Garduino: A Cyber-Physical Aeroponics System

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[Abstract]

The cyber-physical system is an indoor farm that grows plants aeroponically, without soil. It monitors the health of the plants by regulating the water received, and recording the humidity, light, and temperature levels. Sensors connected to an Arduino board and program collect data about (1) the humidity of the enclosed growth chamber, (2) the light supplied by both the ambient light and an overhead light fixture, and (3) the temperature inside the system. Based on researched optimal conditions, the system maintains the best growing environment for the plants. Whenever one of these three conditions drops below the minimal acceptable value or exceeds the maximum acceptable value, the system automatically (without user input) actuates to return the plant to its optimal environment. Actuation includes turning on/off the water pump and turning on/off the overhead light fixture. These data points are plotted, and their graphs are displayed on a website and then shared on Twitter. In addition, users can monitor their plants through a live video-stream.

[Introduction]

Motivation and Background

The global agriculture industry currently faces its toughest demand ever. The declining availability of natural resources like water and arable land, unpredictable weather patterns and changing climates, and an exponentially growing population expected to exceed eight billion people this lifetime have all greatly strained the efficiency and productivity of agricultural systems. Revolutionary inventions such as the plow, irrigation systems, and genetically-modified plants have remarkably transformed agricultural practices. However, as crop yields begin to flatten and production rates approach their natural maximum limit, the agriculture industry -- as it exists today -- cannot continue to support an expanding global population. With one in nine people still living in destitute hunger, the world awaits the next phase of the agricultural revolution.

To more specifically contextualize this problem, last year on January 17, California Governor Jerry Brown declared a State of Emergency due to severe drought conditions. The declaration enacted stricter limitations to urge businesses and operations in the agriculture sector, which accounts for 80% of the water used directly by humans in the state, to reduce their water waste. Despite imposing new guidelines to save water, the state still suffers from severe drought conditions because traditional agriculture -- the process of producing food on outdoor farms using soil -- is inherently water-intensive. This problem, of course, is not unique to California, and the future of agriculture internationally requires innovative, advanced techniques that conserve water and protect the environment without compromising the integrity of the produce.

One such reimagining of how human beings cultivate food on a global scale is indoor farming. By saving between 70-98% more water than traditional farming, indoor farming proves to be superiorly sustainable, both environmentally and economically, and may replace traditional farming because it:

- uses significantly less land (since crops are placed in closer proximity and their growth chambers are stackable),
- protects crops against weather and pests,
- reduces transportation costs (since they can exist anywhere regardless of climate),
- increases production from seasonal to year-round,
- increases production speeds by 30-50%,
- promotes organic produce and counters the usage of GMOs,
- and democratizes the access to healthy and affordable produce.

Despite the advantages of indoor farming, there are several challenges associated with managing this particular infrastructure system. For one, research in this space is still nascent and, at its current developmental phase, cannot be applied at an industrial level. Several research facilities around the world, including NASA, MIT, and General Electric, have been studying the optimal growth conditions of various plants, but even fewer have studied its environmental, economical, and social impact. In addition to research facilities, hydroponics and aeroponics are widely used in personal settings for the growth of specialty crops. The challenge now is perfecting these systems so that they can be applied at a larger scale. Currently, designing and constructing smaller versions of these systems is costly, but will most likely be cheaper on at mass production.

Relevant Literature

The readings that inspired this project and guided the development of the system include research papers that analyzed the efficiency of hydroponic and aeroponic systems, personal tutorials on how to build an indoor farm, and instructions that explained how to care for lettuce and basil plants. In addition, supplementary readings supplied more context on the environmental, economic, and social impact of urban farming. Collectively, these sources -- which range from news articles and blog posts, to peer-reviewed papers and textbooks -- were the backbone of the conceptualization and development phases of Garduino.

Focus of this Study

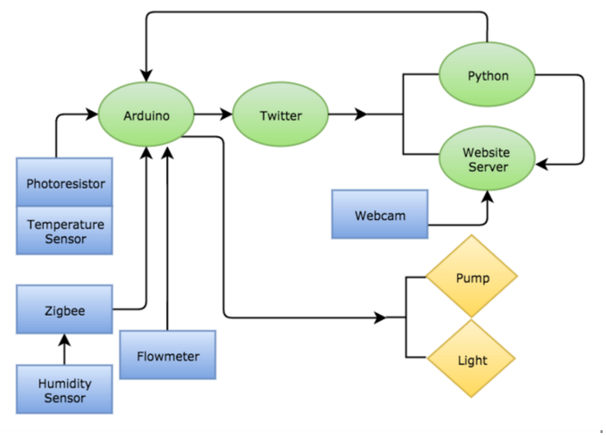
Without compromising on the integrity of the crop, the aeroponics system addresses the water shortage of California by reducing water wastage and optimizing water efficiency, while accounting for ambient environmental conditions such as humidity, light, and temperature.

[Technical Description]

Overview Cyber Physical System

The following schematic (*Figure 1*) demonstrates the overall connectivity between the various layers of this cyber physical system. The physical system is connected to the cyber layer through the communication of various sensors (flowmeter, photoresistors, temperature, and humidity) with the Arduino. A webcam feeds directly into the web server, using a live YouTube stream. The Arduino communicates wirelessly (using the Wifi shield) with Twitter. These tweets are data mined using a Python code, as well as created into a csv file that is uploaded onto the web server. A different Python code performing data analysis also feeds into the Arduino, which actuates the pump frequency and light on/off. The specifications of these components will be discussed in the following sections.

Figure 1



Physical System

The box design for the cyber physical system is a simple and controlled environment in order to produce the most accurate sensor readings and to provide the most control for a home-gardening system. The physical system consists of a 30” x 20” x 30” wooden box with plexiglass covering the sides. The top component is detachable from the base, where the plants reside (*Figure 2*).

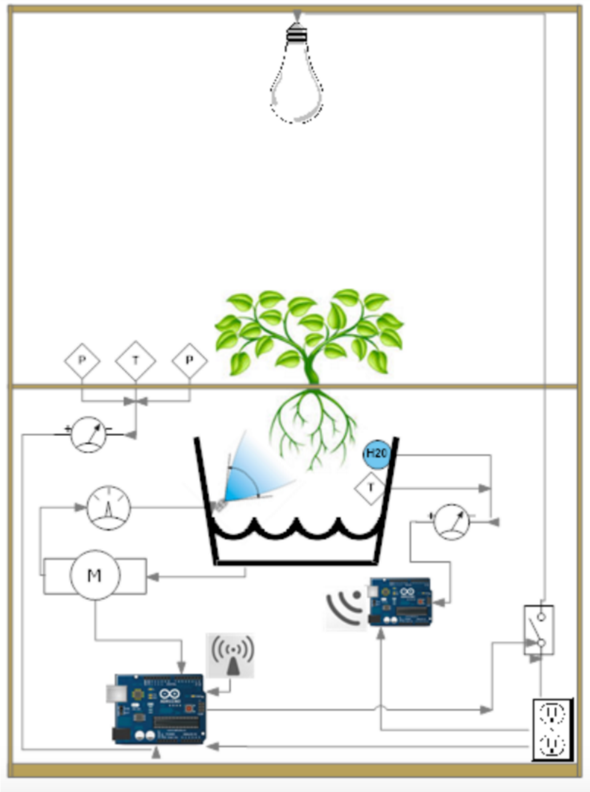
Figure 2

For the purposes of this experiment, basil (ocimum basilicum) is grown due to its short cultivation time, accessibility, and simple growing conditions. For an optimal growing environment, basil requires warm temperatures and lower ambient humidity, while operating under a wide umbrella of growing conditions. The health of the plant is determined from visual inspections and the detection of its fragrant smell. Furthermore, basil is one of the most commonly used herbs across many cultures not only because of its taste, but also because of its short cultivation time and easy growth in varying climates. For testing purposes, lettuce is used for very similar reasons. Both lettuce and basil are great candidates for aeroponics.

Hardware

A hardware schematic of the design is provided below (*Figure 3*), including all its sensors and connectivity components. The photoresistors are labeled as ‘P’, the temperature sensor are labeled as ‘T’, and the humidity sensor is labeled as ‘H2O’. These independent sensing nodes grab data within the system every 15 minutes, and send this information to the main Arduino board and program -- either directly through an ethernet connection or wirelessly through an Xbee radio communicator. Additionally, the overhead light source is powered by a power switch tail, which is also controlled by the main Arduino. Finally, the water pump is connected through the tank and pumps water from the reservoir below into the spigots. When the pump is turned on, the spigots spray the suspended roots thoroughly.

Figure 3



Software

In addition to the code that powers the Arduino board and its sensors, a Python script aggregates the data to be graphed as a visual convenience for users. These graphs are displayed on a custom website, which can be accessed here: http://anshumaskara.wix.com/garduino. The data transfers through an ethernet connection (a direct connection to the computer), but with a functional WiFi shield, the data can be tweeted wirelessly. For now, without wireless communication, all data is displayed on the website.

To qualitatively describe the code, the readings from each sensor is stored as a variable and compared to its specific condition bounds. If the value exceeds the maximum acceptable value or drops below the minimum acceptable value, the code sends a command back to the Arduino program and board to actuate the appropriate components.

Figure 4

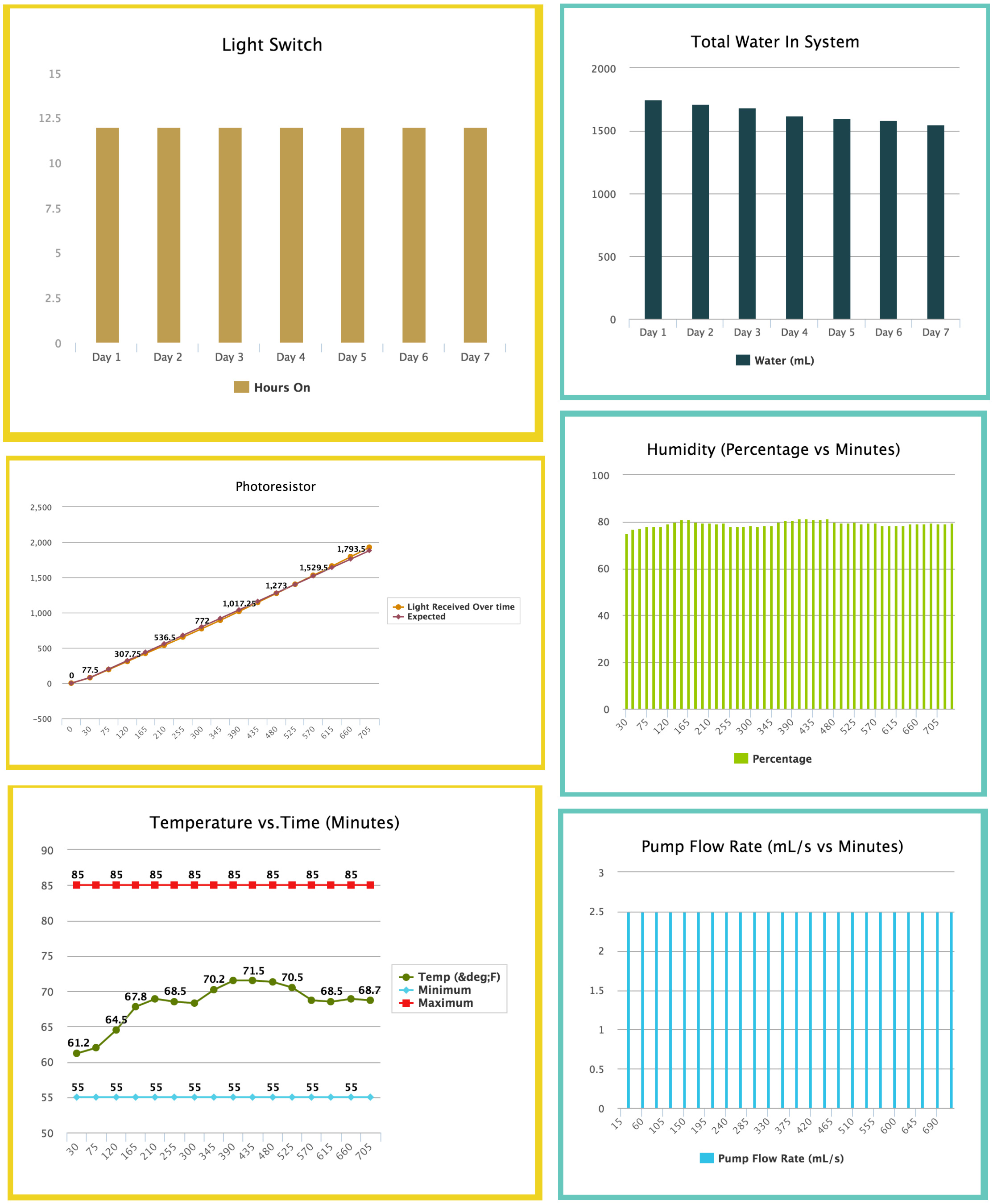
Data Visualization

The following images are screenshots of the website: http://anshumaskara.wix.com/garduino. The data is communicated to this web server through daily csv file uploads, created via a Python script.

Optimize water usage using devices and sensors for smarter and sustainable indoor farming.

Figure 5

Figure 6



Data Analysis

The data analysis portion examines the output readings produced by the temperature, humidity, and light sensors of the system, allowing both the user and the system itself to make the necessary modifications that promote optimal plant growth. These modifications are separated into three categories: light actuation, water actuation, and user modifications -- each subjected to the data collected by the photoresistor, the humidity sensor, and the temperature sensor, respectively. The data received by the sensors is sent from the main Arduino board and program to a Python script that either graphs a collection of recent data points as a visualization for users, or analyzes specific 'check conditions' to determine actuation. More specifically, if these check conditions are violated, a specific command is sent back to the Arduino in an attempt to return the system within the bounds of the check conditions. The check conditions are different for every plant and are established by existing literature.

For the indoor farm, light actuation is dependent on the amount of ambient light the system receives throughout the day. Two photoresistors read at 15 minute intervals over the course of the day. Due to the low resolution of these sensors, the average reading between the two photoresistors is recorded. The photoresistors in the system take readings of a light intensity that corresponds to an output range of 0 to 255 volts, where an output of 0 volts corresponds to complete darkness. A greater light intensity produces a larger output. Existing research has determined that a lettuce and basil plant need approximately 14 hours of sunlight per day at an average of 160 volts per hour in an optimal environment. The system runs a check at each reading to ensure the system achieves this minimum. This check was ran after the first ten hours of the day so that in the worst case scenario, the light will remain on for fourteen hours. The required 160V reading over fourteen hours per day meant that the sum of the readings should be a minimum of 2240 photo-hours. This meant that if the system determined it was not going to meet this minimum for the day, the light is turned on until the next data reading. At which point, the system runs the check again. Once the minimum was met, the light remains off for the remainder of the 24 hour period.

$$E = \sum_{T=0}^{T=t} \left(I_T \times \frac{1}{4} hr \right) + I_t \times (24 - T)$$

$E = expected\ output;\quad I_a = light\ intensity\ at\ time\ a;\quad t = current\ time;$

The expected light intensity (photo-hours) is estimated with the equation above. Throughout the day, the light intensity is monitored at a 15 minute interval from the average reading between the two photoresistors. The summation on the left part of the equation represents the recorded sum of readings, each multiplied by the time they of the reading. We then estimate the total time by adding this value to an expected return if no change is made to the system. The second term represents the current light intensity multiplied by the remaining amount of time, to estimate the total photo-hours the plant is getting over a full day.

The temperature sensor ensures that the user knows the plant is located in an area where ambient temperature is adequate for plant growth. For lettuce and basil, it was determined that the temperature of the system should remain within 55 and 85 degrees Fahrenheit. Through data visualization, the user is able to see if their system's temperature remains within this range throughout the day. If it did not, they are notified to move their system to a location more suitable for the plant's health.

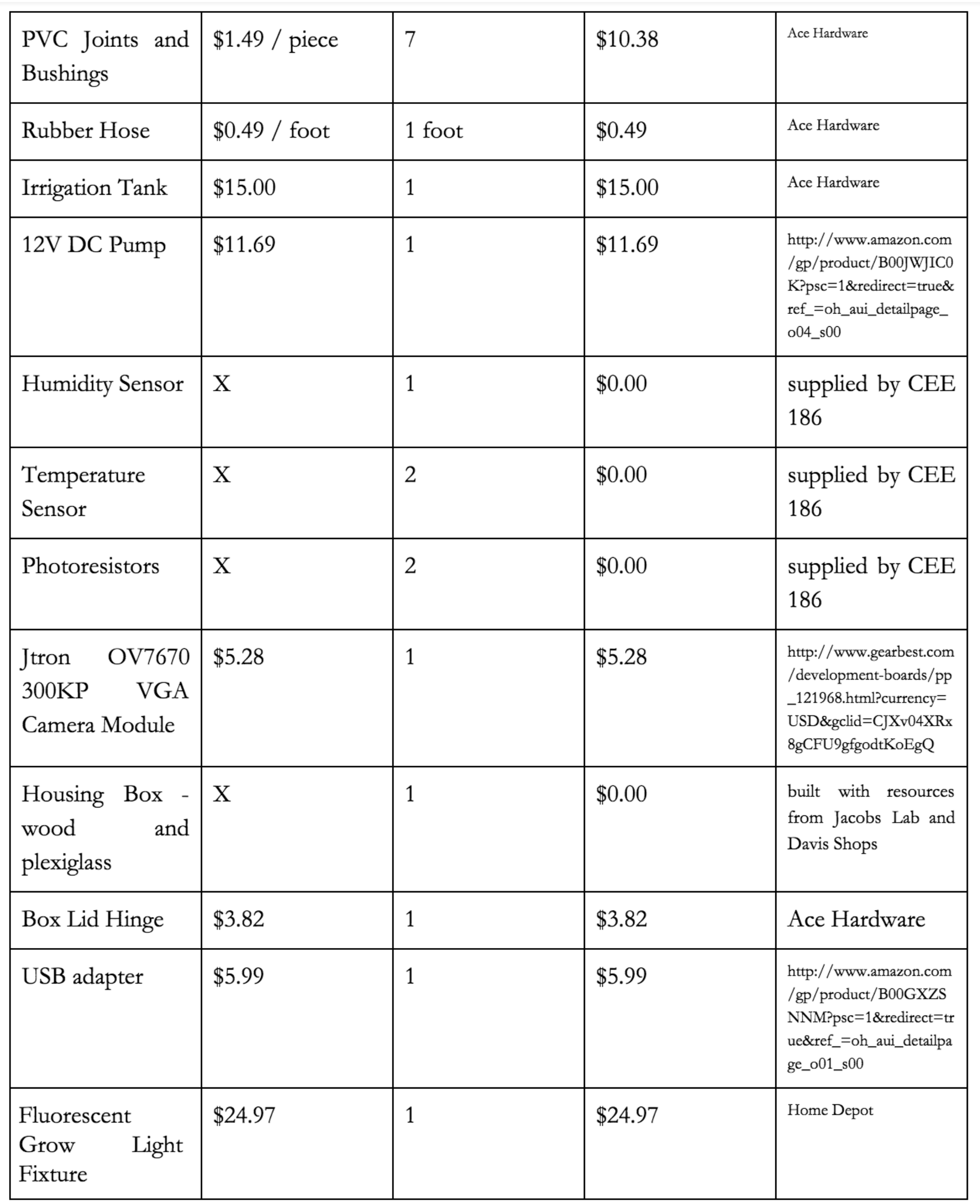
Although our system maintained a constant period between pump actuation to spritz the roots with water, the humidity sensor served as a quality control check to the user to determine the spritzing period. The humidity sensor took readings in between spritzing to see how the system behaved over time. If the humidity level in the root container fell below 65%, the user would know that they should decrease the duration between spritz. If the humidity level rose above 85%, the user would know to increase the duration between spritz. Eventually, the user would be able to maintain the root container at a constant humidity level over time.

Additionally, we attached a flow meter behind the pump to better understand the amount of water flowing into the spray system per cycle. Given the volume reading of flow, we can estimate a percentage of water that will further saturate the roots, while the rest condenses and falls back into the supply tank. This amount is read and fed into our data analysis tool in Python to prompt a user when the water in the supply tank needs to be replaced.

Bill of Materials

Below is the bill of materials, a full list of items that went into the prototype:

Bill of Materials				
Material	**Cost Per Unit**	**Quantity**	**Total Cost**	**Source**
Lettuce	$3.68	1	$3.68	Home Depot
Basil	$3.50	1	$3.50	Trader Joe's
1-1/2" ABS Cleanout Adapter SPGXFPT	$1.97	4	$7.88	Home Depot
Water Spigots	$0.40	10	$4.00	Hydroponic Connection - Berkeley
Flow Meter	$15.95	1	$15.95	Amazon
Garden Plant Wool Sprouting Medium	$11.95	1	$11.95	Hydroponics Store
PVC piping for hydroponics	$0.42/foot	2.5 feet	$1.05	Ace Hardware



PVC Joints and Bushings	$1.49 / piece	7	$10.38	Ace Hardware
Rubber Hose	$0.49 / foot	1 foot	$0.49	Ace Hardware
Irrigation Tank	$15.00	1	$15.00	Ace Hardware
12V DC Pump	$11.69	1	$11.69	http://www.amazon.com/gp/product/B00JWJIC0K?psc=1&redirect=true&ref_=oh_aui_detailpage_o04_s00
Humidity Sensor	X	1	$0.00	supplied by CEE 186
Temperature Sensor	X	2	$0.00	supplied by CEE 186
Photoresistors	X	2	$0.00	supplied by CEE 186
Jtron OV7670 300KP VGA Camera Module	$5.28	1	$5.28	http://www.gearbest.com/development-boards/pp_121968.html?currency=USD&gclid=CJXv04XRx8gCFU9gfgodtKoEgQ
Housing Box - wood and plexiglass	X	1	$0.00	built with resources from Jacobs Lab and Davis Shops
Box Lid Hinge	$3.82	1	$3.82	Ace Hardware
USB adapter	$5.99	1	$5.99	http://www.amazon.com/gp/product/B00GXZSNNM?psc=1&redirect=true&ref_=oh_aui_detailpage_o01_s00
Fluorescent Grow Light Fixture	$24.97	1	$24.97	Home Depot

[Discussion]

Agriculture has continually benefited from the development of new technologies over time -- as seen through the development of tools and machineries such as tractors and threshers -- and the implementation of aeroponic and hydroponic irrigation systems. Garduino seeks to build on these developments and continue this trend as it seeks to integrate present-day agricultural systems with a cyber layer that can monitor and regulate multiple aspects relating to plant health, in order to optimally grow any plant in any environment. This cyber-physical system seeks to solve the inefficiencies found in today's agricultural systems, where the unpredictability of the natural environments can lead to excess water and energy usage with minimal crop yields. As climate change continues to influence the availability of natural resources critical to plant health, it becomes increasingly significant for human beings to develop self-contained environments that can monitor and actuate themselves to provide plants the most favorable conditions to cultivate. In addition to solving the inefficiencies of large-scale farming systems, Garduino provides an accessible and personal system that allows the average consumer to grow the plants of their choice. By providing a connection between the physical agricultural systems of today with existing technology and the internet, Garduino hopes to create opportunities that will improve efficiency, accuracy and economic benefit to the production of crops.

Through the use of the sensors and microcontrollers described in the previous sections, Garduino provides users with up-to-date information on a plant's state of health. The cyber-physical system gives users the opportunity to regularly track multiple variables that relate to the health of their plants. In an age where the internet provides quick connections to data, it becomes increasingly important to utilize this opportunity to reduce the time users spend physically tending their plant. The hope is that users will no longer waste time guessing how much and for how long to water their plants, or even how comfortable the plant is in its current environment. These logistics are easily accessible with an internet-connected device, where the user can identify where adjustments need to be made if their system is not performing as expected. Rather than relying on guesswork and estimations based on the user's botanical knowledge and physical observations, Garduino gives users data that will allow them to make more informed decisions on their systems. This highlights the significance of data visualization, as one can see exactly how their system behaves over time. The history of information gives opportunities to identify where and why the system failed, should the plant not survive. Garduino provides a robust and easily understandable interface that can provide users the accessibility and ease to grow the plant of their choice, tinkering with the variables input into their system, and understanding the outcomes of their actions.

With room for improvement, Garduino sets the basis for smart farming and cultivation of crops in an internet-of-things age. Users continue to improve, expand, and optimize the system in order to accommodate location-specific criteria of the user. As areas throughout the world face their own dilemmas related to droughts, infrastructure failures, climate change, or socio-political problems, Garduino aspires to be the solution that provides homes with the necessary capabilities they need to grow their own food efficiently. Additionally, Garduino provides the opportunity for vertical expansion in areas where land use is limited.

[Summary]

The theoretical advantages of aeroponic systems are clear and has been corroborated by many studies, but these experiments have primarily focused on indoor farming at an industrial level. Garduino is a much smaller physical system, is more portable, and is accompanied with a website and personal Twitter account. As a result, this cyber-physical system appeals to a general consumer audience. Unlike existing indoor farming research, which focuses on studying the optimal growing conditions of plants, Garduino automatically actuates itself to comply with these established growing conditions. Current sensing information includes humidity, light, and temperature, but with additional time and resources, other sensors can be added. Like indoor farming, the purpose of Garduino is not to mimic natural environments, but to simulate the absolute best growing conditions, which often cannot be replicated in nature.

All in all, Garduino aims to reconnect users to how their food is grown by providing user-friendly tools to teach and share information on the health of their plants. Like many places in the world, California is suffering from a severe drought, and the agriculture industry must adapt to the lack of water. By connecting users to every step in the growth of their plants, and thus by showing users how water-efficient aeroponic systems like Garduino can be, the hope is that people become more aware and proactive with their decisions and lifestyle choices in regards to the preservation of our natural environments.

Main Sources

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Supplementary Readings

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