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Resilient Smart Gardens—Exploration of a Blueprint

Birgit Penzenstadler *, Jayden Khakurel, Carl Jason Plojo, Marinela Sanchez, Ruben Marin and Lam Tran

Department of Computer Engineering and Computer Science, California State University–Long Beach, Long Beach, CA 90840, USA; jayden.khakurel@lut.fi (J.K.); jason.plojo@gmail.com (C.J.P.); marinela.sanchez88@gmail.com (M.S.); rubenlmarin92@gmail.com (R.M.); lamtran409@gmail.com (L.T.)

* Correspondence: birgit.penzenstadler@csulb.edu

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Abstract: In an effort to become more resilient and contribute to saving water and other resources, people become more interested in growing their own food, but do not have sufficient gardening experience and education on conserving water. Previous work has attempted to develop resilient smart gardens that support the user in automated watering using simple embedded boards. However, none of these solutions proved to be scalable nor are they easy to replicate for people at home. We set up a student team project that created a safe space for exploring this multidisciplinary domain. We developed a smart resilient garden kit with Internet-of-Things devices that is easy to rebuild and scale. We use a small-scale board and a number of sensors connected to a planter. In this paper, we report on a prototypical implementation for multidisciplinary smart garden projects, our experiences with self-guided implementation and reflection meetings, and our lessons learned. By learning about water conservation using automation on a small scale, students develop a sense for engineering solutions regarding resource limitations early on. By extending such small projects, they can prepare for developing large-scale solutions for those challenges.

Keywords: software engineering; requirements; sustainability; project-based courses

1. Introduction

According to William Rees, "Resilience science is based on the simple premise that change is inevitable and that attempts to resist change or control it in any strict sense are doomed to failure" [1] (p. 5). He adds that, in order to achieve that, development strategies have to abandon efficiency and maximization as primary goals in favor of social equity and ecological stability [1]. As we are observing global effects of climate change in phenomena such as frequent flooding, droughts, and heat waves, developing these strategies is becoming urgent. The mentioned effects directly and indirectly impact the: (i) environment, i.e., changes in soil fertility and the growth patterns of plants and local landscapes [2–4]; (ii) economy, i.e., the need for financial aid due to drought [5]; and (iii) society, i.e., increased food and water prices due to greater demand [6]. For example, parallels can currently be seen in California, where the occurrence of droughts and intense heat waves has increased [7]. To become more resilient to future climate conditions [8], create a greener society, save money, and improve food quality [9], many individuals are practicing home horticulture. Home horticulture is the nonprofessional cultivation of plants for recreation, personal health, cost savings, and environmental and social benefits [2,10,11]. Though mitigating climate change is a motivation to learn home horticulture, individuals still need to reduce their outdoor water consumption. Research indicates that individuals consume more water during outdoor activities such as gardening than during indoor activities due to a lack of knowledge about water usage [12]. Domene et al. [13] argue that garden watering could account for up to a third of household water consumption yearly and close to 50% of total consumption in the summer [13].

Caetano et al. [14] (p. 566) state, "too little water will retard plant growth and reduce quality, while too much will leach fertilizers and reduce aeration". Adequate watering dictates the quality of the harvest, which is why we try to facilitate it by an automation that protects the user from overwatering (wasting resources) and protects the plants from drought.

To reduce an individual's outdoor water usage, researchers and practitioners have developed automated watering systems [14–16]. However, there have been no scalable, affordable, or easily replicated solutions for people at home who lack technological skills. Attari et al. [17] report that participants in their study were ready to simply reduce their usage rather than explore efficient solutions because of the additional expense involved in controlling water consumption through an acquired, efficient system. Research also indicates that do-it-yourself (DIY) solutions enhance consumer's desire by increasing their pleasure and sense of individualism while saving them money [18]. Therefore, the challenge is to find an affordable, scalable solution that can reduce the cognitive effort and cost while closing the gaps for gardeners with limited technological and home horticulture experience.

The **objective** of our research was to develop the prototype of an affordable resilient smart garden education kit that teaches students how to embed technology in a gardening environment to monitor and support the natural growth of vegetables. We applied an action research approach in the context of an undergraduate summer project.

The **research question** that we are investigating for the project in this article is:

What are the insights from and challenges for developing a small-scale resilient smart garden from scratch using off-the-shelf components and permaculture principles?

The **contribution** is to provide a prototypical implementation of a resilience-oriented, interdisciplinary project course for smart gardens. This gives students the opportunity to explore working with limits in terms of natural, technical, and economic resources.

In this study, we built an affordable, resilient smart garden to reduce the experiential learning curve of people who have an affinity for technology but lack gardening knowledge. This was conducted in a hands-on summer research project with four undergraduate research assistants. As educational strategy in this action research we provided a safe-to-fail space where students could figure out creative ways of implementing the design at hand in combination with weekly reflective sessions [19].

Specifically, we used a small-scale embedded board and sensors connected to a pump to control water consumption through data visualization. Data stored in a local database was easily accessible via an online portal and a responsive web application. This application was implemented to improve the interoperability of apps and to facilitate the gardeners' activities. The project connects multiple disciplines, namely computer science, computer engineering, environmental studies, biology, and permaculture [20]. Specifically, the inclusion of permaculture principles differentiates the project at hand from other smart garden projects. The impacts of the resilient smart garden system are that it (1) reduces the cognitive effort and closes the technological gaps for gardeners with limited prior technological experience; (2) reduces the experiential learning curve of people with affinity to technology who have little prior gardening knowledge; and (3) helps to bridge between disciplines—computer science and computer engineering and environmental studies and biology.

The potential **impact** of how this project could be utilized in future work by others in the related research community is to develop similar projects that lead to an educational blueprint for undergraduate action research that ventures beyond computer science into sustainability application domains. It can serve as call to action for reaching out across campuses for interdisciplinary projects, specifically as detailed in the discussion of how to expand on this work.

The remainder of this article provides the background of the research in Section 2, the research design in Section 3, the implementation in Section 4, the results in Section 5, the discussion in Section 6, and the conclusions in Section 7.

2. Background

A closer look at the related work shows that the majority has looked at water conservation projects, resilient smart garden projects and systems used for farming, gardening help systems, micro-controller do-it-yourself (DIY) projects and educational kits for gardening. The referenced projects are summarized in Table 1 and described in detail in the following subsections.

Table 1. Summary of referenced projects.

Project	Description	Pro	Con
Maleficarum [21]	water conservation system for washing machine to toilet grey-water reuse	grey-water reuse	inadequate for classroom project
Amberg [22]	micro-controller and a flow sensor to measure and flag water usage	water conservation	inadequate scope for summer project
Vinduino [23]	reduces agricultural water consumption in a vineyard	water conservation	inadequate for classroom project
Palmer [24]	clock-based irrigation controller	water conservation	inadequate scope for summer project
Connected Garden [25]	outdoor garden and used sensors controlled by a micro-controller board to collect data	monitoring	no intervention
Guarduino [26]	sensors connected to micro-controller for feedback on irrigation	water conservation	no intervention
Automated Aquaponics Design Report [27]	monitors both the condition of a garden as well as a fish tank	aquaponics	scope too large for summer project
OpenAg [28]	personal food computer in closed environment	encompassing system solution	scope too large for summer project
Edyn Smart Garden System [29]	automated garden monitoring and irrigation	commercial-off-the-shelf	no do-it-yourself component
GreenIQ Smart Garden Hub [16]	automated garden monitoring and irrigation	commercial-off-the-shelf	no do-it-yourself component
Daniels [30]	instructions to make an outdoor automatic garden watering device		
Aqib [31]	advanced automatic watering garden tutorial		
Hamza [32]	making a temperature data logger	instructions for part of project	missing context adaptation
Iseman [33]	automatic watering garden using DIY moisture sensors	DIY sensors	too detailed for our scope
Bee Smart kit [34]	educational miniature garden	complete kit for schools	no do-it-yourself component, intended for different audience
Tower Gardens school kit [35]	educational aeroponics garden	complete kit for schools	no do-it-yourself component, intended for different audience

2.1. Small-Scale Water Conservation Projects

A few small-scale water conservation projects discuss and utilise micro-controller boards as a hardware tool with additional sensors. Amberg [22] and Maleficarum [21] offer instructions on water-saving systems using micro-controller tools that are intended to be built at home by a hobbyist. Maleficarum [21] presents a tutorial for a water conservation system project that uses water from a washing machine to recycle to a toilet tank, which can be completed within 10–20 h using an Arduino Uno board, a water sensor and a water pump. Amberg [22] describes the setup, programming and installation of a water-saving device on a tap using a micro-controller and a flow sensor to measure how much water is used. By lighting up red LEDs after one liter of flow, the system helps reduce unnecessary water waste. The project requires 5–10 h of effort. Lee and Gallardo [23] created the project Vinduino, which aimed to reduce agricultural water consumption in a vineyard. This project uses a micro-controller, low-cost moisture sensors, and a solar module—and went on to win a hackathon competition. Palmer [24] developed a simple clock-based irrigation controller that aimed to allow residents with limited IT background to set up a cheap and simple way to monitor and reduce the water they used for irrigation. The project consisted of a moisture sensor, a real-time clock module, and a micro-controller.

All of these projects use micro-controller boards and maker ideas to install water-saving interventions. The proposed Resilient Smart Garden project draws upon these maker principles and applies them to save irrigation water for a small vegetable garden.

2.2. Other RSGs and Systems Used in Farming

The Resilient Smart Garden (RSG) is not the only project designed to bring gardening and technology together to make gardening easier. Many projects exist that use the combination of sensors monitored by a micro-controller board to help make gardening more accessible, especially to those who do not have as much knowledge on proper plant care. Many of these projects provide data from temperature to soil moisture, all which helps take better care of a garden by providing ways to ensure a plant is growing under optimal conditions. This also simplifies at home food production, provides opportunities for community gardens, and can be scaled up to help in agriculture.

Connected Garden [25] was implemented by the University of Central Florida. They set up an outdoor garden and used sensors controlled by a micro-controller board to collect data. The project relied on a variety of sensors to send information to servers. The main focus of this project was to collect data on both the natural environment and interactions with the garden. Natural data consisted of temperature, light and moisture. Interaction data kept track of the tools used while tending to the garden. Compared to the Resilient Smart Garden, Connected Garden was project solely based on gathering data to test server integration. This project only relied on sensors to collect data and was not connected to an irrigation system.

The Guarduino project [26] carried out by students at Poornima Institute of Engineering Technology in India is most similar in design to the Resilient Smart Garden. The Guarduino uses a variety of analog and digital sensors including light, temperature, and homemade moisture sensors that are all connected to an Arduino. The system then records the information collected by the sensors to determine the on/off state of the connected irrigation system. Similar to the Resilient Smart Garden, one of the goals for this project was to help with production of food by optimizing the amount of water delivered to plants when resources are scarce.

The Automated Aquaponics Design Report [27] describes a sustainability project that monitors both the condition of a garden as well as a fish tank. As explained in the article, aquaponics works off the principal that the garden and fish will create an ecosystem where the waste from the fish will provide nutrients to the plants. It is a system that replicates the relationship between fish, bacteria, and plants—a relationship that exists in the natural world [27]. While the system monitors two different elements, the project still has elements that are similar to the Resilient Smart Garden. The System implemented a variety of sensors that were monitored through a micro-controller and a garden environment that was adapted for indoor use. The irrigation system pumped water from the fish tank into the garden, but was not controlled through the controller. The monitoring system only kept track of the water levels from the garden bed, water temperature, LED light levels and room occupancy. While aquaponics are a great project, most small-scale implementations are limited to indoor use in Southern California because the fish tank would dry out too quickly in the dry heat due to evaporation.

OpenAg [28], also known as Open Agriculture, is an open source project developed by MIT that was created to make gardening easier and provide a more controlled environment to care for a garden bed. Out of all the systems found, OpenAg is the most developed and requires a lot more hardware. Their product is defined as a personal food computer. The garden bed is kept in a closed environment that is controlled by a Raspberry Pi. UV lights are used instead of natural sunlight, and sensors help monitor the garden as well as control the environment the plants are growing in. Hydroponics is also the method selected for irrigation. OpenAg focuses on growing and maintaining a garden in a controlled enclosure versus outside.

2.3. Garden Monitoring Systems

There are a few commercial-off-the-shelf "COTS" systems that are available in the market to help gardeners grow plants. The search led to identifying Edyn Smart Garden System [29] and GreenIQ Smart Garden Hub [16].

The Edyn Garden [29] helps gardeners to monitor the environment condition using the Edyn Garden Sensor. This sensor can track humidity, temperature, light, moisture, soil nutrition, then compare those data to provide plant database and soil science, and generate the garden guidance to help gardeners. Edyn garden system consist of setting up mobile apps on both operating systems, i.e., Android and iOS, which is able to send garden data in the real-time to the gardeners such as the condition of the garden and the guidance on how to adjust the garden better through the WiFi network. Furthermore, Edyn garden systems seem to provide value to gardeners with the possibilities to (1) access the database that contains information of over 5000 plants such as optimum climate conditions plants require; (2) deliver suggestions based on plant's growth stage; and (3) alert notification to user when some plant needs attention. The other noteworthy feature of this system is the Edyn water valve which automatically controls the existed irrigation system based on the local weather forecast and number of plants in the garden. It can link to the Edyn Garden Sensor to produce Smart Watering, based on the Edyn Garden Sensor and weather. Additionally, with regards to manageability, Edyn also provides the manual watering option, which does not require an Edyn Garden Sensor, to let users manage water usage and set the specific time and date for watering.

The GreenIQ Smart Garden Hub [16] is a system that helps gardeners grow plants from anywhere and anytime by wisely managing a garden's irrigation system and lighting scheduling using Internet Cloud and mobile technologies. All GreenIQ models are watersense certified by the International Code Council Evaluation Service (ICC-ES), which can save up to 50% on a water bill. There are tree models that differ by the size of the controlled area and by the number of irrigation zones—of which there can be 6, 8 or 16. The system allows users to control and schedule the garden's irrigation and lighting from anywhere and anytime by using desktop or mobile apps. It connects to WiFi networks, collects the information from the nearest weather station and then calculates the water needed for the garden. It includes three components: (1) The GreenIQ Smart Garden Hub connects to a garden's irrigation valves and garden's lighting circuit to control irrigation and lighting schedules via WiFi, cellphone or Ethernet cable; (2) The GreenIQ Mobile App allows users to create scheduling programs for each irrigation zone and the lighting channel; and (3) The GreenIQ Cloud stores system configurations and user's programs, communicates with mobile devices, and configures changes.

Both tools facilitate the gardening and irrigation but are not targeted towards educational use.

2.4. Other Micro-Controller Projects

Electronic DIY projects are more accessible with easily programmable single board micro-controllers. Daniels [30] offers instructions to make an outdoor automatic garden watering device using an Arduino UNO that measures the soil moisture levels. The project is placed inside an enclosure that has a liquid crystal display screen that displays the current moisture levels and is powered by a 12 V battery. Aqib [31] presents an advanced automatic watering garden tutorial that will store moisture, temperature, humidity, heat index, pressure, and value status into a database. The controller is powered by a 12 V battery and communicates with a server locally using an Ethernet Shield. Hamza [32] provides information on making a temperature data logger using a hardware clock. The data is stored locally on a secure digital card and does not communicate with a server. Iseman [33] demonstrates an automatic watering garden using DIY moisture sensors. Two nails are attached to a wire and connected to the micro-controller to detect the soil moisture level by putting a low current through the soil via one nail and detecting the resistance via the other. The more water in the soil, the less resistance there is and vice versa. The temperature, humidity, and moisture data is sent through a serial port, but not stored into a database. The micro controller must be connected to a computer to display the data through the serial port and to power it.

All of these projects have similar approaches to implementing an automatically watering garden. The Resilient Smart Garden shares some characteristics to minimize water usage while maintaining a sustainable environment for the plants, but goes beyond the pure DIY implementation.

2.5. Other Educational Garden Kits

The Bee Smart kit [34] is an educational miniature garden for use in a school or home environment. The educational kit is geared toward children from grades 3–6 to learn about gardening systems in a easy to setup kit. The goal is connecting them to plants, pollinators, food, and gardens by potentially creating habitat for pollinators. The kit itself is very limited with regards to gardening as it is marketed as a simple educational kit with minimal effort by the user.

The Tower Gardens school kit [35] is the educational version of an aeroponic system that uses water, liquid nutrients and a soilless growing medium to quickly and efficiently grow produce. The kit is pre-built and requires minimal effort to set up and begin growing. The kit is built around a portable grow light that lights the vegetation from the inside and requires no setup from the user with regards to hardware. The DIY part involves planting the seeds with ease into the base of the kit and allowing it to grow. The user is only responsible for maintaining the pH and water levels as it does not require sunlight, since it was built with the indoor garden in mind. The downside to this educational kit is the significant price tag. For a basic kit, it costs $45.25 per month, a steep price for an educational system.

Heitlinger et al. [36] argue that research into ubiquitous computing for sustainability must move its focus beyond designing for individual consumer behaviors. Their work on participation, community, citizenship and collective action in London's urban grassroots food-growing communities proposed the Talking Plants Sale prototype, to support the values of the farm.

2.6. Permaculture Principles

None of the previously presented projects explicitly worked with permaculture principles. While the scope of permaculture as defined subsequently goes way beyond what we are able to explore in an undergraduate summer research, we made it a point to educate the research assistants in permaculture and its principles and have them apply the mindset where possible in the limited scope and given context:

> "Permaculture is primarily a consciously designed agricultural system . . . a system that combines landscape design with perennial plants and animals to make a safe and sustainable resource for town and country" [20] (p. 2).

Practices like permaculture (the eco-, human-sustainable design for permanence) advocate for similar ideologies, e.g., apply self-regulation and accept feedback [37]. Although independently ensured food and resource security is an important step in becoming self-sufficient, this transition requires a great time investment to learn these methodologies and their implementation. There is a set of twelve main principles that are observed in permaculture [37]: (1) observe and interact; (2) catch and store energy; (3) obtain a yield; (4) apply self-regulation and accept feedback; (5) use and value renewable resources and services; (6) produce no waste; (7) design from patterns to details; (8) integrate rather than segregate; (9) use small and slow solutions; (10) use and value diversity; (11) use edges and value the marginal; and (12) creatively use and respond to change. We discussed the principles and their application in our project with the research assistants during the design phase.

In permaculture, a garden built of plant guilds can foster human independence from extraneous materials and promises to deliver the highest harvest yield while making keeping the grounds sustained [20].

2.7. Preliminary Work

The work presented in this article is based on a prototype developed for an individual plant in a senior design capstone project from the Spring semester 2017. A first prototype of the Resilient Smart

Garden system had already been built as a senior project by a student team in the Fall semester of 2016 [38] and was expanded upon by a different team in Spring 2017. Four of the students who worked on the preliminary work continued as research assistants over the summer to fully implement the prototype. This article contributes an extension of the results presented at the LIMITS workshop 2018 [39]. Specifically, this article expands on the permaculture perspective, the data reporting, the qualitative analysis of the reflective essays, and the discussion of future avenues building on this prototype.

3. Research Design

3.1. Context: Undergraduate Summer Research

The Resilient Smart Garden is an autonomous controlled garden that efficiently and effectively grows plants. With the Resilient Smart Garden, a hobby gardener will be able to use less water while growing their vegetables with greater ease. While the idea of a small "smart" personal garden may seem to have limited scope, if this type of technology is adopted in large enough numbers, it can begin to have a huge impact. The scope can quickly go beyond an interested hobbyist, to a local farmer's market, to small commercial sellers and may even influence large-scale producers. If the method is simple enough to integrate in a variety of systems, economically viable and is efficient in its use of resources, then the product will no longer be viewed as a small enthusiasts weekend project but as an actual alternative to traditional farming methods. If we can at least begin a conversation of smart technology and sustainable farming in an educational setting, then this project is a success.

The previous prototype of the system for a single plant is extended for a small garden with several plants. This system serves as an educational tool for connecting software engineering to systems thinking and sustainability. The system under consideration is a project developed using a micro-controller board and permaculture principles. These principles allow for sustainable long-term garden cultivation with maximum harvest based on the natural capacity of the soil enhanced by well-planned companion planting [20]. The system vision is to connect a growing bed via sensors to a micro-controller board such that we can measure moisture, humidity, and temperature and log that data. This enables determining the minimally feasible amount of watering, which is an environmentally sustainable measure in drought-prone Southern California. This system enables people with little background in gardening to successfully grow vegetables in the most sustainable and resource-conserving way. Along with the development of the extended version of the system, the research assistants develop a documentation intended for non-technical hobbyists to be able to follow and set up their own Resilient Smart Garden, see Figure 1.

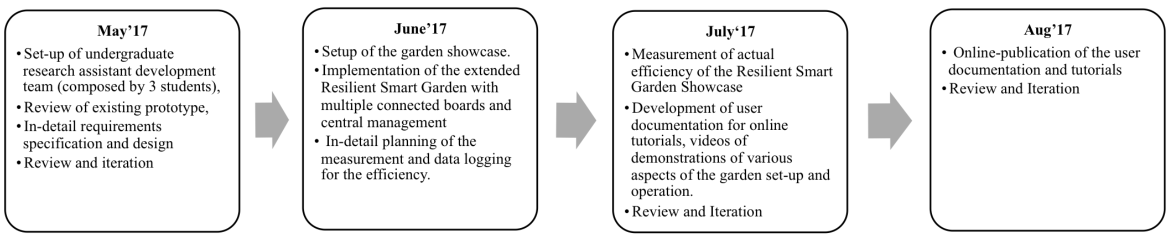

Figure 1. Timeline of the research project.

3.2. Research Vision

The Resilient Smart Garden in the previous prototypical form can manage one plant by using one humidity sensor and one temperature sensor. The envisioned extended version manages 10 plants of different kinds using multiple temperature and humidity sensors. According to companion planting, we select a design that groups together plants that benefit from growing together, for example a tomato plant and a basil plant. The root systems of those two plants use different layers of soil, and the basil keeps potential pests, e.g., snails, at bay with its strong fragrance [20]. The ten plants are planted in two planter boxes each monitored by one micro-controller board.

In addition to the embedded part, a web app provides the front-end user interface where the gardener interacts with the setup of the garden. This includes a companion-gardening design feature that helps the inexperienced gardener to put together the plants, as in the above tomato-basil example. Imagine a zoom-in in Google Maps with a layover of plants that can be dragged and dropped on a garden design canvas. The user receives a list of proposed plants that grow well in that specific area plus feedback on whether a plant grows well next to the plant it is being dropped on the map [40]. Furthermore, users can review the graphics of the measured data over time and adjust the automatic watering. They can see their garden's history and compare data over time and they can opt in to make their data visible to other gardener's using the same web app so they can learn from or be inspired by other designs. This way the platform can grow into an educational tool that gets better over time as more users provide their data.

3.3. Educational Strategy

Undergraduate students benefit tremendously from research experience [41], which is why we proposed the summer project. The students were allowed to work largely self-directed based on their previous experience from the first semester. They reported back weekly and we held reflective meetings to enhance their own analysis skills and learn from how the project unfolded [19].

We wanted to provide students with a safe space to be able to explore the bridge between disciplines and explore the (to them) new application domains of embedded systems and gardening. The reasoning for this is that such a safe-to-fail space enhances students' creativity and after college most of them enter into jobs where creativity is highly valued but often not given said needed whitespace [42]. In addition, while traditional senior year design projects often put students on a strict schedule that doesn't give them much time to tamper around with different solutions and explore avenues that potentially lead to failure, we set out with the mindset of wanting to explore different routes and had the luxury of being able to try, observe, fail, adapt, and try again. This principle of observation and adaptation is fundamental in permaculture [20]. In addition, we were able to involve a few domain experts to give us advice, namely a local permaculture designer, a professor from hospitality management, and two passionate hobby gardeners.

3.4. Data Collection and Analysis

All data was collected by the undergraduate research assistants. The data for this article is comprised of the requirements' specification, project documentation, the garden data that includes sensor measurements as well as manual measuring and observation, the project diary written by the research assistants, and a final reflection written by each research assistant individually. Excerpts from this data collection are shown throughout the remainder of this article.

The data was analyzed under the lead of first author, who was the project supervisor, and reviewed by the second author, who did not participate in the actual implementation of the set-up but joined later on to review the results. While the actual measurements of the sensors only led to several insights about how well parts of the hardware worked and how the set-up had influenced the growth of the garden, the qualitative data from the observations and the project diary helped to identify the majority of the insights and challenges from the project.

4. Implementation of the Resilient Smart Garden

Day zero of the project started with the students and a set of small rubber ducks taking possession of the California State University Long Beach (CSULB) Resilience Lab (also known as the Bat Cave). The students based the implementation on the requirements specification they had elaborated in the Spring.

4.1. Gardenware Set-Up

The watering system was one the important parts in the Resilient Smart Garden. This system involved a water pump that pumped water from a bucket through vinyl tubing; these tubes had small holes all along them in order for the water to pushed towards the plants, the design tried to replicate a drip irrigation system, but with high water pressure and small holes plants were more or less sprayed when watered. The water pump was controlled by the micro-controller board, and it was only activated when the soil's moisture was at low levels. Two planters, two water pumps, four temperature and humidity sensors, and two moisture sensors were used in this system, see schematic layout in Figure 2. They were placed at convenient places to collect the most exact data. For the vegetables, we chose five companion plants: Lettuce, basil, onion, carrot, and tomato. The resources needed for the watering system and garden included: vinyl tube, zip ties, a plug—we used Expo marker caps, two planters (24″ in length, with a width of 7.88″ and a height of 7.25″), Soil, 5 Gallon Plastic Bucket, red-green-blue light-emitting diode trip, and a Glue Gun. Garden and Watering System Setup:

1. For each planter, make two rectangular holes of the dimesions 0.5 cm height times 1.5 cm width on the two opposite holes to attach the humidity and temperature sensors.
2. Drill a smaller hole along the other two walls of the planter.
3. Put the five feet vinyl tube and arrange it along the interior side of the planter. Use zip ties to tie it to the planter and then use the plugs to seal one end of each vinyl tube. Then, use the pins to poke small holes along the vinyl tube to let the water spray towards the plants through these holes.
4. Attach the water pump to the other end of each vinyl tube and place the water pumps connected to the vinyl tube into the bucket.
5. Place the plants in the planters, fill the planter with soil and place the moisture sensor directly into the soil in the middle of the planter. Finally, put an LED strip on the wall of the planters.

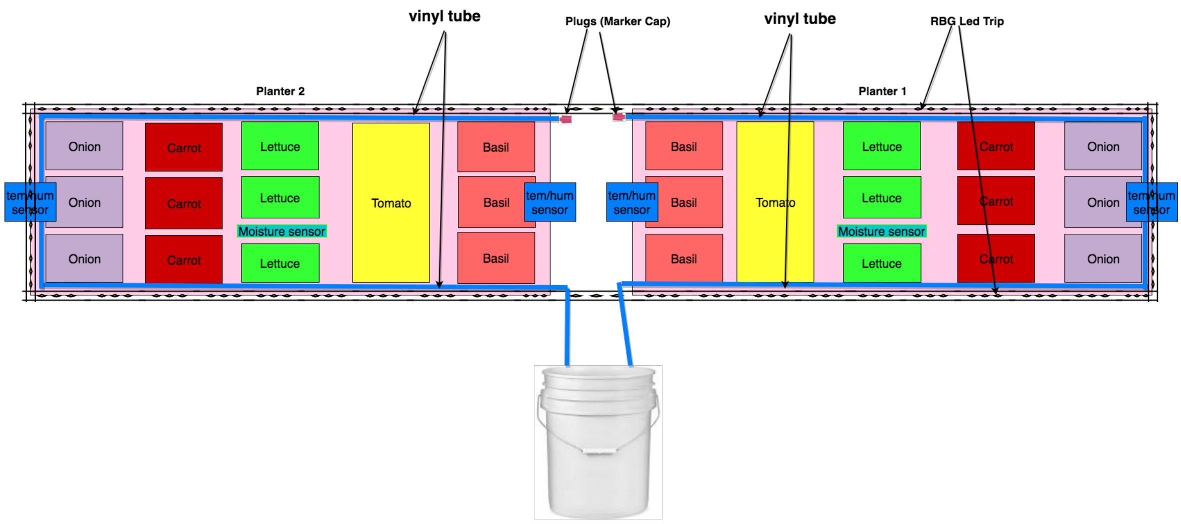

Figure 2. Component plan of the garden setup.

4.2. Hardware Set-Up

The hardware consists of a temperature/humidity sensor, moisture sensor, water pumps, and a project enclosure made from a cardboard box that contains a power strip with Universal Serial Bus (USB) type A plugs, power terminal block, twelve Volt one Ampere power supply, Arduino UNO, nodeMCU WiFi module, logic level converter, and power relay to activate. The micro-controller gathers the readings from the temperature/humidity sensor and moisture sensor. The nodeMCU gets the sensor readings from the micro-controller to send to a server to store the data. The power relays is controlled by the micro-controller and activates the water pump when the moisture sensor readings is below a certain value.

The project enclosure is made from the cardboard shipping box the electronics came in. The cardboard box has a width of 7.25 inches, length of 10 inches, and height of 3.25 inches. Two of the cardboard box flaps at the bottom with the longest length will be cut to repurpose it as a mount for the electronics. There are four electronic mounts in total: two for the pair of micro-controller and power relay, one for the power terminal block, and the last for the nodeMCU. Holes were made on the box flaps to match the mounting holes in the electronics, which are fastened into place using a screw, standoff, and nut. The bottom of the project enclosure is duct taped along the edges both inside and outside to seal it from potential water. Rubber feet were also added to the bottom to further prevent water from entering the project enclosure by raising it from the surface.

The temperature/humidity sensor, moisture sensor, and power relay will be wired to the micro-controller. The temperature/humidity sensor is digital and needs three wires for power (VCC), ground (GND), and data (DATA). VCC is connected to the micro-controller's 5 V pin, GND to GND, and DATA to an available digital pin. The moisture sensor is analog and needs three wires for VCC, GND, and OUT. VCC is connected to the micro-controller's 5 V pin, GND to GND, and OUT to an available analog pin. The power relay needs three wires for VCC, GND, and SIGNAL. VCC is connected to the micro-controller's 5 V pin, GND to GND, and SIGNAL to an available digital pin.

The nodeMCU communicates with the server to send garden sensor readings that are retrieved from the micro-controller through I2C protocol. I2C communication requires two pins for serial data (SDA) and serial clock (SCL). There are dedicated pins on the micro-controllers for I-squared-C (I2C) communication: pin D2 for SDA and pin D1 for SCL on the nodeMCU and pin A4 for SDA and pin A5 for SCL on the micro-controller. The nodeMCU operates at 3.3 V and the micro-controller operates at 5 V; therefore, a logic level converter is needed for communication between the nodeMCU and micro-controller. The logic level converter needs a power source from the nodeMCU and the micro-controller to use as a reference.

The power relay activates the water pumps which is controlled by the micro-controller. The water pumps are off by default when the power relay is not activated. The water pumps are powered by a 12 V one Ampere power supply that are controlled by the power relay. A circuit is made from the power supply, the water pump, and the power relay. The positive wire from the power supply connects to the common (C) pin in the power relay. The water pump positive power wire is connected to the normally open (NO) pin on the power relay. The negative power wire from the water pump is connected to the negative power wire from the power supply.

The electronics are powered from the power strip that includes two power plugs and three USB type A plugs. The pair of micro-controllers is powered through the USB type A plugs using a USB type B to USB type A cable. The nodeMCU is powered by the last USB type A plug using a USB Micro-B to USB type A cable. The pair of power relays share power from the 12 V 1 A power supply that is plugged into the power strip. The power is distributed using a terminal power block that has at least three rows: one from the power supply and two for the pair of power relays.

The micro-controller and nodeMCU use the Arduino IDE development environment to implement code and upload sketches onto the micro-controllers. The WiFi Module ESP8266 package needs to be installed into the Arduino IDE using Boards Manager in order to develop, compile, and upload sketches onto the nodeMCU. The ESP8266 package can be accessed on the Arduino IDE by including a link to the package in the Preferences menu. All libraries used for WiFi communication on the nodeMCU is included with the ESP8266 package. The ArduinoJson library is used on the nodeMCU to format the sensor readings in Java Script Object Notation (JSON) format to send it to the server. The ArduinoJson library can be obtained through the Arduino IDE Manage Libraries.

4.3. Software Set-Up

The software side of the project mostly involved setting up a server written in nodeJS for handling http requests from the micro-controller board. The use of node allowed for an easy set-up for collection of data from the micro-controller board. The server is currently hosted on Amazon Web Services (AWS), using a lightsail instance for deployment. The server.js file is ran by the AWS and the code listens for the requests. However, during the research period, it was impossible to use AWS due to security issues from the university's network. To get around this issue, a local network was set-up and the server was ran indefinitely on a dedicated machine running a basic Linux distribution. The server used several external libraries to implement the features that are required by the project. The external libraries mainly used for the purposes of research are 'body-parser' and 'levelDB'. Bodyparser allows for the http request to read the contents of the body sent within the request, which then stores these contents into a local database set up by levelDB. These two libraries allowed for a simple implementation of the project. For the simple purposes of data collection, only one http request was used, a POST request using the '/data' endpoint that allowed the micro-controller board to send data readings in a JSON format. The server would then read the JSON and parse the data into the .log file created by the local database. The process can be followed easily if broken down into steps: 1. The micro-controller makes an http request using a localhost:3001/data endpoint and sends the JSON data with a header and a body 2. The server checks the header to ensure that the credentials match the expected response 3. The server parses the data stored in a JSON file and prints it onto a .log file created by the database.

5. Results

This section provides a qualitative analysis of the implementation of the project as it occurred in summer 2017, an overview of our data, and the observations we made.

5.1. Project Diary

The students wrote a project diary from the start of the project until the end of the summer when the official data collection was done. The insights from the journal are mainly a documentation of the steps, how much work they could get done every time they met, and some observations about the complications and unforeseen circumstances. A few noteworthy entries are listed in Table 2. For example, students got highly motivated by rubber duck debugging, to the extent that they placed real rubber ducks all over the lab and gave them names. Then, we had a few incidents with technical problems, WiFi problems and later on flooding problems due to a corroded sensor and the software needed to include an extra check for that. The tomato plants grew up to almost five feet but then hit the bottom of the planter and declined, and, finally, we had domain-specific issues coming up in the form of various pests that first ate our carrots and then another one that infected our chives. However, in the end, we harvested some vegetables.

Table 2. Excerpt from project diary.

Day Zero: Ducks everywhere	Got a set of rubber ducks for the lab for rubber duck debugging [43]. They have names and make people smile when they enter the lab.
22 May, Shopping	Worked on shopping lists for both garden and hardware components. Finding planters and soil was relatively easy. Finding the prices for seedlings online was more tricky for the cost estimation, as many of them weren't listed.
Memorial Day, Remote Work	Included some soldering and WiFi module research. The students were so motivated for the project to even put in work on a holiday.

Table 2. *Cont.*

5 June, Irrigation system	We did not have power tools, a power drill specifically, on hand. We had to manually make holes using scissors, screwdriver, and wire cutters. We made use of whatever we had available at any given time.
7 June, WiFi problems	Attempting to get the garden system to communicate with the server has a snag with the campus WiFi. The school is using WPA2 Enterprise encryption and PEAP protocol for user and password authentication. The current stable library for the WiFi module does not support this feature. Temporary solution: Tethering over phone. We now found a permanent solution using a library.
19 June Pests detected	Only 1 of the 4 lettuces initially planted in the planters is alive, and currently struggling. We found a few pests: vine lice were found on the chives in planter 2, a cocooned caterpillar (Shield) was found on the leaves of the lettuce in planter 1, and a caterpillar (Little Jerkwad) ate a good portion of the leaves of the carrots in planter 1.
21 June, Pest control	Vinegar, get the damn pests away. That worked only partially, and one plant died supposedly because of too much vinegar sprayed.
22 June, First flood	Opening the door revealed a big flood on the floor and an empty water bucket. My first reaction is to turn off the power strip.
27 June, Partial solution	Online research suggests that having capacity constantly powered in a moist environment will enhance the corrosion on the capacitor. We minimized the time the sensors are powered.
5 July, Project enclosure	It turns out that the temperature/humidity sensor was mounted upside down, which flipped the polarity causing a short. Remounting the temperature/humidity sensor is unfortunately not an easy option for us, so we flipped the wiring on the micro-controller and breadboard instead.
19 July, Press coverage	In the afternoon, a video team from IEEE Computer Society came in and interviewed us while taking B-Roll shots of the garden and the system. The project got more attention than we expected.
31 July, Harvest	Tomatoes in planter 2 are beginning to split open. We picked them. At this point, the plant also had too little room and started to deteriorate.

5.2. Garden Observations

In our observation spreadsheet, we documented Height or Width in the sense of spread, Color, Critter status, Appearance, Fruit (if), and Scent (see example excerpt in Table 3). Critter status was added as a column once the first ones appeared as we did not foresee that. The tomato plant grew over four feet high. It actually grew to 5 feet but the top snapped during measuring on 12 July and regrew little. That plant brought quite a bit of fruit by 26 July, namely four tomatoes (see Figure 3). Unfortunately, then the roots couldn't go further, so the plant started deteriorating and eventually died. The "white fuzz" detected on the plant (see Table 3) is common to occur in the Long Beach climate, and it may also make it harder for the plant to get the necessary nutrients from sunlight due to reduced photo synthesis. Lettuce never quite caught on. It wilted for a while, it turned yellowish, which may be a sign of over-watering, and then it started regrowing for a bit, apparently liking to get its leaves wet, but it eventually deteriorated. The chives got vine lice after a few weeks and also turned yellowish, and they were never an intense green, which is why we got the light-emitting diode ultra-violet lights, but they didn't improve the situation too much. The carrot plants lasted better, until one of the two got eaten by a caterpillar. The second one in the other planter kept growing, and eventually when we pulled out the harvest, the carrots had grown around the corner because they had reached the bottom of the planter. The basil stayed happiest of all plants, and kept growing. Basil is generally doing better with shade than the other vegetables we chose, and it doesn't root as deep, which is why we think some herbs are better suited for future indoor experiments than vegetables. The most important lesson from the deterioration of most plants after a few weeks is to use a bigger planter next time.

Table 3. Example excerpt from observations on tomato plants in planter 1.

	19 June	21 June	28 June	5 July	12 July	26 July	31 July	9 August
Height	34″	37.5″	46″	4′7″	3′10″ (plant snapped)	4′1″	4′1″	4′1″
Color	green	green	green	green	green	green	brownish, light green yellowish color on leaves and branches	leaves and branches appear to be drier and shriveling
Critter status	none	none	none	white fuzzy stuff on leaves	white fuzz on more of the leaves	white fuzz on leaves	none	none
Appear -ance	healthy dark green color with yellow flowers, leaves are healthy	fruits are ginning to grow from the flowers, some tomatoes still have the blooms hanging from the end of the fruit, tiny and green	healthy dark green color; leaves are healthy; tomatoes are growing larger; 4 flowers	healthy dark green color; more flowers; tomatoes larger with stripes along side; plant leaning; some leaves curling	leaves are green, tomatoes are slowly turning red; 1 is still green and 3 are red, plant looks lush and fuller	leaves are a lighter green color, all 4 fruits are red	Fruits have been picked due to cracking, two got infected. Leaves are withering and beginning to wilt	Plant looks less healthy; leaves are shriveling; the pigment along the stem and branches is beginning to turn brown.
Fruit (if)	4	4	4	4	4	4	0	0

Figure 3. Garden with LED strip, ripe tomatoes, and research assistants.

5.3. Moisture, Temperature, and Humidity Data

While the project was set up with the objective to conserve water, we were not able to successfully collect the data to prove a contribution in this sense. As we didn't have a hose to connect the irrigation to, we implemented a bucket solution (see Figure 4). Filling up the bucket was a slightly arduous task due to its weight when full. Surprisingly, we found that the soil remained really moist with very little watering, especially near the middle of the planter. The data would say that no or only little watering took place during the past week, but the soil was more than humid. We are not sure whether the ventilation in the lab is super low or whether the fact that it was inside is already leading to that outcome. The building our lab is in has air conditioning and there are vents in our lab, but, due to having a north facing room, it may not require much help by the air conditioning to keep the temperature in the building-wide range.

Figure 4. Garden with LED strip and bucket irrigation system.

Due to the corroded water sensors that flooded the lab and threw off the water measuring, we have no insights on potential water savings with our system. In Figure 5, we show a little extract of the sensor readings from our database. It shows the sensor readings of temperature, humidity, and moisture over an interval of two hours. We chose the interval of two hours as opposed to a longer time period because, due to the air conditioning in the building, we had very little fluctuation in the moisture levels as well as the temperature and humidity levels. In order to gain more insight from this data, we need a comparative study that takes place outdoors, which is one of the steps in future work planned for Fall 2018.

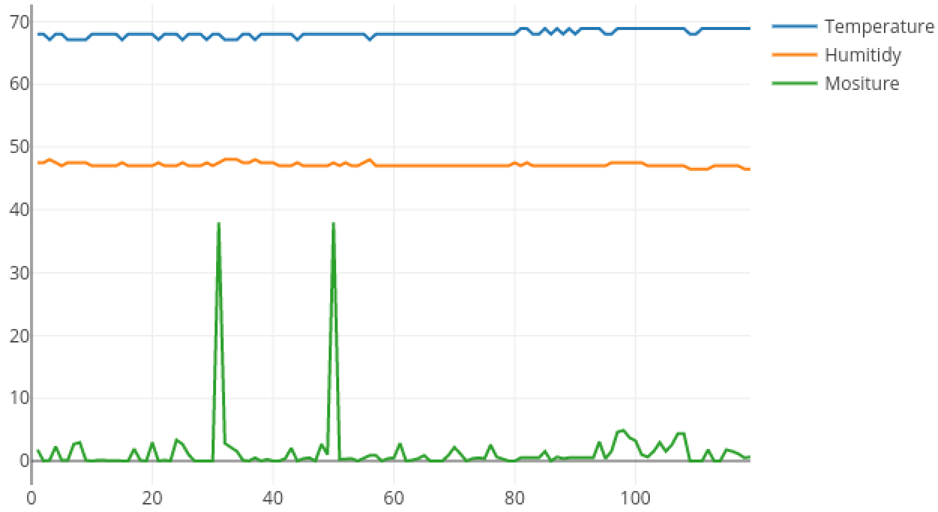

Figure 5. Sensor readings for one planter over a two-hour period (created using [44]).

5.4. Reflective Essays

The research assistants wrote reflective essays of about two pages each that were coded by the first and second author. The main insights are summarized in the following:

New Skills. Students embraced the opportunity for acquiring new skills, related to the project in terms of hardware design, embedded technology, and gardening skills, but also beyond, e.g., as expressed by one of them: "This project was also valuable in teaching me life skills including project management, time management, self management, and learning to adapt to unforeseen circumstances."

Freedom in Team Work. They appreciated the leeway they were given to self-organize: "Having a general timeline provided us direction for the summer research project while not restricting the approach to meeting the timeline specifications or intrude with our team's culture or methods of productivity." In addition, they "were able to divide the work between everyone and everyone tried to get their assigned tasks done on time. The dynamic also carried over from the spring semester so there was never a dull moment."

Safe-to-fail. The students learned that research may require several attempts at accomplishing something, as "in research things are expected to (sometimes) go wrong and it is part of the process of improving the system and finding what works best." Furthermore, the team was helping in recovering from setbacks: "When something happened with the garden, it was treated as more of an adventure than a tragedy. We were all able to laugh it off and then try to work and figure out what was going on with the system."

Pain Points. The restrictiveness of the wireless network, the tediousness of acquisition reimbursements, and the requested documentation were the identified pain points: "Honestly, I disliked documenting step by step procedure to replicate the project". However, they also figured out that "doing documentation as you progress through your project is much easier and less stressful than waiting for the end to get it done all at once."

5.5. Affordability and Continuity

The setup costs for the hardware and the gardening supplies summed up to $192 in total. We did not spend any money on software and relied exclusively on open source for developing our own software. We used low cost components all the way, which in part led to components failing early, specifically the moisture sensors. All costs for purchased hardware are listed with unit prices in Table 4. We have to run a series of tests to find out where it is more feasible in the long run to invest a few dollars more into a specific component, foremost the corroding humidity sensors, and what the most resilient hardware setup for the system is.

This project was continued after the summer as a second part of the senior design project that the students had already been working on during the Spring semester. The students finalized their software products supporting a more versatile use of the resilient smart garden implementation. Figure 6 shows the app interface for the Smart Resilient Garden. In addition, the project served as basis for developing a medium-scale grant proposal for the National Science Foundation (NSF) program Advanced in Informal STEM Learning (AISL).

Table 4. Overview of hardware and tool expenses.

Hardware	*Price*	*Qty*	*Total*	*Notes*
12 v 1 a Power Supply	\$8.66	1	\$8.66	To power the water pump
Terminal Strip (5 Pack)	\$11.61	1	\$11.61	To distribute power to water pumps from power supply
HiLetgo NodeMCU WiFi ESP8266	\$8.79	1	\$8.79	WiFi module
Tolako 5 v Relay Module	\$5.80	2	\$11.60	To turn on water pump
OctagonStar DHT11 (4 Pack)	\$7.66	1	\$7.66	Temperature and Humidity sensors
Docooler 12 v Water Pump	\$10.35	2	\$20.70	2 water pumps for the two planters
50 Ft Vinyl Tubing	\$15.99	1	\$15.99	To deliver the water to the garden.
Phantom YoYo High Sensitivity Water Sensor	\$6.98	2	\$13.96	Moisture sensors
Beard Board (3 Pack)	\$7.49	1	\$7.49	To wire up the WiFi module and Arduinos
Logic Level Converter (5 Pack)	\$6.99	1	\$6.99	For communication between Arduinos and WiFi module
USB Power Strip	\$14.99	1	\$14.99	2 standard plugs, 3 USB ports to power all electronics
6 Ft USB A to B	\$1.29	2	\$2.58	To power and program the two Arduino boards
Wire for Power Cord, 25 feet.	\$8.99	2	\$17.98	For powering
Wire Cable Connector Fork Spade	\$8.10	1	\$8.10	For connecting the wires (200 pieces, for several projects))
3 Ft Micro USB	\$1.99	1	\$1.99	To power and program WiFi Module/Garden Manager
Planters (24 in.)	\$7.47	2	\$14.94	24 inches long
Soil (1 cu. ft.)	\$3.97	1	\$3.97	For planters
Shovel	\$0.99	1	\$0.99	For planting
Cherry tomato	\$2.99	2	\$5.98	No Tax.
Basil	\$3.99	1	\$3.99	No Tax. Pack of 6 plants
Carrot	\$3.99	1	\$3.99	No Tax. Pack of 6 plants
Onion	\$3.99	1	\$3.99	No Tax. Pack of 6 plants
Lettuce	\$3.99	1	\$3.99	No Tax. Pack of 6 plants
Total before Tax			\$174.85	
Total After Tax			\$191.92	

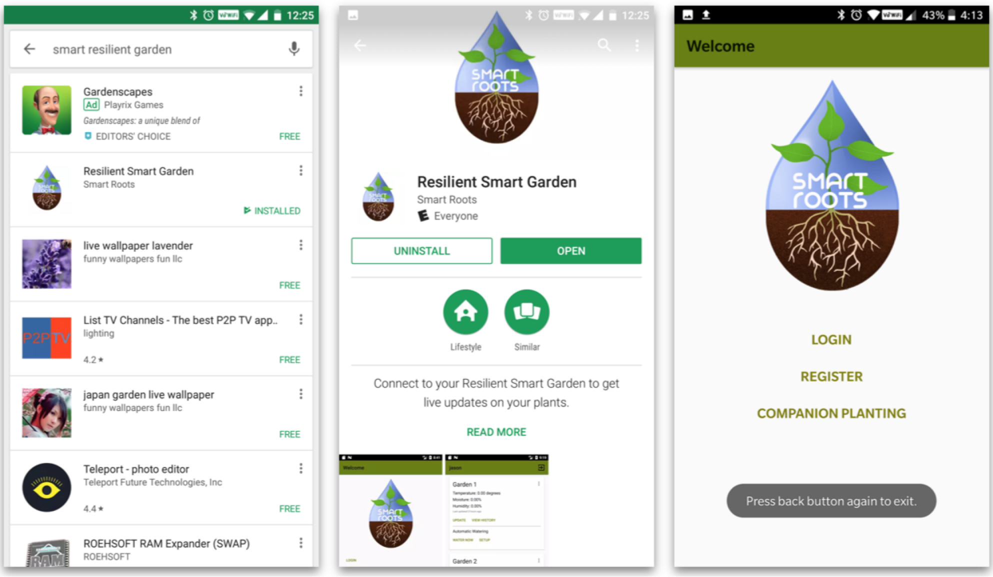

Figure 6. App interface for the Smart Resilient Garden.

6. Discussion

6.1. Computing within Limits

This project is intended to provide students with the opportunity to work with computing within limits, a rising topic in a growing research community [45]. The LIMITS research community integrates three topics: (1) current and near-future ecological, material, and energetic limits; (2) the ways new forms of computing may help support well-being as these limits become more determinative across the globe; and (3) the impact these limits are likely to have on the field of computing [46].

The Resilient Smart Garden project worked with limits in several dimensions:

- Natural limits: We only had two small planters due to little space and used a simple water bucket solution with a pump for the automated watering. Outdoors, this would be using grey water. In addition, we used means like companion planting to increase harvest.
- Economic limits: The constraints of a small budget made us stick to the bare essentials—we were able to keep the costs at $192, of which $25 were spent on garden ware that can mostly be reused, about $25 on seedlings and soil, and the rest on the computational and electronics hardware setup. We are confident that this can be further reduced in the future, as we had to start from scratch with no reusable old parts of any kind.
- Technical limits: The sensors and boards were very basic and the software had to work with the limited availability of computing power.

Bridging Disciplines. In many topic areas relevant to limits, we have to bridge disciplines. While we had only computer science students working on this project, the topic would have lent itself well to an interdisciplinary team.

Companion Planting. The method mentioned above that we used in the project is companion planting. It is a technique that helps get the highest possible yield out of a limited amount of land by using synergies between plants. For example, the first one works as a nitrogen fixer for the second one that, in turn, provides shade for the first one.

Non-computational Solution Alternatives. There is justified skepticism of approaches for decreasing consumption of water or other resources that simultaneously employ active means like sensors, actuators, software, artificial lighting, etc. These are often omitting much simpler, tried-and-true passive means like tenting/greenhouses, ollas, and increased-organic-matter soils. The research project at hand uses active means because it was a feasible way to expose computer science students to a hands-on agricultural topic.

LIMITS thinking emphasizes incentivizing long-term returns [46]. As such, the Resilient Smart Gardens project contributes to a set of educational blueprints that help a better understanding of how to grow food in a sustainable way for the future.

6.2. Benefits

6.2.1. Fun

The students had fun doing this project, so it was a research experience that keeps their motivation and interest up for further research. It was adventurous as the excerpts of the diary show, and they "made friends" with caterpillars, and had a high level of engagement. One student noted how easy it is to become a perceived expert in a domain, in that case particularly the gardening domain. Knowing the most out of a team of four, she had been declared the "expert" early on during the project. The unexpected "catastrophes" like the flooding of the lab floor due to the corroded sensor as well as the uninvited guests in form of various little pests on the plants certainly added to the entertainment factor of the research, and are lessons learned in terms of unforeseen side effects and risks.

6.2.2. Hands-on, Self-Guided Work

Students developed a strong connection to the project. Specifically, they developed a sense of ownership as they were building the entire project by themselves from scratch. They developed a sense of contribution to the team, and everyone's contribution is visible. Furthermore, a sense of knowledge, namely an in-depth knowledge and understanding the very foundation of electronics, hardware and software and the experience of putting them together. Their sense of solution developed further with contributing a small research effort in the direction of solving the California drought problems. Finally, a sense of control as do-it-yourself implies that it is possible to deviate from any plans and modify according to needs.

6.2.3. Educating in a Safe Space

In many educational settings, students unfortunately only get one shot. One try to get everything right, and, even if they get feedback, they often do not have the opportunity to work in that feedback and submit an improved version of their project. Secondly, our educational systems often allows for little freedom to let students "figure things out". However, exploring a domain by themselves (self-guided learning) increases their motivation in comparison to simply following a prescribed list of steps. Thirdly, we learn the most from failure. All three of those points taken together, the summer project gave the students the chance to explore, fail, explore more, run into a different problem, solve it, have another problem come around the corner, and revise their work several times. At the end of the summer, they submitted a decent project and self-reported to have learned a lot. While we do not have a formal evaluation of this safe space paradigm, we have found it beneficial in several projects and we are intending to add a component evaluating this aspect in future research.

6.2.4. Connection to Permaculture

The project provided a balance between disciplines and every team member, some with non-garden experience and some with less technological expertise, were able to significantly contribute. It was an opportunity for multidisciplinary work—the familiar computing domain and the unfamiliar application domain, which is something students will often encounter in their future work environments where software developers have to familiarize themselves with new application domains on a regular basis.

With regard to the permaculture principles cited in the background, Section 2.6, students were able to apply more than half of the principles directly: (1) observe and interact—tending to the garden; (3) obtain a yield—harvesting the tomatoes and carrots; (4) apply self-regulation and accept feedback—deal with the pests in a natural way; (6) produce no waste—all plants were transplanted into larger gardens or composted to fertilize same gardens; (8) integrate rather than segregate—in the composition of plant guilds per planter; (9) use small and slow solutions—prototyping and learning with a small garden; and (12) creatively use and respond to change—using recycling materials to build enclosures.

The other principles will be used in future extensions of the project, namely: (2) catch and store energy—with a solar panel; (5) use and value renewable resources and services—solar energy and grey water, and the remaining three ones are all to be applied in a larger garden setting planned to be carried out in Fall 2018 in the university gardens: (7) design from patterns to details; (10) use and value diversity; and (11) use edges and value the marginal.

6.2.5. Scalability

It is possible to add another micro controller anytime, and therefore we can add as many temperature/humidity sensors as we need. The embedded system of the Resilient Smart Garden was designed with scalability in mind. A single planter can have as many sensors as needed to increase the accuracy of the readings as long as the micro-controller has enough available pins. The sensor readings will be averaged to produce a value that will be sent to the server. The controllers and the nodeMCU communicate through I2C, meaning up to 128 controllers can theoretically be connected to a single garden. All extensions of hardware can easily be incorporated into the software by adding a few lines of code. The logic for the sensor readings and i2c communication will be scaled according to the amount of hardware that is integrated to the garden system. The amount of water pumps will depend on the amount of controllers implemented in the garden, as each planter is designated one water pump. The water pumps will scale along with the controllers but requires planning before implementing the power delivery system. The power supply will depend on the amount of water pumps that will be used and the amount of amps it will need. The terminal block that will distribute the power to the water pumps must also have enough rows for each water pump and the power supply. Once it has been planned out, the positive and negative wires from the water pump can easily be placed in a free row in the power terminal strip. Another set of power supply and terminal block may be added if there is an available power plug on the power strip in the case that further unplanned expansion is needed.

6.2.6. Flexibility and Variety

We are able to modify to certain needs, for example there are also other micro controllers that we can use for a same or similar setup. It doesn't have to be same brand of moisture sensor. We can use actual drip irrigation instead of crafting one out of vinyl tube.

We used one plant per companion plant group (figuring out "friends" and "enemies") and there are many other options for which plants can go into that size of planter. One task currently under work is developing a companion planting database that supports adequate choices for planting vegetables together in a confined space.

6.2.7. Wireless

Having wireless communication for flexible placement that is not tethered to Ethernet cable makes the system's deployment more versatile. A WiFi connection provides flexible placement of the garden system. Data collection of moisture, temperature, and humidity sensor readings from other micro-controller DIY projects are done locally through an Ethernet cable which restricts the placement of the garden system. The placement of the garden will have to consider the location of the router, which could result in a lengthy Ethernet cable that would need to be routed. An ethernet cable to connect the garden and the server is not an ideal situation when placed in an outdoor environment. Having a WiFi connection will eliminate the limitation of being tethered to a router via Ethernet cable. It may seem counterintuitive to have a WiFi connection on the garden system when it is tethered to a power plug, but there is more availability of power plugs in a typical household in comparison to routers. The garden system is powered through a power strip that provides enough USB plugs for the micro-controller and nodeMCU. The power strip needs to be plugged into the wall to deliver power to the garden system. Having a WiFi connection means having one less wire to consider when planning out the placement of the garden system. The quality of the connection will depend on the location of the router, but it can be easily extended with a WiFi range extender if needed.

6.3. Limitations

6.3.1. Indoor Setup and Power Supply

The lab we were using to perform the experiment came with a few limitations. We had a north facing room and therefore little light. We tried to mitigate this by installing LED UV lights, but we are not convinced of their actual efficiency. We think that they may actually have been counterfeit, as later on one student took the planters home and outside, where the plants went back to growing. Furthermore, the planters we chose fit the table designated for the project, but they turned out to be too small in the long run for the plants to grow effectively. Moisture level readings suggest that indoor environment has an influence on how frequent the garden is water. Moisture levels remained the same for a week without any watering. Plant symptoms suggest that the plants were over watered, even though water was rarely delivered.

Our system was powered from the wall, which can be restricting. In our current solution, we are limited to powering the system with a wall plug and an extension cord. This restricts us to deploying the system in an area that can be supplied by extension cord. However, in the next iteration of the system, we are planning to take it outdoors and use a solar energy source. Most of the DIY projects do not have a project enclosure. We provide documentation to build a simple project enclosure using common tools. In current work, we are developing a more weather resistant enclosure that will enable us to take the project outdoors.

6.3.2. Maintainability

For the longer term use, we had to recalibrate the sensors a few times. One of our water pumps also burned out as a result of the bucket being emptied, and the system wanting to reach its appropriate moisture level, but no water ever reached the garden, so the system never shut off the pump, allowing it run indefinitely in an empty bucket. We also had to refill the bucket multiple times. The Resilient Smart Garden will automatically provide enough water to keep the plants alive, but it will require maintenance for proper functionality.

The automatic watering system depends on the moisture sensor and it needs to be functioning correctly. The moisture sensors will eventually fail from corrosion/oxidation due to the moist environment, enhanced by the power that is being delivered to the moisture sensors. A failing moisture sensor gives the garden false readings, which can flood the garden. The life span of the moisture sensor can be extended by limiting the power duration, but the moisture sensors need to be replaced as they cannot be repaired. Some research and advice from peers with more expertise on sensors suggested that we look into alternating currents, which would mean having different voltages running along each prong of the sensors at different times, to prevent corrosion over time, and looking into gold-plated sensors.

The moisture sensors need to have accurate readings for the automatic watering system to function correctly. Each moisture sensor will have different maximum values due to the analog output. Each moisture sensor will need to be individually calibrated to ensure accurate readings. The calibration process involves putting the moisture sensor in moist soil and getting the maximum raw value that is output. The calibration process requires judgment from the user and it may be prone to error if not properly performed.

The water bucket must have water to ensure that the plants are receiving water and the water pumps will not burn out. The Resilient Smart Garden was intended for outdoor usage, but this research was conducted indoors. As a result, the water source for the garden system is a bucket that requires the user to check and make sure that there is water. There must be water in the bucket for water delivery system to function as intended. The plants will be put at risk if there is no water in the bucket. The water pump is also at risk since it will continue to run until the moisture levels are back to normal values. The water keeps the water pumps cool and will burn out without it.

6.4. Future Work

We did not have a comparative study set-up, which is why our insights are not as extensive as they could have been in a comparative setting. However, the exact numbers on how much potential water savings we could have had in a comparative setting are also strongly influenced by the particular environment of the room and building we were hosted in. The Resilient Smart Garden potentially helps fight the drought by providing knowledge and material to answer the call to action. On the foundation provided in this paper, we plan several strands of future work as follows.

6.4.1. Outdoors

The first step in future work is to repeat the experiment outdoors with the equipment in an enclosure as the current version does not have a project enclosure. Options we are currently exploring are to use a ready-made box, to 3D print one in the on-campus 3D printing lab, or to repurpose some other materials.

6.5. Innovation Challenge

The students also participated in a team in the campus-wide Innovation Challenge [47] to propose an easily replicable Resilient Smart Garden Education Kit with an online portal that educates the user beyond set-up tutorials on how to gain the best possible yield from a tiny to small-sized garden.

6.5.1. User Intention

We are planning an empirical analysis on factor affecting the user's behavioral intention to use DIY kit for smart gardening. For example, factors can be self-efficacy, usefulness, attitude towards usage, benefit, etc. One hypothesis could be that attitude will have a significant positive effect on the intention to use a DIY kit for smart gardening. Future studies will be testing these hypotheses.

6.5.2. Scalability

As mentioned throughout the report the Resilient Smart Garden can easily be scaled up to include multiple gardens by adding controllers for each garden. Another opportunity to scale up the project in the future lies in expanding the Resilient Smart Garden past the garden and into agriculture by adapting the system to work with different types of irrigation systems [48]. One of the objectives of this project was to facilitate raising a garden in areas dealing with droughts, like Southern California. As mentioned by the California Ag Water Stewardship Initiative [48], water quality is no longer the only concern when it comes to agriculture. With the growing population within California, water becomes a more limited resource, so the concern is to use sufficient water so that crops get the necessary amount while minimizing the amount of water used.

While the project at hand had constraints that make it hard to draw conclusions on the water savings, we are still interested in further investigating the potential for recharging groundwater and supporting non-crop ecosystems.

6.5.3. Greywater Solution

Our long-term vision is a Resilient Smart Garden Showcase that uses grey water, e.g., collected rainwater, to water the plants and thereby makes the system even more environmentally sustainable, given our setting in Southern California, which would include a more sophisticated collection system that includes the collection of morning dew [49]. Using renewable energy by connecting the system to solar panels is planned for the next iteration.

6.5.4. Education Kit

A future iteration of the DIY kit with evaluated user instructions could become an educational toolkit for use in schools as well as Information and Communication Technology for Development (ICTD) work for developing countries. A research proposal by principal investigators joining forces between several departments and colleges is currently under review. This proposal includes the aspects of an outdoors development that scales to the university garden growing beds, as depicted in Figure 7, and uses solar power and grey water. Within that setting, we are also planning to conduct a comparative study that evaluated the effectiveness of active means to lower resource consumption, by sensors and water pump, with passive means like increasing the soil quality with organic matter.

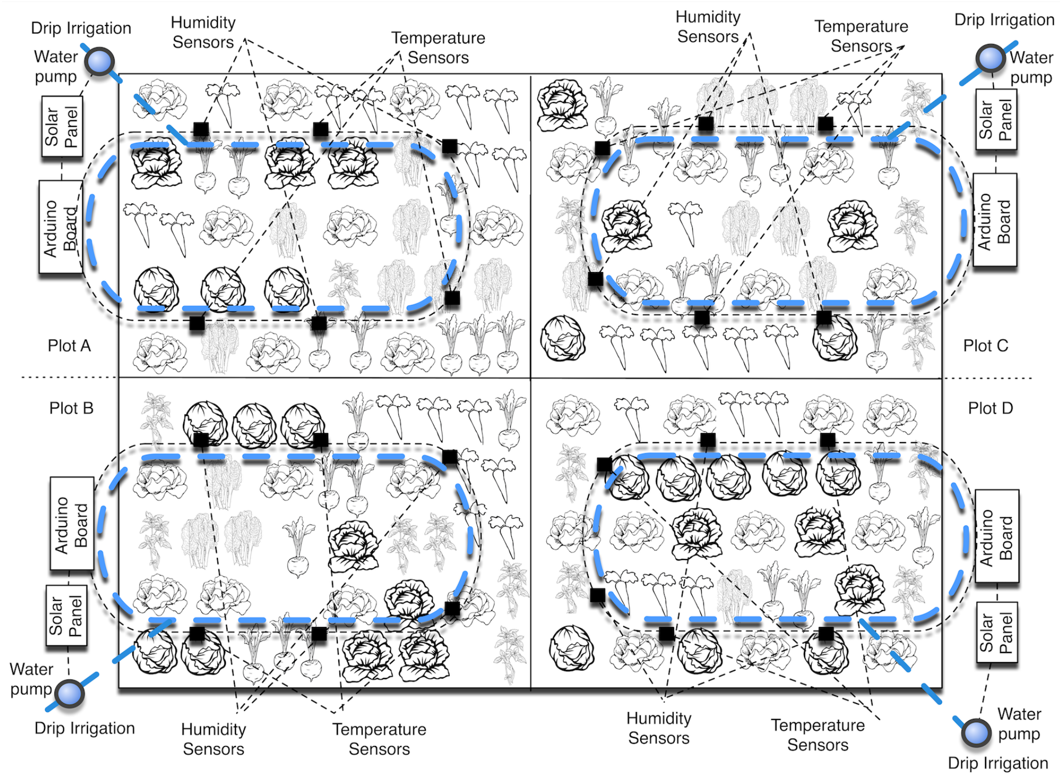

Figure 7. Sketch of the growing bed plan for the expanded outdoor version of the project.

7. Conclusions

With a rapidly changing climate, we notice a significant effect on the environment, most noticeable in the drought-prone state of California. Every year, California faces severe drought during the summer, sometimes resulting in a state of emergency. Conserving water is crucial, but it is difficult due to California's agricultural production. This results in a societal effort to become more sustainable, motivating individuals to take an interest in growing their own food. Despite the good intentions, few people have gardening experience and even fewer are educated in water conservation. Others have attempted to remedy this issue with automated systems; however, they do not account for scalability or ease of replication for the average consumer. By developing a smart resilient garden using basic IoT devices, we can promote a sustainable system that anyone can build and use with minimal difficulty. An open source system will allow the average user to integrate a smart garden into their homes and promote sustainability and collaboration in community gardens and open source development for future enhancements.

The **objective** of the Resilient Smart Garden is to minimize water usage while maintaining a sustainable environment through automation. The Resilient Smart Garden is built using commercial off-the-shelf parts, making it accessible to anyone. There are no strict build guidelines, providing flexible integration. Expansion requires little effort as the hardware is designed to easily scale.

To answer the **research question** on insights from and challenges for developing a small-scale resilient smart garden, we can summarize: students profit from a safe-to-fail action research environment and enjoy self-directed knowledge acquisition and team work. Challenges mainly arose from a restricted lab environment that imposes impractical constraints.

The **contribution** of this article is the report of action research for a prototypal implementation of a multidisciplinary project that supports community resilience. The results make us confident to develop this into an educational blueprint for projects that connect computer science to sustainability domains.

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