ESE 451 - Spring Final Report - May 6th, 2019

Team 2, TeaBot

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I. Executive summary

At present, tea harvesting requires a great deal of manual labor. As with many industries requiring repetitive actions, there is a desire to automate this process and remove the need for human laborers. Our project seeks a solution to this problem by developing a robot that harvests the desirable parts of tea plants (usually the three youngest leaves at the tip of the sprout).

The robot consists of two main subcomponents: a vision component and a mechatronics component. The vision component requires the ability to view the plant through an RGBD camera and locate the desired part of the plant as well as localize its position relative to the camera. The mechatronics component consists of a mechanical arm receiving information telling it where to reach in order to extract the leaf. The two components integrate to create a robot that can perceive and interact with its environment.

Given that this is a challenging open question in research, we were only able to create a proof of concept prototype and not a robust product that would be viable in an agricultural environment. There is still much work to be done after our project in order to make the robot truly mobile and capable for field use. Nonetheless, we believe the demonstration of the vision and mechatronic systems together provide a solid foundation for future improvements.

II. Overview of project

By creating TeaBot, we are trying to automate the process of tea harvesting, in order to solve the rising problem of scarcity of trained labor availability in rural areas where tea plantations are located. According to the Ministry of Agriculture of the People's Republic of China, China alone has 77 million acres of land devoted to tea cultivation and produces 25.8 million metric tons of tea every year. Tea production has increased steadily for the last 10 years and this trend is expected to continue.

However, as the economy of countries where major tea plantations are located develops, the labor force starts migrating more into the city as urban jobs are much more desirable, leaving an insufficient labor force left for tea harvesting in rural areas. This causes a major problem since tea harvesting is very time sensitive. If the young buds are not harvested in time, they are no longer desirable for high-end tea. Research has shown that if no buds were wasted, each acre of land can produce up to 3 times more tea. Therefore, an automated harvesting process is crucial to the longevity of tea plantations going forward. With this problem in mind, TeaBot is designed and developed to be the all-in-one solution to tea harvesting, where preliminarily it accurately detects and picks desired tea leaves. Future developments would include making the robot mobile, as well as incorporating solar panels for a more sustainable design.

Figure 1: The trend in tea production; shows the motivation behind autonomous tea harvesting

III. Technical description

When designing this system, we had to keep in mind the final environment in which the system would be deployed. In our case, the system should be robust enough for outdoor environments where lighting and wind conditions vary drastically. Additionally, this system is meant to replace the need for human labor, which means the amortized cost should total to be less than the cost of employing human laborers. On average, Chinese tea harvesters are paid 200 yuan per day. Assuming that the tea harvesting season is six months long, this means a plantation pays $6000 USD for a single laborer. If our system is able to match the efficiency of a single human, the cost of the system should be less than $6000. This is a reasonable target because the system would be able to last multiple harvesting seasons and therefore have an amortized cost that is less than the cost of human labor.

These requirements led us to select the delta robot configuration to handle the mechanical actuation and harvesting motions. This kind of configuration is ideal for rapid pick and place tasks because the driving motors are fixed to the base plate, allowing the end effector of the robotic arm to be very lightweight. Additionally, the parallel configuration shows better stiffness, positioning accuracy, and load carrying capacity compared to serial manipulators. Currently, these robots are very popular as a new configuration for 3D printers as well as in factories for pick and place motions.

Before settling on the delta robot, we considered using a serial manipulator like the Lynxmotion 5-DOF robot. However, these robots are not able to make rapid motions because each serially connected motor would introduce some degree of overshoot, causing the final position to be inaccurate. We also did not need five degrees of freedom because we only need to control position and not orientation. Using the Lynx robot would mean powering two additional motors which would increase the weight and power consumption of the overall system.

After determining that the delta robot should handle the motion to mimic a human arm, we had to determine how to mimic the motion of human fingers harvesting the tea leaves. We considered three different motions for removing the leaf from the plant using a gripper: twisting, pulling, or cutting. After doing some research into the tea industry, we discovered that most plantations actively avoid cutting the leaves because it alters the stem and can cause a subtle change in the flavor of the tea. After visiting the tea plantation in person, we were able to determine that both pulling and twisting are viable options for leaf removal. Since the tea leaves that we are interested in are the young buds, pulling of the leaf off directly requires very little force. Therefore, for our final design, we decided on the simplest method of pulling straight upward. This further helps to lighten the end effector because we don't need an additional servo to create a twisting motion.

Our final prototype is a custom-built delta robot mounted on an aluminum frame. The delta robot consists of a combination of steel, acrylic, and plastic components in order to ensure sturdiness while keeping a lightweight design. The delta robot is actuated by three stepper motors (DQ-42HB60A) which are driven by three individual motor drivers (TB6600). These motors are controlled by the grbl library loaded onto an Arduino Uno which allows the motors to be driven in parallel. A second Arduino is used to control the servo motor used to drive the gripper attached to the end effector. All of the inverse kinematic calculations (used to convert x, y, z positions to motor angles) are performed in Python.

One challenge we came across when driving the delta arm was the stepper motors did not have enough holding torque to hold the forearm above 45 degrees. We tried to fix this problem by replacing the steel components with acrylic and 3-D printed parts, but the weight of the servo and gripper on the end effector still restricted the motion of the forearm to 80 degrees. We needed the range of motion to reach 110 degrees, ideally. We had to either creatively reduce the effective weight of the arm, or replace our stepper motors with higher torque motors. The problem with the high torque motors was that they had different dimensions from the steppers we were already using, so making the switch would mean replacing many other custom parts. Instead, we decided to attach a spring between the base plate and the end effector. This helped to reduce nearly half of the effective weight of the arm and allowed it to achieve a full range of motion.

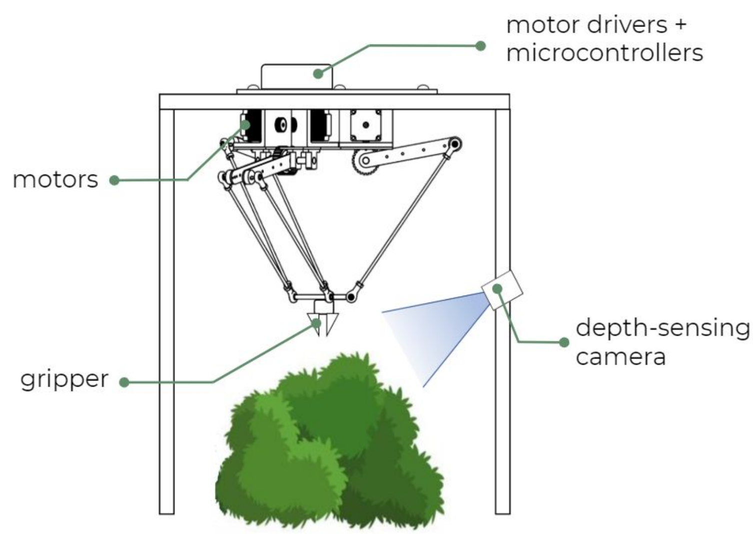


Figure 2: Final system design diagram

On the vision side, we are using the Intel Realsense D415 RGBD camera to retrieve both color and depth frames. The color frames are used for identifying the target leaf and the depth frames are used to find the location of the leaf in 3-D space. In order to identify the target leaves, we first convert from the RGB color space to the HSV color space because this allows our color segmentation to be more robust to lighting changes. We then threshold on the HSV value to isolate the shade of green that corresponds to the young buds and leaves. We tested this algorithm on a video of tea bushes taken at the tea plantations, and the algorithm was able to correctly identify the young buds with few false positives.

Figure 3: Left - Raw image of tea buds among tea bushes; Right - Algorithm output correctly identifying the target tea buds

In order to integrate the vision and the mechatronic components, we tried two different approaches. The first approach was moving the end effector to 8 pre-programmed positions, allowing the camera to read these positions, and then using the Procrustes algorithm to calculate the transformation matrix from the camera frame to the robot frame. In theory, after we determine the transformation, we can take the positions from the camera frame, convert them to positions in the robot frame, and then convert these positions to motor angles using inverse kinematics. However, since our robot was self-built, many of the geometries were imperfect, causing the inverse kinematics equations to be inaccurate. When the end effector was commanded move four inches, it would move closer to 3.5 inches instead. Since the motion of the end effector does not have a linear relationship to the motor angles, it was difficult to accurately compensate for these errors. Given our limited time frame, we had to think of an alternative solution that bypasses the need for the inverse kinematics calculations.

Our second approach was quantizing the reachable workspace of the end effector and creating a mapping from the camera coordinate to the corresponding motor angles at each quantized point. Then when the camera locates a target leaf, it will find the four closest positions in the map and interpolate the motor angles needed to reach the desired point. The idea behind this is that although the relationship between the position and the motor angles are not generally linear, they can be linearly approximated at short intervals. Creating the mapping was a tedious process, but the arm was much more accurate and could actually grasp the target leaves after we made this change. The main downside to this approach is the relative position of the camera to the arm must stay the same, otherwise the mappings will have to be readjusted. We ensured that the camera and robot were both tightly secured to the frame before proceeding with taking measurements.

IV. Self-learning

From our background research on this project, we realized that the majority of the data processing is most efficiently done through Python and its popular libraries like Pytorch and OpenCV. So, without any of us having much prior experience with using Python, we had to self teach Python and how to use its libraries from online resources. In addition, we had to learn to operate the firmware of our Intel Realsense D415 3D depth camera, in order to record and extract data from it. Furthermore, in order to determine how to control the motion of the robot, we had to learn about forward and inverse kinematics for parallel manipulators, and then solve the equations using Python.

MEAM 520 and CIS 580/581 were helpful for this project for the mechanical and computer vision portions respectively. MEAM 520 provides the background on how to control the kinematics of a serial manipulator, so it was relatively easy to translate the knowledge over and apply it to parallel manipulators. CIS 580 covers projective geometry while CIS 581 covers computer vision and computational photography. This gave a good background on basic computer vision principles and how to use OpenCV and Pytorch, which proved to be useful in the computer vision component of our project.

Taking ESE 305 in the Fall provided basic knowledge on Python and some of its basic libraries. Though none of those libraries learnt in ESE 305 were particularly relevant to our project, having basic knowledge on the language helped us quickstart the self learning process. Additionally, the entire team took ESE 350 in Spring 2018, which has helped accustomed the team members to embedded systems and how we might go about designing our robot. This was especially helpful as we pulled together the two components of the project in the Spring, as we may needed various embedded components to help power and control our robot.

V. Ethical and professional responsibilities

One ethical issue that our project may encounter is that of the economic implications of job automation. If this technology comes to fruition, it may cause displacement of laborers. Automated machines such as our TeaBot are able to do more fine, detailed work than humans can, and they respond to situations way faster than humans can. As a result, it is estimated that 500 million jobs could be automated by 2030. This automation of jobs in society will lead to the growth of inequality because low income and middle income workers are the first to be replaced and the excess revenues from production, are only then re-distributed to the smaller portion of the economy that own this technology.

Despite that, the benefits of our project outweigh the negative impacts. The goal of our project is to eliminate repetitive tasks, but still creating more productive tasks for people to focus on and to also create more opportunities that will arise as a result of the growth of the automation industry.

In terms of safety, our robot also has to be environmentally safe for it to be distributed and used by end users. In order to ensure this, we have been investigating more into these potential risks. The goal is to minimize the risks as much as possible, and to provide usage guideline to make sure that our robot is not used in any harmful way or for illegal purposes.

VI. Meetings

We met with our primary adviser, Dr. Taylor, every three to four weeks on average, in order to give him updates on the progress of our project as well as to receive feedback on what we may do in the future. We often consulted Dr. Taylor for advice on computer vision specifically.

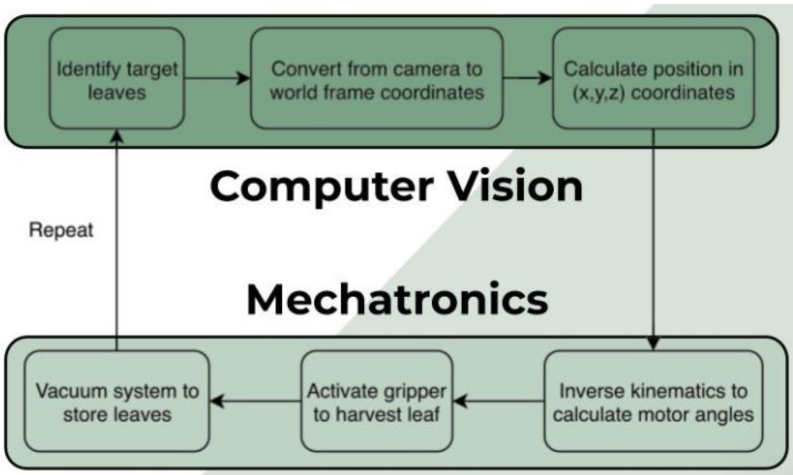
Throughout the course, Professor Taylor similarly suggested scaling down the idea. Instead of trying to tackle and combine all the different fields, he advised perhaps choosing a specific area of the entire problem to focus on. He was particularly concerned with our lack of MEAM for this kind of project; he mentioned how robot hand manipulation for plant harvesting is still an unsolved problem. He suggested that we seriously considering seeking out someone with that appropriate background - perhaps reaching out to a MEAM faculty member to be a technical adviser. He emphasized focusing on good electromechanical design and he thought that the software functionality could come after. He told us to do plenty of prototyping, and to expect failure - it should be an iterative process as we try and discuss a progression of designs.

We also reached out to Dr. Sung for advice on mechanical design. Professor Sung helped us with our design choice of a delta robotic arm and she gave us more insights on most of the options for robotic arms that we could go for.

VII. Proposed schedule with milestones

Our focus in the Spring was refining our individual subcomponents and then integrating them. For our mechanical component, we found continued issues during the Fall semester, in developing what kind of mechanical arm we wish to use. The design of our arm has continued to evolve, especially as we consider what kind of gripper we need for our task. The design of the mechanical arm continued to evolve throughout the project. Eventually the design converged on a delta arm, as this provided the necessary mobility and stability for the motions. For our computer vision component, there were difficulties in the compatibility of our Intel RealSense camera device, as well as choosing an appropriate model for our image recognition process. We eventually upgraded to a newer model, from the R200 to the D415, which solved many of our difficulties in the computer vision aspect of our project.

Fortunately, we were able to use the last few weeks of the Spring to focus on the integration and development of our final robot. The following is a visual representation/block diagram on how the subsystems interacts, which helped guide us as we integrated our project:



A diagram of the subsystem design and flow of our project.

VIII. Discussion of teamwork.

Brandon and Peak lead the development in the computer vision area. They demonstrated an image processing program that can take in photos of tea plants and perform a leaf segmentation algorithm, outputting the parts of the image that correspond to the leaves that we are interested in. Using the Intel Realsense Camera, they wrote a program that outputs the x, y, z coordinate of the leaf in space. Brandon was also very proactive when putting together the deliverables for the team. This included write ups as well as presentations.

Eileen and Fari worked on the mechatronics components together. Together Fari and Eileen put together the mechanical components part of the project. Fari brought in knowledge from MEAM when printing and designing the robot. Eileen worked on the kinematic motions of the robot in Matlab, and focused heavily on the integration code for the computer vision and the kinematics of the robotic arm.

IX. Budget and justification

Hardware components:

- 3D-printed robotic arm (instead of manufactured arm)
- Two Intel Realsense cameras (R200 and D415) and robotic kit ($300)
- Plants for testing ($12)
- Motor Drivers ($35)
- Stepper Motors ($60)
- Grip Kit ($37)
- Frame Parts($60)

Our budget was within roughly $60. Note that any software we have used has been free (either open-source or licensed, but paid by Penn).

X. Standards and compliance

There are quite a few engineering standards that guided us as we worked on our project. Our designs and specifications are in acknowledgement of IEEE 1872-2015, which is a Standard Ontologies for Robotics and Automation. We also observed the Standard P7007l, an Ontological Standard for Ethically Driven Robotics and Automation Systems. This standard specifies what constitutes an ethical robotics design, and it was also our guiding principle in designing an environmentally safe robot. After doing our best to comply with these standard, we are sure that our robot is safe for the users as well as the environment.

XII. Work done since last semester

It would be accurate to say that the bulk of the project was accomplished in the Spring semester. Early on in the Spring, we were able to acquire the necessary parts to begin building our robot, which allowed us to test our kinematics equations. Furthermore, after struggling for a while to get the R200 model to work, our freshmen mentees were able to assist us greatly in working with the R200. Ultimately we decided to upgrade to the newer D415 model, which fortunately proved to be much easier to use. We focused on integrating in the last few weeks and were able to produce an end result that we were quite pleased with.

XI. Future improvements

Software

- Improve computer vision algorithm by using deep learning for bud/leaf recognition
- Use optical flow to track leaves of interest and implement closed control loop

Hardware

- Lighten components to allow for faster motions
- Use multiple arms in parallel to increase harvesting efficiency
- Add solar power to make it more sustainable in outdoor environments
- Add self-driving component

XII. Discussion and conclusion

We are happy with the progress we have made over the past several months. Much of the Fall was spent planning our project. Because none of us have tried to tackle a robotics project of this caliber before, there was a significant amount of time spent researching and preparing for various aspects of the project. Given the difficulty and amount of moving parts in this project, we were surprised but proud with what we were able to accomplish. It was a long and challenging process, but we're very excited with what we have done and hope to improve upon this model in the future.

XIII. Appendices

See images in corresponding sections: **II. Overview of project**, **III. Technical description**, **VII. Proposed schedule**