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INTELLIGENT FARMING USING MODULAR MOBILE ROBOTS

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Introduction

Problem Statement

Traditional farming techniques are increasingly being replaced by mechanized solutions, but there are many farming problems today that can only be solved by manual labor. Crops like grain and corn are all collected and processed mechanically, and at a very high efficiency. However, delicate crops like tomatoes and oranges must be picked, processed, and packaged by hand. This process is extremely labor intensive.

Most of the technologies that can enable the automation of these tasks are simultaneously coming down in price and up in quality. These changing factors are making robotics and automation a more viable solution for farming problems. Robots and automated systems on the cutting edge of technology are already handling dangerous explosives (Zuniga A, Pedraza O, Gorrostieta, Garcia-Valdovinos, Ramos, & Gonzalez, 2008), and driving cars on their own (Ozguner, Stiller, & Redmill, 2007).

There are also many future uses of robotics technology. Increasing interest in space exploration and eventually colonization creates a perfect opportunity for automated farming, as any attempt for humans to exist away from Earth for any prolonged period of time will require some sort of sustainable food source. A garden is the obvious choice for food production, and automation of that garden enables explorers to attend to more important matters. With water found on Mars, someday humans may be erecting greenhouses on Martian soil, attempting to colonize the planet and grow plants there. Robotic technology can fill these needs.

This project aims to adapt current technologies into a simple and robust system that can grow a garden with minimum human intervention. In doing so, solutions to the basic problems of object identification and manipulation will be developed. These two problems are pervasive in many areas outside of farming. The results are immediately applicable in fruit and other delicate farming operations around the world. Looking forward, this technology may also be applicable to space travel. The work done on object identification and manipulation can also be translated to materials handling, and automation of many other common tasks that are currently done by humans.

Objectives

The first objective of this project is to build a growing area that can be used to autonomously plant, grow, and harvest cherry tomatoes. To enforce the use of robotic systems, a few rules have been established for the project. Human interaction with the growing area is forbidden once the seeds are planted: the only thing that can enter the growing area is a mobile robot. The infrastructure and robot may be remotely controlled, or may be autonomously controlled. The growing area is designated as the three planter boxes used in the experiment, and the platform surrounding them, all painted white. The area will be kept under video surveillance, with pictures being taken and saved to an on-site computer once a minute. Images are also transferred to a remote FTP server once an hour, for redundancy.

This project can be broken down into three separate sub-topics. Each of the topics has an individual set of objectives:

Part 1: Garden Construction and Maintenance

- Build a growing area and instrument it for data collection and autonomous control.
- Create a system capable of tending to the basic needs of growing crops (water, light, fertilization).
- Deploy a mobile robot to aid in these basic needs when necessary.

Part 2: Crop Isolation

- Reliably identify ripe tomatoes in the robot's field of view using image processing techniques.
- Identify and distinguish between ripe and non-ripe tomatoes.
- Provide necessary information for a robotic arm to move in and collect the crop.

Part 3: Crop Harvesting

- Design and build a gripper and robotic arm apparatus that is able to collect ripe tomatoes.
- Minimize damage to crops while they're being collected.
- Collect crops as quickly as possible.

These objectives are designed to be encountered and overcome in sequence as the project progresses. As solutions are found, the project will progress until the tomatoes are successfully harvested.

Literature Review

The problem of creating an autonomous agricultural robot has been an area of interest for quite some time. In the paper, *Design of an Autonomous Agricultural Robot*, Y. Edan investigated the state of the problem of autonomous harvesting (Eden, 1995). The paper divides the problem of autonomous harvesting robots into several constituent parts: fruit location, gripper and manipulator design, and motion control. The state of the art in fruit localization at the time was based on visual and other light based identification forms. Regardless of the algorithm used, success of location is only 85%. Control of the gripper systems is typically targeted to take 2 seconds to harvest each fruit. This means that the actuators have to move fast, but they don't have to be as accurate when compared to high-quality industrial actuators. Because of this, the gripper must be able to adapt to variations in positioning from low-accuracy actuators.

Greenhouse guidance is another consideration Eden takes into account in his paper. Greenhouses are inherently a more controlled and stable environment, and Eden claims that automated harvesters in greenhouses can "reduce hazards of automatic spraying, improve work comfort and labor efficiency and potentially increase accuracy of operations." At the time, there were systems that were able to navigate autonomously, but any other tasks had to be performed manually.

In another paper, Kondo and Ting outline the various requirements for an effective robotic design. The paper separates these requirements into a list of key components, such as the manipulator, end effectors, and visual sensors (Kondo & Ting, 1998). Each category contains design criteria and considerations for what makes an effective system. What is more interesting, however, is the idea of manipulating growing conditions to better suit a robotic harvester. The end of the paper outlines a way of growing tomatoes such that they hang from the ceiling and grow downward. This presents several advantages over growing tomatoes in the ground in terms of automation. First of all, the tomatoes require less training, so no stakes or cages are required to keep the tomato plants upright. The technique also produces more uniform and consistent growth patterns, which makes training a machine to collect the crops much easier. The crops are also within reach of a ground-based robot, which can access the fruits from either the bottom or sides. This approach represents a compromise between agricultural and robotic technologies that makes horticultural robots more effective.

Since then, there has been much more development in terms of managing growth of crops with automated systems. Hashimoto et. al. looked at hydroponic tomato growth, which has the advantages of being easier to control and more space efficient for closed systems (Hashimoto, Murase, Morimoto, & Torii, 2001). They were able to identify that the tomato has two growth modes: the root, stem and leaf growth, and the flower and fruit growth. In a hydroponic system, these two factors can be balanced by changing factors such as nutrient content. In essence, they were able to decompose hydroponic growth of tomatoes into an optimization problem, which is useful for studying how best to control the automated system. They also looked at the state of intelligent robots used for agriculture. Navigation through crop rows has been achieved using vision systems in Japan, eliminating the need for expensive range-finding equipment. As far as automated harvesting robots, however, little has been achieved. The paper cites poor robotic performance, and the superior cost and reliability of human operators as the reasons why harvesting robots are not more prevalent.

One group of researchers from the Netherlands has shown tremendous progress in robotic harvesting, using cucumber plants. Many fruits are grown in greenhouses in the Netherlands, and they said it usually takes about 12 people to collect all the crops from one greenhouse (Van Henten, et al., 2002). They created a robotic system to drive around a greenhouse and harvest cucumbers in the place of laborers. In their system, they have combined a mobile robot travelling on a track, visual identification of the cucumbers, a 7 degree of freedom robotic arm, and a gripper with a thermal cutting device to prevent the spread of viruses between plants. Using spectral analysis, the robot is able to isolate the ripe cucumbers from the surrounding foliage, move in, and cut the cucumber from the plant. Their goal was for the robot to only take 10 seconds to collect a cucumber, but their system took about 45 seconds for each cucumber to be picked. They cite an 80% identification rate for the ripe fruits.

In the area of gripper design, much has been done. Grippers for fruits have to be able to quickly secure, detach, and transport delicate fruits from the plants. One design for such a system is a vacuum assisted gripper for an apple picking

(Setiawan, Furukawa, & Preston, 2004). Their gripper uses a pneumatic system to cradle the apples while they are removed from the tree. The gripper is a tube, which is lifted to contain a hanging apple. Two air bladders inside of the tube are then inflated, cradling the apple in a protective air pocket. Then they could remove the apple and deflate the bladders, moving on to the next apple. Low cost, low complexity and adjustable gripper pressure are benefits of this design.

Tomatoes are much more delicate fruits than apples, and require a more fragile approach to harvesting. A vacuum-assisted approach was taken by Monta, Kondo, and Ting. In their paper, they describe a gripper that consists of a vacuum pump and two fingers for securing tomatoes on the vine (Monta, Kondo, & Ting, 1998). Their gripper consists of a small vacuum pump that extends to the fruit and engages. Once the suction grip is attached, the vacuum pump retracts and pulls the tomato between two padded fingers. These fingers close on either side of the tomato, holding it steady so the tomato can be detached from the vine. Their paper outlines two design iterations: as the initial prototype was flawed and would pull the tomato off of the vine before the tomato was secured between the gripper's fingers. The entire picking process takes about 4 seconds, which is 50% slower than the target Eden cites for a viable system (Eden, 1995).

Another approach to the tomato gripping problem is to use a manipulator without any form of vacuum assistance. A group of researchers formulated various gripper designs with various joint configurations, cutting blades for separating stalks, and sensors for detecting the pressure applied to the fruit being harvested (Ceccarelli, Figliolini, Ottaviano, Mata, & Criado, 2000). They begin by analyzing how a human hand grabs onto a tomato in order to pull it off of a stalk, taking into consideration the different pulling and twisting forces. From this analysis, they go on to postulate several gripper designs that mimic the forces applied by a hand harvesting the tomato. Their designs consist of opposable fingers that curl in to grasp the tomato. The fingers are all padded to increase contact surface area and decrease the likelihood of damaging the crop in the harvesting process. They settled on a simple two-finger mechanism, and built a prototype. The pressure sensors in the contact pads let them control how much grasping force is applied to the tomato, and they are able to grab on to tomatoes at an acceptable force without damage. They conclude that a simple gripper design with simple force control is suitable for harvesting tomatoes without damage.

Visual identification of crops is a large problem. In the Netherlands, past results show that spectral analysis can be used to differentiate desired fruits from undesired foliage (Van Henten, et al., 2002). This is just one of the many novel approaches to crop identification. Another way to distinguish between different crops is to use a wavelet analysis of the image (Chou, Chen, & Yeh, 2007). This group took ten different types of crops, and applied a wavelet analysis to identify each crop. Using the first day as a control, they took images from the different crops each day, and tried to use their method to associate which plant matched up with the control groups. After tuning their method, they were able to identify which crops they were looking at 98% of the time. This approach might be useful for different parts of the same crop in addition to different crops altogether.

Another group in Spain used range and reflectivity information from a laser range-finder to construct a scene and identify spherical fruits in an unstructured environment (Jimenez, Ceres, & Pons, 2000). Using a laser range-finder, they took a scan of an area and gathered the 3D range and reflectance data from the infra-red laser. With that information, they broke the scenes down and analyzed four different primitives: contour, crown, reflectance, and convex. Each of these is a different property that can be gathered either from the laser ranges or reflectance information. Each of these four techniques provides a hypothesis for where the spherical objects are in the frame. From there, all four hypotheses are combined and weighted, providing much more confidence in the identification of spherical objects. The authors say that this technique is being used on an orange harvesting robot with good results.

Researchers in Italy have been able to localize spherical fruits using traditional camera sensors (Plebe & Grasso, 2001). Also focusing on orange picking, this group takes a slightly different approach to crop localization. Instead of using a static image analysis, they use stereo vision correspondence to isolate spherical fruits in space. Using one camera, the stereo image is generated by moving the camera back and forth between two points. Their robot is equipped with two arms, so two stereo pairs are used to localize the spherical fruits. Identification of the fruits takes place using a colorspace manipulation. They morph the RGB image in the HSV colorspace, where individual colors (hues) are more easily picked out. Since oranges are always orange, this allows for easy color isolation. The oranges are identified and then an edge-fitting algorithm is used to isolate the circular shapes of the oranges. Once the shape has been isolated, stereo vision is used to provide coordinates of the spherical fruit.

Design Needs

This project statement dictates several design needs. Each component of this system was designed with consideration toward the respective objectives. This section breaks down the individual design needs for the separate components of the project.

Growing Area

The growing area is a key element of the project. Given the goals of eventually using this system in an outdoor growing environment, the design of this space needs to simulate a field of soil. However, creating one large box of dirt to grow the plants in introduces a variety of problems. Containment of the crops for simpler navigation, and the ability of the available indoor robots to travel around are large considerations in this design. The design of the growing area also had to fit within a 14' by 12' allotted space, which limited the amount of growth area vs. the amount of area required for the robot to travel. The floor of the greenhouse is a mixture of gravel and concrete, designed for drainage. This makes it even more difficult for the robot to get around, so the design had to provide some sort of stable platform to allow the robot to navigate.

In order to keep the plants healthy, an irrigation and monitoring system had to be created. Due to the greenhouse environment, irrigation and artificial light could be used to accelerate the growth of the plants. These systems could also be made independent of the robot, running in the background to decrease the amount of complexity on the system. With only a standard garden hose hookup as a water source, some way had to be devised to get water from the hose into the growth area at an acceptable and controllable rate. A way to control this water flow lights also had to be designed. Finally, there needed to be a way to monitor the status of the crops, to be sure that they were getting a sufficient amount of water and sunlight.

Mobile Robot and Arm

The mobile robots used in this experiment were already designed and built to an extent, but needed to be refurbished for general use in a controls class. Previously, the robots were instrumented with expensive digital signal processor boards as the sole means of control. They had to be redesigned to provide a modular interface to the control systems, so that the class could explore various hardware methods to control the robots. With this in mind, a new interface board and upper deck had to be designed to accommodate a wide variety of controllers.

The robot had to be able to navigate across the growing area, carry some sort of payload (arm and harvested crops), and it had to be controlled remotely. Once the robots were refurbished, some sort of control system had to be implemented to translate computer commands into movement, and translate sensor feedback into a format that could be read in by the computer. This system had to be wireless and allow for remote control, either manually or via a software algorithm.

The robotic arm is a vital the success of this project. The arm had to be designed to the pulling and size constraints of the robot. It also had to be long and strong enough to reach and grab the tomatoes off of a vine. The arm also had to be built to accommodate various sensors, including position feedback for control, imaging to identify the tomato crops, and range finding to the target.

The gripper needed to be designed to be large enough to grab a cherry tomato, and strong enough to pull it off of a vine without dropping it. At the same time, the gripper could not be so strong that it crushed or damaged the tomatoes. Finally, the gripper had to be designed to be able to navigate through leaves and other overgrowth that may obscure the tomatoes as they grow on the plant.

Software Design

With so many different hardware components present in this project, a software design had to be created that could control each piece of hardware reliably.

For the growing area, software to regulate and monitor state information had to be created. The software needed to expose the functionality of all of the sensors and actuators in the growing area.

The robot and robot arm had to be programmed to be controlled by a computer. A software interface had to be created to allow the robot to be driven either manually or by the computer. The robot arm and gripper had to have similar functionality, to allow it to be controlled either manually or via the computer. Further, an image processing algorithm had to be created to translate image data from the arm's camera into arm movement commands. The robot had to be able to tell where the tomatoes were and whether or not they were ready to be picked.

System Layout

The layout of the whole system needed to be simple and modular. Because of the scale of the project, no one component could be overly complex or it would take too much time away from developing the rest of the components. Simplicity can be achieved by using existing frameworks, software, and common off-the-shelf components wherever possible. To maintain modularity, the same software interfaces should be used for the growing area, arm, and mobile robot. By doing this, a controller algorithm can use one or all of these hardware components without any added complexity.

Methodology

Metrics for Success

Each part of this project is responsible for different actions, so there are different criteria for success of each component. The components are again separated into three different areas, and the criteria for a successful experiment are outlined for each part. These criteria reflect the design goals for each part of the project as well as the overall results.

- Garden Construction and Maintenance – mechanical/software design:
    - Maximize how many plants live to bloom and yield tomatoes
    - Minimize the failure rate of a robot and of task attempt
    - Create efficient ways to test algorithms before deployment
- Crop Isolation – image processing:

    - Reliably identify tomatoes ready to be picked
    - Minimize how many “green” tomatoes were isolated
    - Minimize how many times ripe tomatoes are ignored
- Crop Harvesting – mechanical design / remote control:
    - Quickly identify and collect tomatoes without causing damage
    - Test manipulator outside of growing area
    - Find the tradeoff of remote control versus autonomous control
    - Minimize supervisory steps for autonomous control
    - Minimize manual steps required to pick tomatoes

Design of Experiment

The experiment is designed to be immersive in nature, and focus on several problems at once. The goal of this method is to see how all of the design components and problems that were previously described can be intertwined to solve a complex problem. At the same time, this experiment seeks to find a simple solution to each problem faced, so that the end goals can be reached within a reasonable amount of time.

This experiment first requires that a growing area be built for the crops. This growing area will also handle day-to-day needs like watering and lighting. The growing area will also have to facilitate the robot’s movement around the crops. Once the system is ready, the planter boxes are filled with dirt and the seeds are planted. As the seeds germinate and grow, tasks like watering and monitoring should happen independent of the robot. A camera will be mounted to watch the garden area, and log pictures of the growth process.

A robot will be built concurrently and equipped with an arm and gripper. The robot should be able to navigate through the garden and access all the crops growing. The robot's purpose is to bring the arm and gripper into proximity to the crops. The arm and gripper will be responsible for moving in to the crop area, identifying the tomatoes, and eventually picking them.

To identify the crops, a camera will be used. The camera is mounted on the arm of the robot, to provide a "sniper scope" view of the crops. Having the camera mounted on the arm allows for a direct point of view when identifying and harvesting crops. The camera and its image processing algorithm must be simple and be able to translate a red tomato in the field of view to a goal set of coordinates for the robot arm.

The control and image processing software responsible for making all of this happen must be written to be simple and straightforward.

Design of Growing Area

The growing area for the crops was designed to be traversable by a robot, and to provide a growing environment similar to a field for the crops. To do this, three 16" by 48" planter boxes were built to contain 12" of soil. This was to provide ample room for root growth without being so large that the fruits were inaccessible for the robot.

The planter boxes are situated on a 9' by 12' plywood platform. The boxes are staggered so that a track made of flexible PVC tubing can curve between them and make a complete circuit. This closed track serves to guide the robot across the flat surface, and since the track forms a closed loop, it allows the robot to follow the track all the way around the garden indefinitely. This design choice was made to simplify the navigation algorithms for the robot. Without a track, the robot would have to find its way to each planter box using some other more complex means.

The front of the growing area, where the track travels across the length of the garden, serves as a "staging area" for the robot. Since the robot is not allowed to be touched while in the garden, an area outside the garden had to be defined. This staging area is the easiest area to access, and provides a long runway where the robot can be interacted with and sent into the garden.

The irrigation system, lights, and soil moisture monitoring are all handled by a small microcontroller contained in a waterproof box to the side of the garden platform. This design choice allows the day-to-day watering and lighting of the crops to be handled whether or not the robot is active. The microcontroller is set up to actuate 3 relays: a water solenoid valve, a water pump, and the lighting system. The water pump is a submersible low power model, commonly used in small decorative ponds. It is contained in a large Rubbermaid storage bin, filled with water. When the water level drops below a certain point, a solenoid valve connected to a garden hose spigot opens to refill the tub. The water level is also monitored by the microcontroller, in the same manner that soil moisture is monitored. When the pump is on, water flows through garden hose through a 3 way splitter. From there, one hose goes under the growing platform for each planter box, coming up through a hole next to the box. Inside the planter boxes, a hose barb connects the garden hose to slow-drip tubing, which runs the length of the box. This tubing provides a slow but constant drip of water at low pressure, ideal for gradual watering of the plants.

Each box is also equipped with two soil moisture sensors, one at each end. These sensors consist of two 3” nails that have been soldered to wires. The wires run back to the microcontroller. One wire is provided with a 5v source voltage, and the other wire is connected to an analog input on the microcontroller via a voltage divider circuit. As the soil becomes moist, the electrical resistance between the nails drops. This lowers the voltage drop between the nails, which registers as a higher voltage at the microcontroller’s Analog to Digital converter. Using this method, one can tell when the soil is dry and when it is very moist, and experimentally determine a target average moisture level for the six sensors.

Construction of the planter boxes experienced several delays. Once the boxes were built and filled with dirt, several severe leaks were discovered. The leaks had to be isolated and fixed with silicone. Wiring the Sanguino with an Ethernet module to communicate with the host computer was also the source of a long delay. Compatibility issues plagued the entire process, and after a solution was not found, a separate Arduino was used as a “slave.” The Arduino was connected to the Ethernet shield, and transmits all of the information it receives over a TTL serial line to the Sanguino. It also listens for TTL serial signals from the Sanguino, and routes them back over Ethernet. These delays pushed the seed planting date to the end of March.

Design of Robot and Arm

The robot used in this experiment was designed to be used with any number of microcontrollers or other control hardware. The robot contains a hardware interface board, which provides power and connectivity to the motors and wheel encoders. It exposes functionality through one power plug and a harness containing all necessary signal I/O lines to move the robot. The robot was also designed to be easily serviceable. The battery and control board can be accessed quickly by lifting up the hinged upper deck. With the upper deck down, anything from a small microcontroller to a full sized laptop can be carried by the robot.

To control the robot, an Arduino microcontroller was used. Based on the AVR ATmega168, it provides digital and analog I/O, and a USB connection to a computer. The Arduino serves as a hardware interface between the robot and a laptop. A simple client program loaded on the Arduino listens for serial commands from a computer. When it receives a command, it reacts accordingly by returning a sensor value or updating a set point. The Arduino uses wheel feedback and PID control to regulate the wheel speed of the robot. It also reads sensors on the robot, such as the sensor that follows the track around the platform. A laptop on the robot can then determine whether or not to turn, slow down, or stop.

A robotic arm was designed for the robot to enable crop harvesting and manipulation. Because the robot is already carrying a microcontroller and laptop, the arm had to be built as a separate unit. The arm is mounted on a 1'x1' trailer, which is pulled behind the robot through the garden. The arm has 4 degrees of freedom: a swivel mount connected to a servo motor, two 12" linear actuators that control the movement of the two arm segments, and a gripper wrist that is capable of pivoting up and down. The gripper is also controlled by a servo motor, and is able to open and close.

The arm is controlled by a separate Arduino, running similar control code. Position feedback from the linear actuators is obtained via a built-in potentiometer, so the Arduino is able to provide PID position control for each actuator. The other degrees of freedom are standard servos, which are controlled by an off-board servo controller linked to the Arduino. The laptop on the robot connects to the arm via USB and sends commands to and from the arm. The arm is also equipped with a Firewire camera, mounted near the gripper. The camera has a wide-angle lens for maximum field of vision, and provides a view of what the arm sees at any given time. The camera is also connected to the laptop.

Design of Software

Every sub-system is controlled through the open source Player platform. Player is a "robot abstraction layer," in that it provides a standard set of interfaces to interact with common robot devices. A small driver had to be written for each of the microcontrollers to expose the functionality to the Player platform. Once the interfaces are in place, they can be read and written to from any computer networked with the Player server. This also allows the Player server to provide the sensor data and interfaces to multiple programs.

The growing area's microcontroller is connected over Ethernet to a server located in the greenhouse. A Player server runs on that computer and provides the moisture sensor information, as well as the controls to turn the pump, lights, and fill solenoid on and off. Two client programs run on that computer and interact with the server. A data logging program records the state of all sensors and relays each minute. A planner program also runs, turning the pump, light, and fill solenoid relays on and off throughout the day.

The robot and robot arm also use Player. A Player server runs on the laptop and connects to the two Arduinos, providing all of the functionality of the robots through the "position2d," "limb," "camera," and "gripper" interfaces. The laptop connects to a wireless router next to the garden. The robot and arm can be controlled over the network, either manually from another laptop or automatically with a client program.

The image processing algorithm for identifying tomatoes in the frame is designed to be simple and effective. Using the RGB color space, the blue channel is ignored. The intensity of the green channel is doubled, and then those values are subtracted from the red channel. What is left is then thresholded into a binary image, and connected round blobs are used to signify tomatoes. This algorithm works by taking advantage of the fact that the tomatoes, which are red, are surrounded by a lot of green foliage. Since red and green are two of the three constituent colors of the RGB color space, no further transforms are needed to isolate the red and green components. The red tomatoes are assumed to have very little data in the green channel. When the green channel is subtracted from the red channel, the only data that remains is the parts with lots of red and no green: the tomatoes. Once the binary image is found, each connected round blob is identified as a tomato. The distance from the blob to the center of the frame is proportional to how far the arm must travel to isolate the tomato, so the arm keeps moving until the blob is aligned with the gripper in the center of the field of view. The gripper moves in until it gets close to the tomato, as determined by an on-board IR range sensor. The gripper then closes around the tomato and pulls it off the stalk.

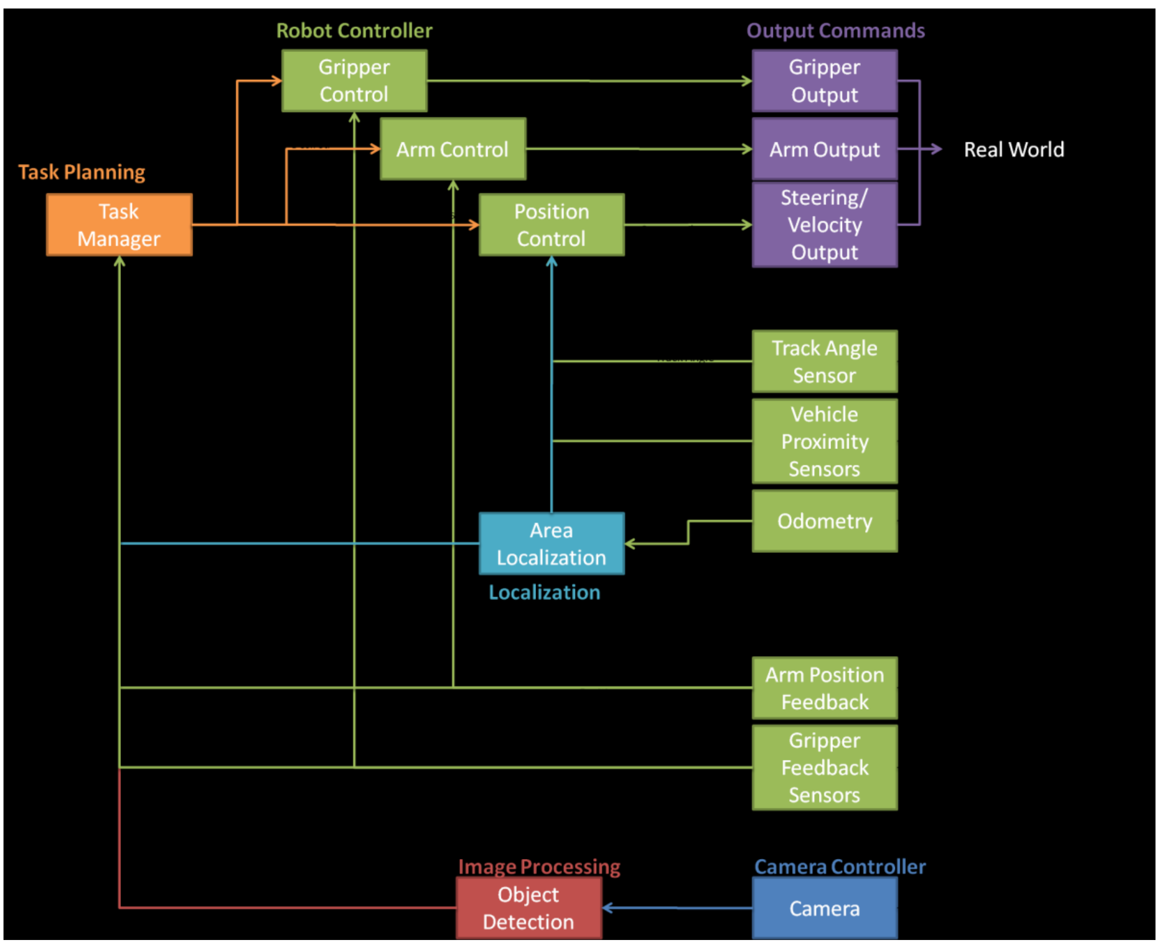

Figure 1: Control Architecture for robot system

Using these design goals, an overall control architecture was devised, as shown in Figure 1. Each box color represents a different system, which matches a corresponding label in the figure. The software components for each part were then designed to fit the input and output information for each block.

Results

Data

Garden Construction and Maintenance

The growing area was the first part of the project to be completed. Since it was set up, moisture sensors and water level sensors have been logged by the on-site computer. Once the seeds were planted, an algorithm was started to manage the lighting, water pump, and water fill solenoid. State information for the system continued to be logged once a minute. An example of a day of state information is given in Figure 2. The top graph shows an average of the 6 moisture sensors' readings. Readings for these sensors are given in voltage, where a lower reported voltage corresponds to a lower relative resistance, or higher moisture. The lower plot is the status of the pump throughout the day. A value of 1 indicates the pump was switched on, while a 0 indicates the pump was switched off. The graph shows a correlation of moisture increasing when the pump is active, and slowly decreasing or drying out after the pump is turned off.

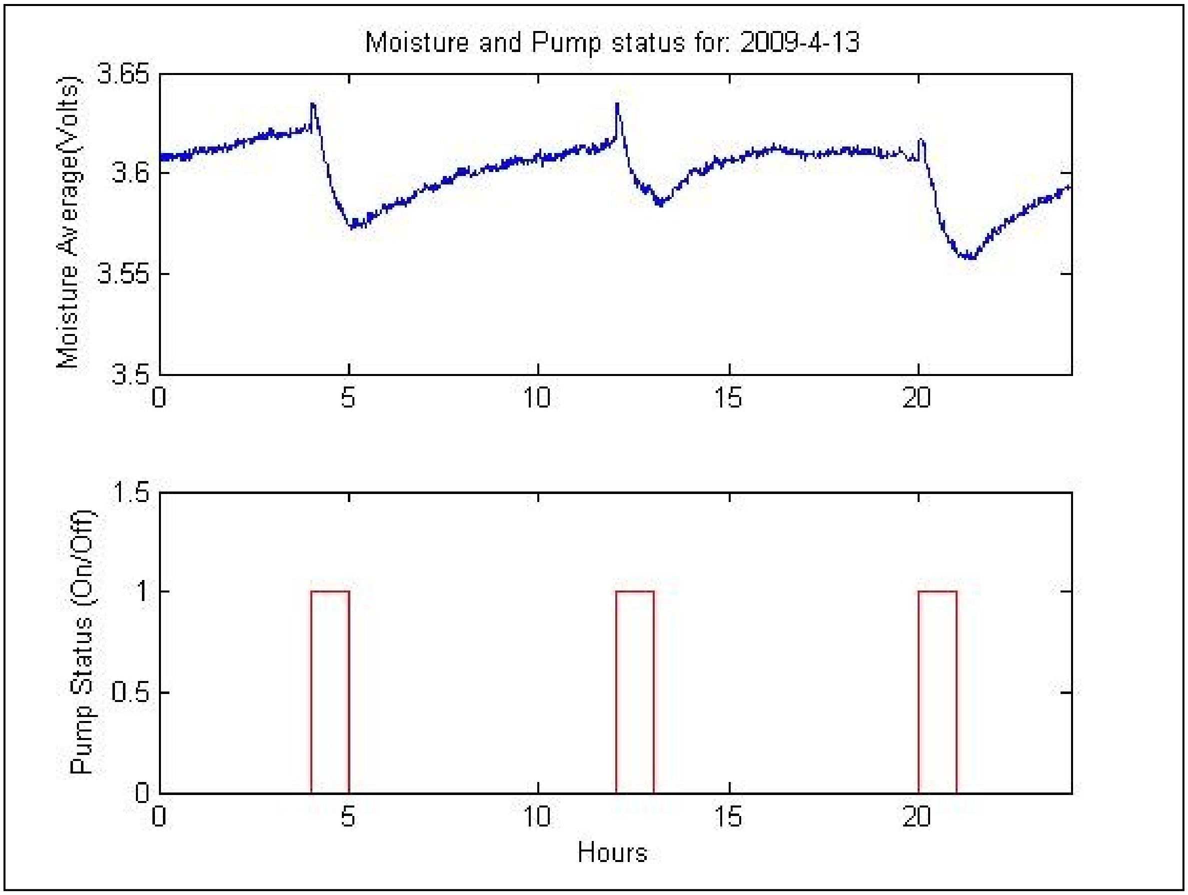

Figure 2: Plot of pump status and moisture level for April 13, 2009

The peaks and noise in the above graph could be attributed to the imprecise nature of the sensors themselves. The nails are placed in the ground 2 inches apart, and there may not be enough current traveling through the soil to get a precise measurement. As the pump turns on, the relay and transistor are pulling more current from the 12v power source. This could cause noise in the signal lines, or drift in the analog reference voltage as regulated by the Sanguino. Placing the nails closer together or sanding the galvanized coating off could make them more conductive, but they are within the off-limits garden area. Isolating the power sources for the relays and microcontroller may also clean up the signal.

The microcontrollers attached to the growing area were able to operate without interruption for 27 days. On each of the remaining 28 days, some sort of system crash or interruption caused the microcontrollers to have to be reset. Once reset, the server could be re-initialized and data could be collected again. This indicates that on 50% of the days that the system was operational, it encountered some sort of error or crash that halted normal operation. Log files reported when the system stopped responding.

Lighting and water were provided to the plants on a fixed schedule. In order to keep the soil moist at all times, the pump was turned on three times a day for one hour at a time. The times for the pump were 8 hours apart, resulting in operation for one hour, and a off period of 7 hours. This time step was based on experimentation on the soil before the seeds were planted. After running the pump for an hour, the soil showed signs of drying out after about 8 hours. Lighting was also controlled on a fixed schedule, turning on at 8pm and off at 4am. The extra 8 hours of daylight allow for crop growth to take place during the night. Since the experiment was planned to take place during the winter and early spring, natural sunlight alone would not be able to sustain normal growth of these summertime plants. Extra lighting would be needed to accelerate the growth of the tomato plants.

The robot's physical design was finalized as shown in Figure 3. A track following sensor was mounted on the front of the robot, and the upper deck was made large enough to carry a laptop around. In testing, the robot was able to make a complete circuit around the track in 2 minutes and 30 seconds. The robot was only carrying a laptop on its upper deck, and was not pulling the arm.

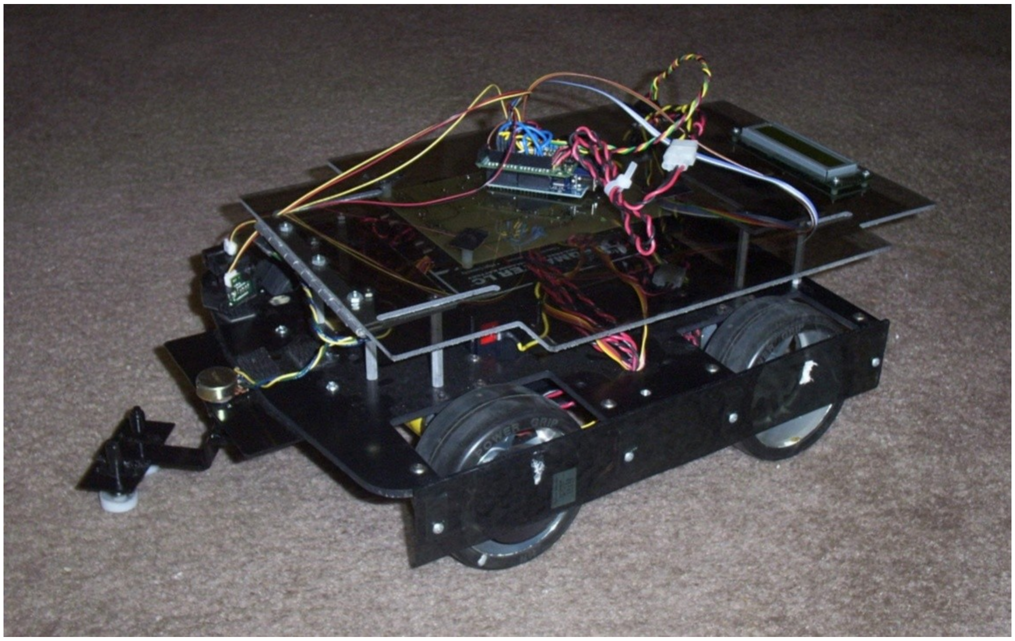

Figure 3: The robot equipped with a track following sensor and microcontroller

Crop Isolation

Isolation of the tomatoes based on images of the plant was achieved using sample images of other tomato plants, since there are not yet any tomatoes on these plants. Using MATLAB as a testing environment, several different techniques were used on the sample image set. The method that produced the best results was one of the simplest. Using the method of separating and combining the RGB channels as described in the Software Design section, images could effectively be modified to isolate ripe tomatoes. The results are shown in Figure 4. The left side of the figure is the original image, and the right side is the image after the thresholding had been applied. The ripest tomatoes show up the brightest in the processed image.

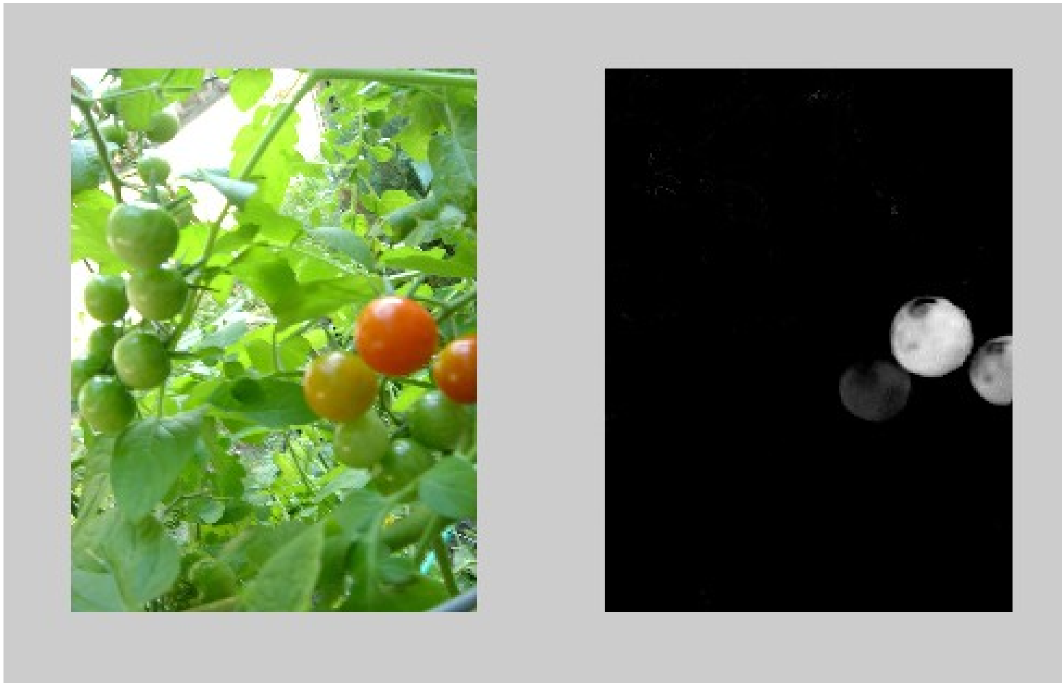

Figure 4: Crop isolation in sample image

Crop Harvesting

The robot arm has been equipped with all of the necessary equipment and sensors to harvest the tomatoes, but no progress was made as the tomatoes had not yet ripened. As it stands, the plants have not yet flowered, and the tomato plants are expected to bloom in early May. Delays in construction were responsible for the late planting time. Software to enable the robot arm to navigate to a desired position was not complete enough to be tested.

Analysis and Interpretation

The growing area was able to successfully perform maintenance tasks such as watering and lighting, though the reliability of operation was only about 50%. Having to constantly check in and make sure the system is still running does not achieve the target of minimal human intervention. Further, if the system crashes while the pump is operational, the pump will drain the tank and run dry, which can overheat the pump and damage its impeller. If the system shuts off while the water tank is refilling, the tank will overflow and water will spill everywhere. Building in fail-safes can remedy these problems, but a different combination of controller components may be able to eliminate the crashing behavior altogether.

In spite of the crashing behavior, all of the tomato plants were able to grow successfully. None of the seedlings died after sprouting, and all of them are growing around the same rate. The system is therefore capable of supporting the plants, and the sensor data shows that the system is able to keep the soil moisture consistent over the course of a day. The pump and lights are turned on and off based on a fixed timer schedule. Based on the successful growth, sufficient light and water were provided on the fixed time schedule.

The robot's construction is suitable for the navigation of the area, and it is successfully able to complete a circuit around its track within a reasonable amount of time. The robot platform is therefore capable of navigating through all of the area it needs to, and can indeed facilitate access to all of the planter boxes. The robot arm, when in tow, is long enough to reach any point within or around the planter boxes where the tomatoes may be growing.

Using a simple image processing algorithm provided promising results for isolating the crops that are ready to be picked. Separating the ripest tomatoes ensures that only the best tomatoes will be picked. Since the harvesting work is done by a robot, the same plant areas could be re-visited several times to ensure the tomatoes are only picked when they are at the ripest point.

Impact

The impact of a tomato picking robot is immediately apparent. The world's food supply is largely provided by farms, but when farming delicate crops the labor required is immense. Outfitting a robot with sensors to go out and identify where crops are ready to be picked, and giving them the ability to pick them safely, could cut down on expensive labor costs for farmers.

The impact of an intelligent growth area is also important. Be it in a greenhouse or out in the fields, outfitting the crops with sensors to monitor their status, and actuators to control water and nutrient flow allow for precise and localized maintenance of crops. Each crop can be individually monitored, watered and fertilized, instead of globally applying water on a fixed schedule. Watering the plants only when they need it could result in less water having to be used on the crops, which could result in savings for the farmers.

Having a robot roaming the fields with the ability to visually recognize things can have other peripheral impact. Herbicides and pesticides are commonly used in large-scale farming to ensure that no weeds or pests are hindering the growth and development of crops. A robot could be programmed to identify weeds and either pull them up or locally apply an herbicide. The same idea could be used for pests; they could be neutralized on sight instead of through massive application of dangerous chemicals. Fewer chemicals means there is less of a risk for harmful effects such as ground water contamination.

Conclusions

Summary

The design and construction of the robot, arm, and garden area were all completed by the beginning of March due to unforeseen delays. Seeds were planted at that time, and the watering and lighting system has been online since then. Sensor information has been logged to monitor the state of the plants based on visual information and sensor readings. At the time of writing this paper, the tomato plants are about 18-24” high and have not yet sprouted any flowers or fruits. A simple image processing algorithm has been devised for isolating crops that are ready for harvesting. Work is continuing on integrating the robotic arm movement with the image processing.

Suggestions for Future Work

In future work, closer attention should be paid to the growth and development time of the tomatoes. As of the writing of this paper, no tomatoes are ready to be picked. Once tomatoes are ready, further testing of the gripper, robot, and arm integration could be completed. Planting a second set of cherry tomatoes in an accessible area before planting the ones in the automated area could provide a “practice” set of crops, to ensure the robot algorithms work well before they are deployed. Additionally, further gripper configurations could be explored. Adding pressure sensors or more fingers could help in the process of grabbing the tomato.

Overall, this project was a bit too ambitious. Given the time constraints associated with a full-time class schedule, it became increasingly difficult to finish parts of this project. Selecting a smaller, more focused subset of these problems would have allowed a timely conclusion to this project.

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Appendix I: Growth Progress

3/23/2009, 12:00PM

3/30/2009, 12:00PM

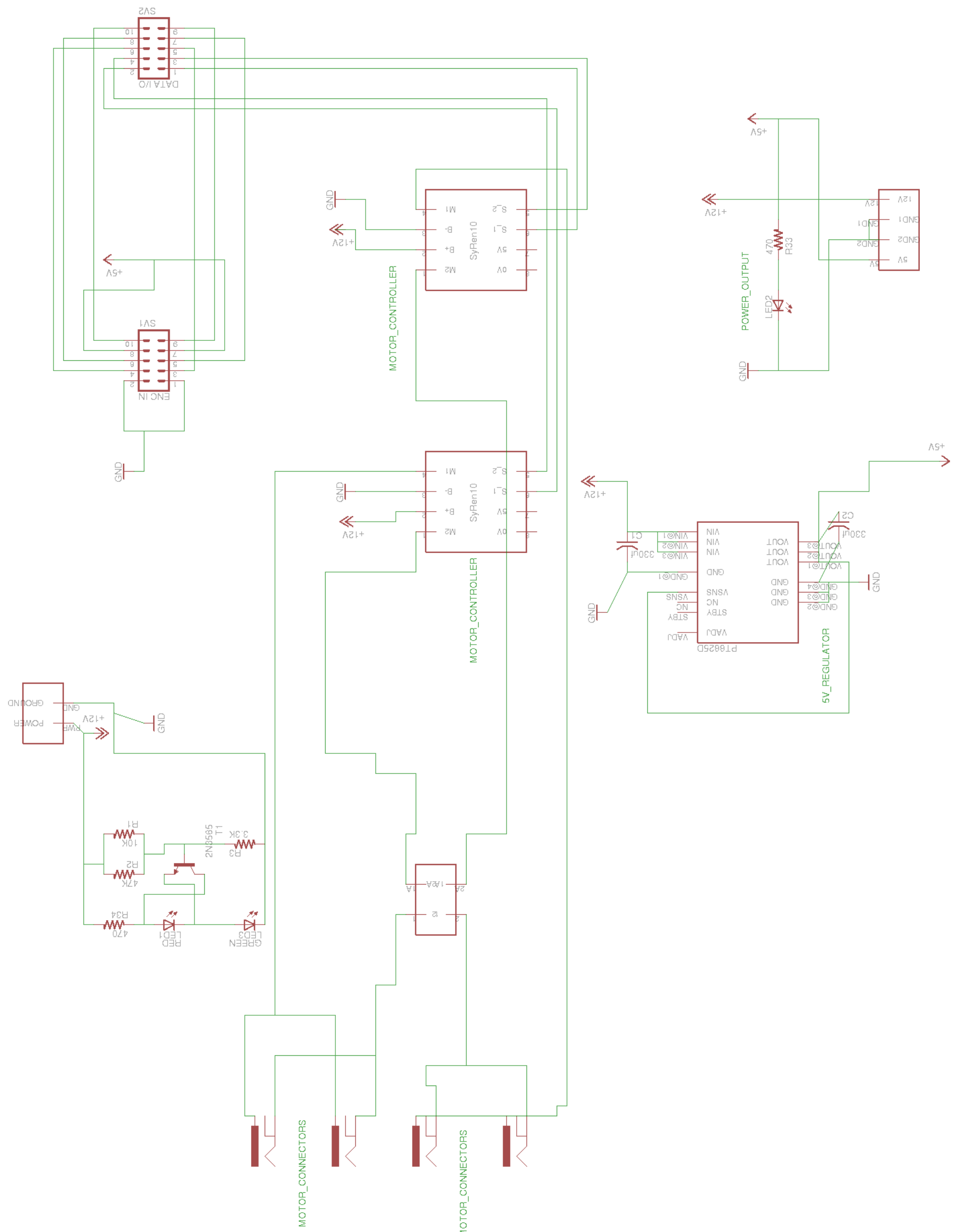
4/6/2009, 12:00PM

4/13/2009, 12:00PM

4/20/2009, 12:00PM

Appendix II: Electrical Schematics

IIA: Robot Control Board Schematic



IIB: Growing Area Control Circuit Schematic