the pollen tube was longer than the diameter of the pollen grain. The pollen length was measured using imaging software cellSens™ 1.6 (Olympus America, Inc., Center Valley, PA). Data were analyzed by PROC GLM using SAS version 9.3 (SAS Institute, Inc., Cary, NC). Differences in pollen viability were determined by Tukey's significance test at $P \leq 0.05$. We found that viable pollen can be collected two and three days after anthesis (flower opening). Pollen collected one and four days after anthesis had not dehisced and had significantly lower viability, respectively. Two methods of pollination (the robot's end-effector and hand pollination) were compared to a control where flowers were not intentionally pollinated. There was no difference in the number of drupelets between the no pollination control and the robot pollination. Robot pollination produced larger berries than the control, although hand pollination produced the highest number of drupelets and the largest fruit.

PUBLICATIONS (not previously reported): 2019/11 TO 2020/11

1. Type: Conference Papers and Presentations Status: Published Year Published: 2020 Citation: Mills, S. A., Gu, Y., Gross, J., Li, X., Park, Y. L., & Waterland, N. L. Evaluation of an Autonomous Robotic Pollinator. American Society for Horticultural Science Annual Conference. August 10-14, 2020. (Virtual presentation)
2. Type: Other Status: Awaiting Publication Year Published: 2020 Citation: Mills, S. A., Gu, Y., Gross, J., Li, X., Park, Y. L., & Waterland, N. L. 2020. Evaluation of an Autonomous Robotic Pollinator. HortScience (Abstr.)
3. Type: Theses/Dissertations Status: Published Year Published: 2019 Citation: Watson, R., Enabling Robust State Estimation through Covariance Adaptation, WVU Ph.D. Dissertation, Dec 2019.