UNIVERSITY OF CALGARY

ENEL 300

ELECTRICAL AND COMPUTER ENGINEERING PROFESSIONAL SKILLS

Final Technical Report

Authors
Bogdan BACEA
Austin NGUYEN
Ziad SHAMMA
Bihan WANNI ARACHCHIGE

Course Instructors
Dr. Laleh BEHJAT
Ms. Sarah SHAH

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1 Introduction

Our product is named “The Green Thumb.” It is an automatic plant watering system meant for busy people who may not have the time to care for their indoor plants and gardens. Its main components include three AVR128DB28 microcontrollers, a resistive moisture sensor, and a water container with a peristaltic pump controlled by a DC motor. “The Green Thumb” ensures that the plant it is potted with is watered only when necessary, which is determined by the moisture sensor, embedded in the plant’s soil. The user may interact with the product by selecting a plant watering type from one of four pre-calibrated options. The product interacts with the user through status lights that display the relative soil moisture level, current plant watering type setting, as well as a “currently watering” indicator LED. There is also a speaker which plays a melody when the on-board water container is low on water, detected by a level sensor structure inside the water container. This level sensor structure is based on another resistive moisture sensor, with long copper leads attached to the sensor on one end, while the other ends of the leads are embedded in the water container. Finally, a photoresistor is used to detect if it is night. This sensor will override the input from the moisture sensor, disabling the device when darkness is detected, to avoid the device producing sleep-interrupting noise at night. By automating watering, needless water wastage is avoided, and the use of energy efficient components make “The Green Thumb” an environmentally friendly product which makes measurable impact towards United Nations Sustainable Development Goals. This product is envisioned to be a low-maintenance, sustainable tool for any busy gardener to implement in their home gardens.

We are making this product for numerous reasons, the primary one being making plant care easier for those who lead busy lives. “The Green Thumb” was designed to automate one of the most important aspects of plant care, so that busy workers of any stature may take care of their houseplants. It also serves to make the watering process easier, while freeing up the user’s time. Another reason for creating “The Green Thumb” is that it fills in a gap in the market between moisture sensors and plant water delivery mechanisms, on small scales. We discovered that while there are such schemes available for industrial greenhouses or even farms, for a simple houseplant in a ceramic pot, most similar devices involved constant drip watering or timers. While some current patents or widespread devices water houseplants based on soil moisture, that is often where the smart features of the product end (an intellectual property assessment is provided in Appendix A). With the existence of this product, there is finally an affordable and feasible solution for automated watering of indoor potted plants, with more quality-of-life improvements targeted towards busy people. Finally, we created this product to promote sustainability, especially water conservation. By optimizing the amount of water delivered to specific plant types, water wastage is minimized. On the scale of one device, this is a nearly negligible. However, with many multiples of this device, perhaps used in commercial or government applications such as office buildings or public parks, the impact of “The Green Thumb” on water security greatly increases. An outline that expands on additional planned sustainable aspects of the product is provided in Appendix B.

Originally, “The Green Thumb” was meant to use a solenoid with a hose to deliver water while being powered entirely by a solar panel. However, we realized that the solar panel would be slightly impractical and inconsistent as a power source for the sensor, AVR128DB28s, and the solenoid. After switching to a battery supply, we recouped the loss in sustainable impact by replacing the solenoid with the peristaltic pump and DC motor combination. This mechanism allows for more fine delivery of water (minimizing water wastage even more), while also consuming less power. Even without these aspects, “The Green Thumb” is still an extremely useful tool for indoor gardeners with very little time.

As part of the design process, we also planned out portions of documents and samples that could be used if the product were to be marketed and sold, as if to establish our own start-up company. A user manual for “The Green Thumb” is provided in Appendix C. As part of planning for future marketing opportunities, a sample brochure and a sample sustainability promotion flyer are provided in Appendix D and Appendix E, respectively.

Figure 1: Our product, “The Green Thumb”

2 Persona and Product

Although the main problem that "The Green Thumb" aims to solve is to automate watering for busy people, it can also be useful in the lives of other users who are not as busy. One such example is in one of the user personas considered in the development of this product, the elderly. Sometimes, certain elderly individuals may have impairments that make watering their plants consistently and effectively a difficult task. "The Green Thumb" would be able to automate this process, easing the life of the user.

2.1 Persona

Our user persona is Hector Slacimon, an elderly individual who immigrated to Canada from Mexico. Hector used to always love the idea of taking care of plants in his younger years, but never had the time to take care of them and kept forgetting. As he got older, he gained more free time, but his memory worsened further, and he constantly forgot to water his plants. Recently, he has fallen ill, and consequently spends lots of time in and out of the hospital. He feels embarrassed to ask others to help water his plants while he is being taken care of, not to mention the language barrier present due to English being his second language. He dreams of growing a collection of herbs that he can use when cooking, which would remind him of his childhood, when his parents would grow green onions, garlic, dill, and parsley, using those herbs in home cooked meals.

Unfortunately for Hector, his health conditions result in his plants withering and eventually dying while he is stuck in the hospital. The sadness at seeing the waste from every failed attempt piles up on Hector's mind, which is only exacerbated by the annoyance of having to repurchase and replant the entire garden, an already difficult task due to other age-related complications.

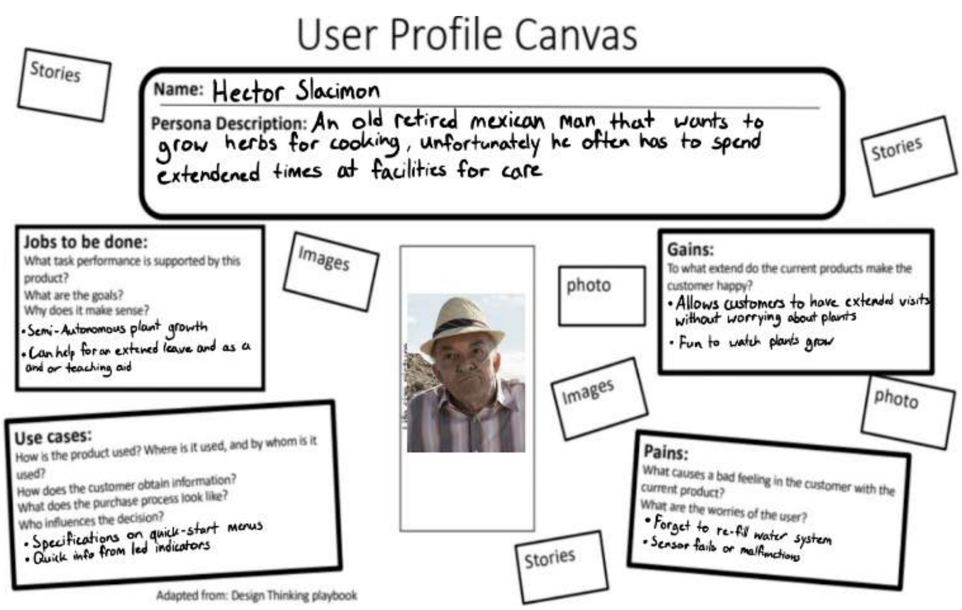


Figure 2: User Profile Canvas

Figure 3: Empathy Map

2.2 Product

Below is a story that comprises various user stories we created in the development of this product. They focus on how “The Green Thumb” assists Hector with his indoor garden.

One day, Hector hears from a friend about “The Green Thumb”, an autonomous gardening tool that incorporates a moisture sensor and a motor to automatically water plants. He orders the product online in hopes of rekindling his love for gardening.

Hector sets up the device in the soil his herbs are planted in, fills the container with water, and sets the device to the ideal moisture level for his different plants. He uses the guide that comes with the device to determine this, as the manual explains which type of plants use which watering mode.

Hector is delighted that he can once again cook his meals with freshly homegrown herbs. He no longer worries about the health of his plants when he is away, or when he has an extended stay at the hospital. “The Green Thumb” ensures that his plants will thrive, and it grants him the ability to enjoy his passion even when he can’t physically be present to tend to his plants. He feels a sense of newfound relief knowing that the product takes care of his herbs, and a sense of accomplishment at the success that is his indoor garden.

Hector has recently been able to expand his indoor garden to include new herbs and vegetables, due to the convenience provided by “The Green Thumb.” This has allowed him to experiment with new dishes, which he can recreate again and again because of the reliable watering system of the product. After having used the product for many months, Hector even introduces “The Green Thumb” to some doctors and nurses at the hospital. They have also expressed desire in caring for plants, yet struggled with not having the time to manage an indoor garden. After many more months of word-of-mouth marketing of “The Green Thumb” within the hospital, the kitchens and cafés in the hospital start to include freshly grown vegetables in their menu items, using “The Green Thumb” to grow them.

2.2.1 Value Proposition

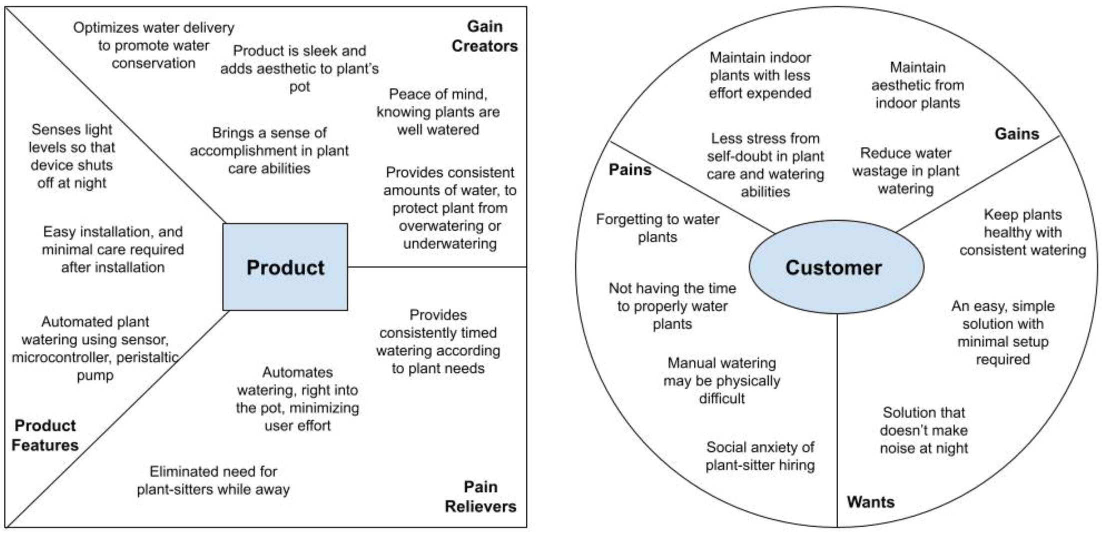


Figure 4: Value Proposition Canvas for "The Green Thumb"

Our product targets individuals who forget to water their indoor plants, are too busy to water their indoor plants, or cannot water their indoor plants for other reasons. Their pains may include:

- Not having enough time for proper plant care
- Physical disability or a handicap making plant care difficult
- Not being at home for an extended period
- Forgetfulness when it comes to watering plants
- Having too many plants to monitor carefully

To create a unique selling proposition for our users, we wanted to implement a system that was semi-autonomous, while also reducing the hassle for our end users as much as possible. To accomplish this task, our product features:

- An automated plant watering system using a sensor and pump
- A night mode for fewer interruptions to sleep

- Easy and painless installation
- Easy and effortless maintenance
- An audio alert to notify users of low water level in the water container

The gains created for the users by our product include:

- Peace of mind, knowing plants are cared for
- Promotion of water conservation from water delivery optimization
- A sense of accomplishment from taking care of indoor plants

Additional consumer pains, product features, and product gain creators, as well as consumer wants, consumer gains, and product pain relievers are summarized in Figure 3.

2.2.2 Impact and Feasibility

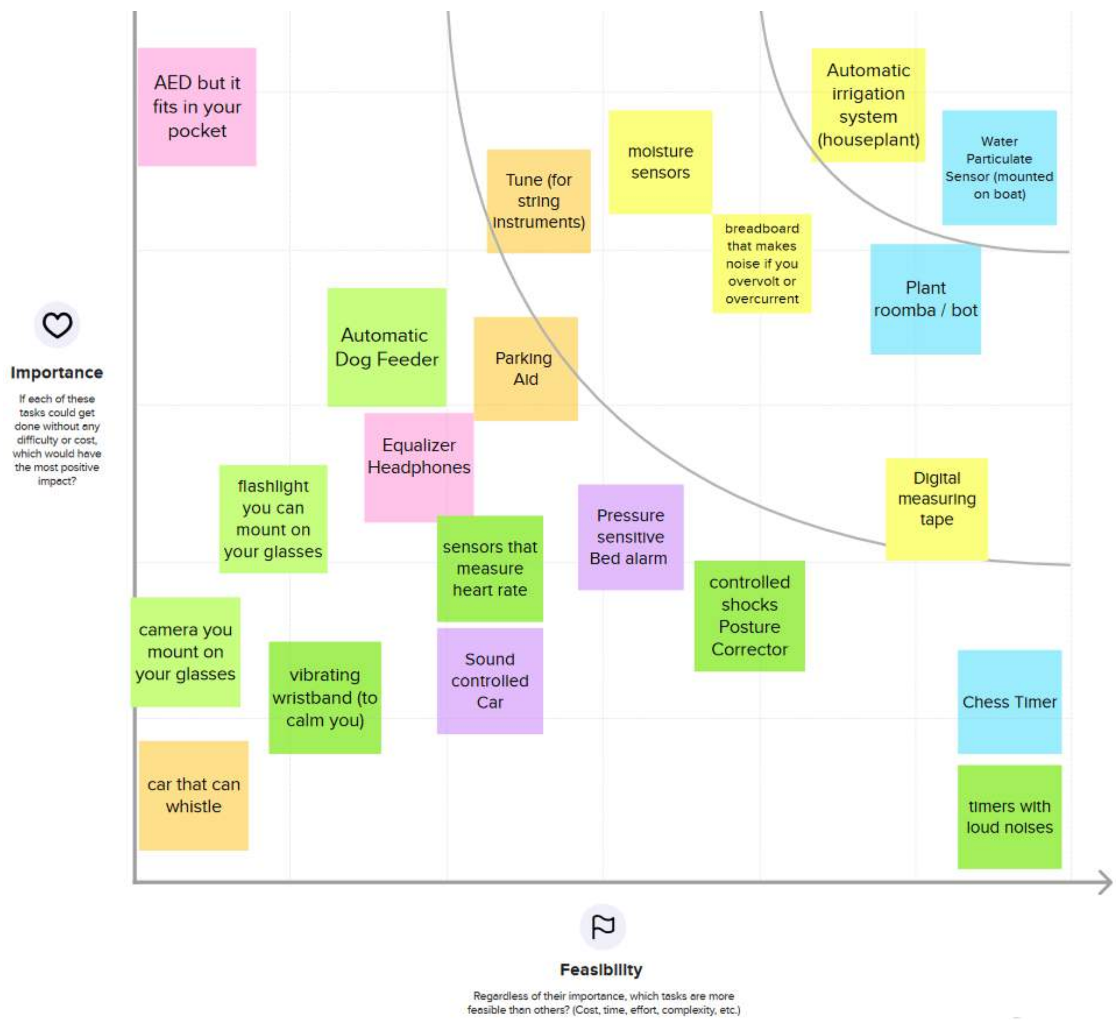


Figure 5: Importance versus Feasibility Chart for our ideas

When we were first brainstorming an innovative and sustainable product, most of the initial concepts we imagined were deemed low on the importance and feasibility scale for the final product. These initial ideas were quite unconventional and eccentric, such as:

- a whistle-controlled car
- electric shock based posture corrector
- pressure-sensitive bed alarm

While these concepts were not deemed important or feasible for a final project, they served as a starting point for generating more ideas.

After further deliberation, we became inspired from the concepts of automation and sensor-based control systems that stemmed from the whistle-controlled car and pressure-based bed alarm. This led to us brainstorming other products incorporating these concepts, such as an automatic dog feeder, and a parking aid.

We ultimately settled on two product concepts that combined sensor-based technologies with automation. The first idea was an automatic irrigation system that would eventually evolve into "The Green Thumb," while the second was a water particulate sensor mounted on a small boat. From our unorthodox initial ideas, we managed to develop a product we believe is significantly sustainable and innovative.

2.3 Other Users

Although our primary user persona during development of "The Green Thumb" was Hector Slacimon, one other main target user-base is busy people. We have included a sample user interview and sample feedback form in Appendix F and Appendix G, respectively, of one such busy person, to demonstrate our thought for this other demographic of our expected users.

3 Technical Description and Difficulty

"The Green Thumb" utilizes many types of circuits and devices for full functionality. These include:

- DC motor with peristaltic pump
- Moisture sensor with noise filter
- AVR128DB28 microcontrollers
- Photoresistor-based daylight detector
- Boost convertor and relay
- Speaker with low-pass filter and signal amplifier
- 7-segment display and mode select dial
- Indicator LEDs
- Battery power supplies and buck convertor
- Protective casing
- Water container level sensor (utilizing a secondary resistive moisture sensor)

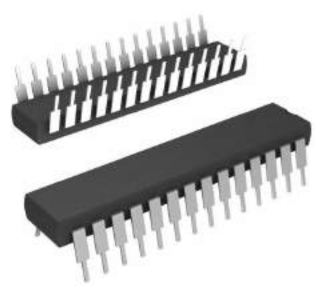
More details about each component are provided below:

DC motor with peristaltic pump: To implement the watering feature of "The Green Thumb," a reliable pump was required. After conducting research, a DC motor-based peristaltic pump was chosen. It was recommended by a team member due to its small size, portability, power efficiency, self-priming capability, and its ease of maintenenace. The implementation of the pump was relatively simple since the integrated DC motor did not require a complex control scheme (such as pulse width modulation). The greatest challenge was in supplying power to the motor, as it drew 0.8 A at 12 V when at peak draw. The experience of maneuvering through this challenge granted us valuable insights into electrical circuit components we had not discussed in course content previously, as well as insight into optimizing the power consumption of our entire product. This device is managed by the primary microcontroller.

Course content used: ENGG 201, ENGG 225, ENCM 369

Moisture sensor with noise filter: To implement the moisture sensing feature of "The Green Thumb," we selected a second resistive moisture sensor, chosen for its very low monetary cost compared to other sensors. It was incorporated into the design by being the main input to the primary microcontroller, where it would read the moisture level of the soil it was in and send its result to an analog to digital convertor on the AVRs, which we learned of in ENCM 369. One challenge with the moisture sensor was calibrating it and determining accurate thresholds for the device to trigger the pump. We addressed this by conducting tests on soil samples of varying moisture, following testing stories drafted in ENEL 300, logs of which are included in Appendix H. The output of the sensor is routed through a low-pass filter (discussed in ENEL 343), reducing the noise in the signal and increasing the accuracy and efectiveness of the sensor. Finally, we implemented a system where the sensor would only turn on for seconds at a time during operation, instead of always being on, to save power. The implementation of the moisture sensor enabled "The Green Thumb" to automate plant watering based on a sensor input.

Course content used: ENEL 343, ENCM 369



AVR128DB28 microcontrollers: The microcontrollers used in this product are the AVR128DB28s, which we studied extensively in ENCM 369. The greatest difficulty we overcame with these microcontrollers was learning how to extract the necessary information from the extremely long datasheet. Our task was made simpler by our repurposing of circuits from ENCM 369 hands-on exercises, such as a sinusoidal DAC output, timer based functionalities, and potentiometer controlled logic circuits. We also combined circuits from hands-on exercises in ENEL 343 and ENEL 361 with the microcontrollers, such as various analog filters and a photoresistor-based daylight detector, discussed below. Each of the three microcontrollers manage different aspects of the product. The primary one manages the moisture sensor embedded in the soil, the indicator LEDs, the boost convertor, relay and motor with peristaltic pump. The secondary microcontroller manages the 7-segment display, the plants watering mode selector, and communicates with the primary microcontroller to inform it of the selected plant watering mode. The tertiary microcontroller manages the moisture sensor connected to the on-board water container, and the speaker alert system as well. The primary and the tertiary microcontrollers are also connected to the photoresistor-based daylight sensor, as they are planned to be disabled at night.

Course content used: ENCM 369

Photoresistor-based daylight detector: To implement a feature that would disable the device at night, we opted for a photoresistor-based daylight detector, drawn from our work with photoresistors in ENEL 361. It was a controlling input to the primary and tertiary microcontrollers, and its output was measured by an analog comparator on each, which we studied in ENCM 369. Physically, it was simple to implement, but there was difficulty in its software implementation, specifically in determining where in the overall code the logic of the daylight detector would be located.

Course content used: ENEL 343, ENEL 361, ENCM 369

Boost convertor and relay: In the implementation of the DC motor, a way to provide it with 12 volts and a method of triggering its high load was required. One team member suggested a boost convertor and a relay that they had in an old electronics kit. Although we did not learn about these components in previous engineering courses, we quickly learned their functions after some experimentation by that same team member. When the primary microcontroller is to activate the motor, a 5 volt signal is sent to the relay, which connects the boost convertor's 12 volt output with the motor. The greatest challenge with this configuration is that it consumes a comparatively large amount of power compared to other device elements, so we had to carefully consider our device power domains throughout development.

Course content used: None, we learned this on our own, independently, beyond second-year ECE student knowledge

Speaker with low-pass filter and signal amplifier: To implement the audible cue to the user of when the water container had a low amount of water in it, we adapted a circuit from ENEL 343 involving a speaker, and low-pass filter and signal amplifier, and combined it with the functionality of a digital-to-analog convertor on the tertiary microcontroller, which we learned of in ENCM 369. The DAC would output sinusoidal waves into a low-pass filter designed to smooth the input signal, as well as eliminate high frequency noise. A non-inverting amplifier build with an op-amp was used to amplify the loudness of the sound outputted by the speaker. The trickiest part of this implementation was in the specific signal that we chose for the DAC to output: a complex sea shanty-esque melody, rather than a beeping tone. Using knowledge of signal sampling and its relation to music from ENEL 327, we were able to successfully implement the multi-note tune.

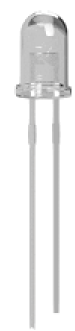
Course content used: ENEL 327, ENEL 343, ENCM 369

7-segment display and mode select dial: To implement a display to the user to present their plant watering mode choice, a 7-segment display was utilized. After researching the specific model of our common cathode 7-segment display, we relied on knowledge of LEDs we gained in ENEL 361 to properly connect the component to the rest of the device without burning out any segments. Additionally, a potentiometer dial was used to select the plant watering mode, a circuit we adapted from ENCM 369. The dial would be used to select a plant watering mode, which is sent to the secondary microcontroller, which adjusts the output of the 7-segment display. Overall, the difficultty of implementation of the 7-segment display was significantly less than we initially believed, as it was only somewhat more complicated than a regular LED.

Course content used: ENEL 343, ENEL 361, ENCM 369

Indicator LEDs: To implement indicators on the device to inform the user of soil moisture level, LEDs were used. Using LED protection schemes discussed in ENEL 343 and ENEL 361, we implemented three LED indicators: a red one indicating insufficient soil moisture, a green one indicating sufficient soil moisture, and a blue one which would blink during the water process. These LEDS were controlled by the primary microcontroller.

Course content used: ENEL 343, ENEL 361, ENCM 369



Battery power supplies and buck convertor: To power "The Green Thumb," we required a reliable yet compact power source. After consulting with experts, we agreed upon a 6 volt battery back combined with a buck convertor regulated to output 5 volts, as the microcontrollers and the design of many subcircuits depended on a 5 volt source. We also decided on implementing a dedicated 9 volt battery for the boost convertor and the DC motor to use, as stepping up 9 volts to 12 volts was more efficient than stepping up 6 volts to 12 volts with the boost convertor. This would also avoid the problem of potentially not having enough power for every single component when the motor was activated, especially after a long period of use, when the 6 volt battery pack was more discharged. Ensuring that the power sources would provide enough power and current to properly operate the device was our primary concern throughout the entirety of "The Green Thumb" development, which we achieved with these power sources.

Course content used: None, we learned this on our own, independently, beyond second-year ECE student knowledge

Protective casing: To protect the internal circuitry of "The Green Thumb," we designed a 3D printed case. We used PLA material to manufacture this case, due to its ease of use, lower 3D printing energy requirement, and lower amounts of byproduct waste compared to other materials used in plastic casing production. The greatest challenge with the case was that for every evolution of the product, we required an update to the case's model, so it was important to make sure we had a design "set in stone" before we submitted the print files to the University's print queue management portal.

Course content used: ENGG 200

Water container level sensor (utilizing a secondary resistive moisture sensor): To implement the water container level sensor, we used a moisture sensor attached to long copper leads. The copper leads extend partially into the container, so that as the water level falls, the copper leads will have less contact with the water, which changes the resistance perceived by the sensor. This will cause the moisture sensor to eventually output a low enough voltage to trigger the analog-to-digital convertor of the tertiary microcontroller it is attached to. This event would also activate the speaker to play a tune to alert the user of the low water level. The greatest difficulty with this feature was making its components pleasing to a potential user. In its first iteration, the water container level sensor appeared as dangling wires floating in the water, which was reported to 'cause unease' when presented to a potential user. Our final solution was to make these leads detachable with clips, for the user's convenience in refilling the container.

Course content used: None, we created this on our own, independently, beyond second-year ECE student implementation skill

The implementation of the components of "The Green Thumb" demonstrate knowledge that is both on par and exceeds that of second-year Electrical and Computer Engineering students. We used concepts from ENGG 200, ENGG 201, ENGG 225, ENEL 327, ENEL 343, ENEL 361, and ENCM 369 to implement the DC motor with peristaltic pump, the moisture sensor with noise filter, the AVR128DB28 microcontrollers, the photoresistor-based daylight detector, the speaker with low-pass filter and signal amplifier, the 7-segment display and mode select dial, the indicator LEDs, and the protective casing. Independent of any second-year ECE knowledge, we learned how to implement the boost convertor, relay, battery power supplies, and buck convertor on our own. We also developed our own water container level sensor using a spare resistive moisture sensor and spare copper leads, which was an unfamiliar area that we navigated together. The process of learning and designing these extra components was challenging and technically difficult, but our team pushed through each obstacle in our way, managing to make our product a technically difficult implementation for second-year ECE students.

A full schematic of the internals of the product is provided in Appendix I. A listing of the product's source code is provided in Appendix J.

4 Teamwork and Agile Project Management

We developed this product using agile project management, utilizing a scrum framework and carrying out development in four sprints. We used this structure to manage division of labour and communicate effectively about conflict and progress.

Our team made use of multiple different scrum ceremonies as part of the scrum framework. Each member participated in daily stand-ups, in which we discussed what each member had done the previous day, what each planned to do that day, and what each was currently having issues with. We also made use of retrospectives at the end of each sprint to reflect on the strengths and weakness of our team in the previous sprint, while also examining our product opportunities and threats. We also held sprint planning meetings to take advantage of those strengths and opportunities, and mitigate those weaknesses and threats as much as possible. These ceremonies also encouraged communication and minimized team conflict, as well as allowing us to bond more in the course of development.

For each sprint, our team chose multiple items from our product backlog to implement onto our product. The sprints allowed us to break down this project into smaller manageable pieces, and also allowed us to iterate our design, pivoting on certain choices with relative ease. By focusing on specific tasks within the sprint period, we were kept on track, and always moving towards the final product. The use of a burn down chart in each sprint (following Sprint 1) also helped to motivate us to complete our required components. The burn down charts created in sprints 2-4 are included in Appendix K. The sprints allowed us to organize product goals, and be motivated and productive in bringing the final product into fruition. Without sprints, our product would have been stale, and it would most likely have incorporated shaky solutions for any problems that cropped up in development.

A typical sprint planning session for our team had two parts: a portion where we selected tasks from our product backlog, and a portion where we conducted task division for the next sprint. In the first half of these sessions, we discussed which tasks we wanted to implement in the next sprint, taken from a list of potential tasks we had made earlier. We specifically considered how feasible each task would be in the given length of time that was the next sprint, as well as how easily we could integrate those new features with pre-existing ones from previous sprints. In the second half of our sprint planning sessions, our team conducted divisions of labour, assigning to different members the tasks we selected. Typically, we would let group members choose which tasks to take on. We conducted this task division to minimize conflict and to make sure each member was absolutely clear on what exactly they were responsible for at the end of each sprint. This task division kept us accountable to each other, and also to our product manager. Without this task division, our product would be much more rushed, and much less technically innovative.

Our retrospectives allowed us to critically reflect on the sprints we finish. Our team carried out our retrospectives with a slight variation on the standard SWOT analysis, opting for a different order of discussion. We started with the strengths we observed in our team, so that we could resolve to continue taking advantage of those strengths in the next sprint. Next, we analyzed the opportunities presented to us, both during the last sprint, and upcoming in the next sprint. From this, we pursued those observed opportunities as best we could. Following this opportunity discussion, our team delved into our weaknesses. This is the main part of the meeting where our team learned how to manage conflict, as we collectively decided to conduct this part of our retrospective with a constructive attitude, to counter the common tendency to approach such a topic with hostility and blame. We each committed to learning how to give constructive feedback through the sandwich method (sandwich suggestions between compliments) and using 'I observed' statements over 'you did' statements. In general, our weakness analysis usually ended up being more representative of the team through these strategies, so that we could more easily mitigate their effects in the next sprint. Finally, we ended our retrospectives with a discussion of threats to our product. Oftentimes, this conversation bled into discussions about how those threats could be minimized or even eliminated, with just as much brainstorming going into this aspect of the retrospective as into sprint planning meetings! Not only did our retrospectives assist us in improving our product, but they also improved our teamwork and conflict management skills.

The most important teamwork practice our team utilized was communication. Communication kept us working towards the same final product, communication allowed each of us to be aware of what the others were working on, and communication was what bonded our team the most. Our team communicated mostly in-person and over Discord. We tried to use Trello at first, but found that it was not a helpful tool for us, so we decided against its further use in Sprint 2. To share files, our team used Google Drive and Discord. Our team also practised active listening in our communications, and we constantly gave each other feedback on ideas, code, and potential designs. Without effective communication, our product would be much less functional, as it would be so much more difficult to get each part of it to work with other parts.

Figure 6: LC 8-A, "The Green Thumb" development team, with "The Green Thumb"

5 Future Work

"The Green Thumb" has many opportunities for future work. Some of these opportunities are listed below, in increasing order of complexity:

- Addition of other sensors: Currently, the product only senses the moisture of the soil, but other sensors such as thermistors or humidity sensors could be used to further monitor plant health
- Customizable plant watering modes: "The Green Thumb" currently offers 4 pre-calibrated options, but in the future it could be possible for the user to set their own mode for their specific plant
- Design for outdoor applications: We designed this product for indoor potted plant use only, so some modifications to the product's components to help them withstand the rough conditions would be required
- Power supplying solar panel: In order to become an even more sustainable product, "The Green Thumb" could include a solar panel in a future iteration, once the issues of expense, inconsistency, and impracticality are solved
- Data analytics capability: "The Green Thumb" could have functionality in the future to store data from the sensors, and output that data to a spreadsheet or display, to give insights to the user
- Integration with Internet of Things: In the future, "The Green Thumb" could connect with systems like Google Home, following voice commands and uploading collected data to the cloud

6 References

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A Intellectual Property Assessment

A.1 Similar Patents

When looking for patents with similar concepts to our product, quite a few patents came up. However, many patents seemed to focus on the watering and monitoring of large industrial-scale farms. Of the patents that did have a similar concept to ours, most of them seemed to base watering off an integrated timer or constantly drip-feeding the plant small amounts of water. These systems, while similar to our product, have an easier technological implementation but are arguably less flexible. There were some that had a similar concept, but were implemented in different ways, and did not have as many inputs involved.

One specific patent with a similar system but a different implementation that we found was patent US8408229B2 [1] created by Leonard Goldberg, James P. Romano, and John J. Feketa. It includes a microcontroller based watering-system based on time intervals integrated into a houseplant pot. This patent expires in 2027.

Adding keyword changes that were recommended such as a “moisture sensor”, “automated”, and “household” did help narrow the scope of the search results but still resulted in search results that were mainly targeted towards miniature greenhouses with microenvironments, which our product is not trying to create.

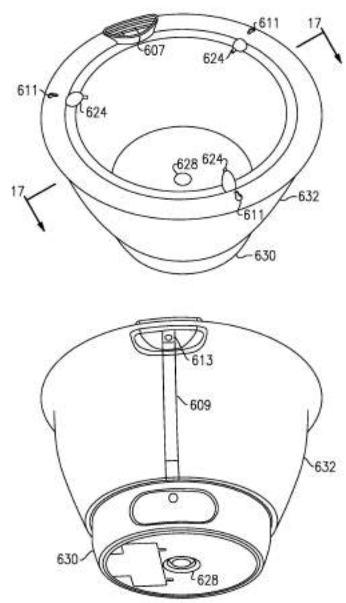


FIG.15

FIG.16

Figure 7: Art of patent US8408229B2

A.2 Similar Trademarks

Searching for the name of our product, “The Green Thumb,” on the WIPO Global Brand Database only resulted in one match for a South Korean Company that had its trademark expire in the 2000s.

B Sustainability Plan

B.1 Contributions to United Nations Sustainable Development Goals

Our product contributes to the following United Nations Sustainable Development Goals (UN SDGs):

SDG 2: Zero Hunger

This product may provide an alternative to manual crop irrigation for small-scale farms. Through the promotion of water efficiency, food security may improve in areas where water is scarce. It also encourages sustainable agriculture practices, which increases crop yields with less damage done to soil.

SDG 4: Quality Education

The implementation of this product in classroom gardens or similar projects would provide students with hands-on experience with sustainable practices. Students would come to appreciate water conservation and how technology may be used to supplement these sustainable practices.

SDG 6: Clean Water and Sanitation

By reducing unnecessary water waste, this product reduces pressure on Earth's remaining water sources, allowing for greater accessibility to clean water from those sources. In areas where the same water is used for drinking and non-drinking purposes, this product reduces the waste of sanitized water used for gardening.

SDG 10: Reduced Inequalities

By improving food security and clean water access, this product will reduce inequalities between developing and developed regions in terms of these resources. As these inequalities reduce, developing countries may start to prioritize reducing other inequalities.

SDG 11: Sustainable Cities and Communities

This product reduces water demand in cities by minimizing water waste, in numerous possible implementations between small scale gardens and community-wide irrigation systems for urban green spaces. This will lead to more sustainable cities and communities, especially in areas where water demand is high.

SDG 12: Responsible Consumption and Production

This product reduces unnecessary water waste in plant watering, leading to more responsible consumption of water resources by consumers. This responsible consumption also reduces the strain on water treatment plants in urban areas. Additionally, this leads to more water preserved for responsible production as well.

SDG 13: Climate Action

By reducing strain on scarce water sources, this product contributes to reducing the risk of droughts, which are a direct effect of climate change. Additionally, reduced water wastage puts less pressure on bodies of water which trap heat, keeping the planet cooler.

SDG 14: Life Below Water

This product strongly encourages water conservation, which reduces stress on water sources. With this reduced stress, less stress is placed on oceanic ecosystems and freshwater ecosystems, protecting the life within those ecosystems.

B.2 Implementable Sustainable Design Practices

Our product will employ the following sustainable design practices:

Aesthetic Lifetime: This product is planned to retain its aesthetic value throughout its lifetime. This will remind the user of the reason they obtained this product in the first place, increasing their emotional attachment to the product, increasing its longevity.

We aim to achieve a similar effect as products presented in Jasper Morrison's and Naoto Fukasawa's exhibition of "Super Normal," (partially pictured left) which featured products of discrete design which have become icons of their use [2]. The sleek design and easy-to-use functionality attempts to make this product a "Super Normal" part of the user's plant care routine. If the product reaches this "Super Normal" status in a user's home, the likelihood that a user disposes of the product will be reduced to almost 0%.

Design for Disassembly: This product is planned to be easy to disassemble, and its materials easily separable. This allows the product's materials to be more reusable, and specific components easier to replace, rather than replacing the entire product.

The scale of the ease of disassembly will be similar to products developed by Fairphone. No part of the Fairphone is glued together, so that it is relatively simple for a user to remove and replace certain components. By employing design practices used in the Fairphone, our product aims to achieve a 10/10 from iFixit's repairable design score, just as the Fairphone 4 (pictured right) did [3].

Up-Cycling: This product is planned to utilize up-cycled material for some of its components, specifically plastic, from products which may be lower value, such as plastic water bottles. This will minimize resource usage.

While it may be difficult for developers and designers to acquire waste streams to up-cycle from, we plan to make use of services provided by THE UPCYCL platform to connect us to potential waste streams [4]. Pictured on the right is the part of THE UPCYCL platform where companies may connect with waste streams of specific materials. Our product would make the most use out of packaging material waste streams, such as plastics, papers, and cardboards.

Ethical Supply Chain: This product is planned to have an ethical supply chain for each component comprising it. This will lead to users feeling proud of their purchase, and its ethical supply chain, so that they are more likely to form an emotional attachment to it, increasing the product's longevity.

Two specific values that our supply chain will include are sourcing materials from conflict-free areas and allowing labourers to form unions. Many existing sustainable companies (e.g. Fairphone) already conduct research and audits of suppliers for these specific points [5], and more. We plan on working with labour auditors and potentially even reaching out to suppliers directly, to ensure that the supply chain is indeed ethical. This could contribute to our goal of our product acheiveing the 'Fair Trade Certified' label (label pictured left), just as the Fairphone 4 has.

Environmentally Friendly Materials: This product is planned to use environmentally friendly materials in its composition. This usage of these materials will contribute to pollution minimization efforts and resource responsibility efforts.

One such material that this product will use is plastics. One such way of making this traditionally unsustainable material more environmentally friendly is to incorporate plant material and recycled plastics in its creation, similar to the PlantBottle initiative (pictured right) from Coca-Cola [6]. The usage of a partial plant material plastic as the casing of our product would also weave a story of sorts for our users, as our product serves to water plants itself!

Technical Durability: This product is planned to have a material lifetime that lines up with the product's lifetime. This will minimize overall resource wastage associated with the production of the product, as well as ensuring that less resources are used per unit overall.

Specific calculations and numbers will be determined by using protocols from International Organization for Standardization, such as ISO/TR 21960:2020(en) [7], which defines properties and specifications of plastics.

Production on Demand: This product is planned to only be produced on demand, or only when a user purchases a unit. This will minimize overall resource wastage associated with the manufacturing of this product.

In the days before the product's availability on the market, we plan on using a service such as Kickstarter to facilitate production on demand [8], as well as collect an estimate for the demand of our product.

Labelling: This product is planned to have appropriate labelling denoting the recyclability of its components and the operation of the device. This will increase the likelihood that its components are properly disposed of, and that users do not immediately toss out the device if they cannot figure it out.

We plan on using 'ecolabels' registered on the Ecolabel Index [9] to ensure that the product can reach as wide an audience as possible, while also simultaneously marking its sustainability. Examples of ecolabels our product may attempt to utilize are the 'Carbon Footprint of Products' label, or the 'U.S. EPA Safer Choice label', including others registered on [9].

E-Shop: This product is planned to be sold on an online shop, so that users may purchase it on their personal devices. This will support communications with users about the sustainable impact of this product, economically through the E-Shop and physically through demonstration videos.

Our E-Shop will be more than just a place to buy the product, but it will also serve as a communication platform to inform our users of our future sustainable efforts, similar to how Patagonia uses their E-Shop (pictured right) to discuss their activism efforts [10]. Additionally, it has been found that on average, ecommerce greenhouse gas emissions are approximately 17% lower in the United States compared to physical retailers [11].

C User Manual

INSTALLATION AND USER INSTRUCTIONS

The Green Thumb

DISCLAIMER

The material in this manual is for informational purposes only. The products it describes are subject to change without prior notice, due to the developer's continuous development strategies. The developers of "The Green Thumb" make no warranties with respect to this manual or with respect to the products described within it. The developers of "The Green Thumb" shall not be liable for any damages, losses, costs or expenses, direct, indirect, or incidental, consequential or special, arising out of, or related to the use of this material or the product described within it.

Table of Contents

1 Preface

1.1 Description of the user

This user manual is meant for indoor gardeners using “The Green Thumb” to automate watering for their potted plants. There are no special skills required of the user, nor are there any skills, training, certification, or expertise required.

1.2 Explanation of safety warnings

CAUTION! Caution indicates a hazard with a level of risk which, if not avoided, could result in injury.

NOTICE Indicates information considered important, but not hazard-related.

1.3 Retaining instructions

- Read and understand this manual and its safety instructions before using this product.
- Follow all the instructions. This will avoid hazards.
- Keep all safety information and instructions for future reference and pass them on to subsequent users of the product.

2 Description of the product

2.1 Purpose of the product

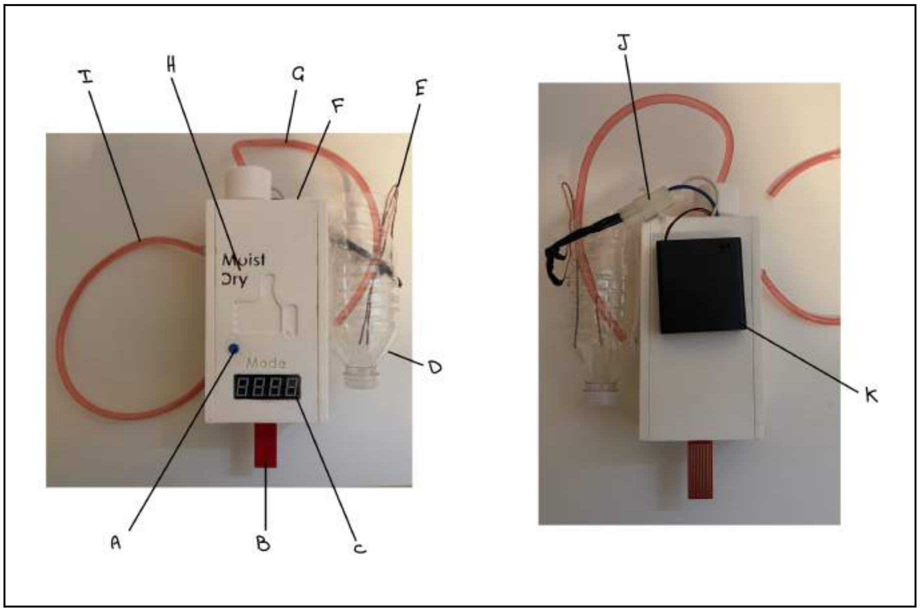
“The Green Thumb” is an automatic plant watering system designed for busy individuals who may not have the time to care for their indoor plants and gardens. It uses a moisture sensor and a pump to water plants from its onboard water container, ensuring that plants are watered only when necessary. With four pre-calibrated watering options and indicator lights, “Thee Green Thumb” makes it easy for users to care for all kinds of plants, while monitoring their watering status. A daylight sensor on the top of the device will disable the device at night to avoid disturbing your sleep. Its energy-efficient components and water conservation features also make it an eco-friendly choice for sustainable indoor gardening.

2.2 Specifications

Water Pump: AE1207 12V DC
Battery: 4 x AA
Battery Capacities: 3200Ah collectively
Weight: 700g

1

2.3 Product Elements



A. Moisture Mode Select Dial
B. Moisture Sensor
C. Moisture Mode Select Display
D. On-Board Water Container
E. Water Container Level Sensor
F. (not pictured) Daylight Sensor
G. Inlet Water Tube [to water container]
H. Moisture and “Currently Watering” Indicator Lights
I. Outlet Water Tube [to plant soil]
J. Water Container Level Sensor Clips
K. Battery Pack (for 4 x AA batteries)

3 Safety instructions

3.1 How to use this product safely

CAUTION! Active electronic components inside. Can shock or burn. Keep out.

3.1.1 General safety

- Only use water with this product
- Do not allow any water to enter the device's internal spaces
- Unclip the water level sensor clips before refilling container
- Do not consume water delivered by this product

3.1.2 Battery safety

- Do not use batteries that:
  - are swollen
  - are dented
  - have torn plastic wrappers
  - show other signs of damage or wear
- Ensure that batteries are inserted with the correct orientation

3.1.3 Storage safety

- Keep the original box that the product shipped with for future storage use
- Before storing the product after some time of use, ensure that the water container is completely dry
- Before storing the product, ensure that no water remains in the watering tubes
- Before storing the product, ensure that no batteries are left in the battery holder

4 Installation

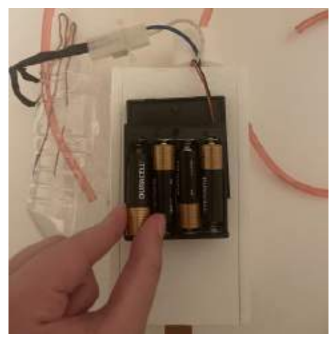
4.1 Packaging contents

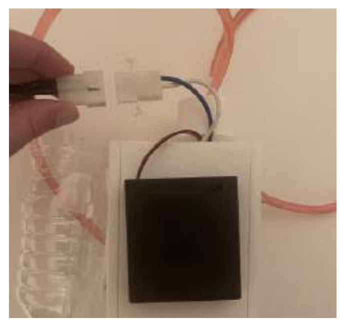
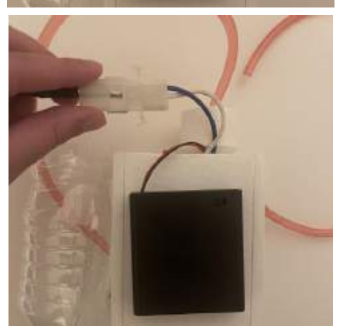
The packaging for this product includes:

1. “The Green Thumb”
2. 4 x AA batteries
3. Small flat-head screwdriver

4.2 Installation

To install the product:

1. Install the included batteries into the battery holder	

2. Insert the device, moisture sensor first, into the soil. Ensure the moisture sensor is covered by the soil.	
3. Attach the clips for the water container level sensor. Ensure the daylight sensor is not covered or blocked.	 

5 Operation and Use

1. Turn on the switch located on the battery holder
2. Using the flat-head screwdriver, adjust the moisture selection dial to the moisture level that best suits your plant (see Appendix A for suggested moisture levels for common houseplants)
3. Unclip the water level sensor clip
   CAUTION! Ensure that the water level sensor clip is unclipped prior to filling the water container
4. Fill the container about ¾ full of water. More is acceptable, but too much may overfill the container
5. Put the outlet water container tube in the plant's soil
6. When there is a green light behind the "Moist" indication window, the soil is at or above the target moisture
7. When there is a red light behind the "Dry" indication window, the soil is below the target moisture. The product may water the plant soon.
8. When there is a blue blinking light behind either indication window, the product is currently watering the plant
9. When the device's musical jingle plays, refill the water in the water container (refer to section 6.1)

After installation, your device and pot should look something like this!

6 Maintenance

6.1 Product maintenance by users

To replace the batteries:

1. Turn the switch on the battery holder off
2. Remove the old batteries, disposing them as appropriate in your area if they are non-rechargeable
3. Add the new batteries, and close the battery holder
4. Turn the switch on the battery holder on

NOTE: We suggest replacing the batteries every 6 months, or when the batteries are fully discharged, whichever occurs first.

To refill the water:

NOTE: This product will play a short song to alert you to when the water container is nearing low levels of water

1. Unclip the water level sensor clips
2. Gently pour water into the water container until it is ¾ filled with water
3. Clip the water level sensor clips once again

6.2 Other product maintenance

We created this device with the intention of it being very low maintenance for users. However, we recognize that occasionally, things go wrong. If this occurs:

1. Email us to let us know that your device requires other maintenance
2. Download the prepaid shipping label sent to you, and attach it to the outside of the original product box
3. Pack the product in its original box, ensuring that storage safety guidelines in section 3.1.3 are followed
4. Mail the package back to us. The device will be repaired and mailed back to you

7

A Suggested modes for different plants

We suggest the following plants make use of the following moisture modes, based on the *Acurite Recommended Soil Moisture Levels* [1]:

Moisture Mode 1	Moisture Mode 2
African violet Agave Cactus Cassava root Cinquefoil Rugosa rose Sedum Yarrow	Aster Beardtongue Beebalm Blanket flower Butterfly weed Catmint Christmas fern Coneflower Daffodil Daylily Heather Hyssop Iris Lavender Lemon balm Lily Marigold Ornamental grasses Pansy Peony Petunia Plantain lily Poppy Tulip Violet Zinnia
Moisture Mode 3	**Moisture Mode 4**
Asian bleeding-heart False goat's beard Hellebore Ironweed Jack-in-the-pulpit Joe-Pye weed Lupine Mayapple Queen of the prairie Swamp milkweed Blueberry bush Blackberry bush Strawberry bush Raspberry bush Dwarf lemon tree	Cranberry bush Lobelia Marsh marigold Meadow rue

Note that all vegetables should use Moisture Mode 3. Unlisted flowers should utilize Moisture Mode 2.

References

[1] A. R. Team, "Guide: Soil moisture recommendations for flowers, plants, and vegetables," *Welcome to AcuRite.com*, 28-Mar-2022. [Online]. Available: https://www.acurite.com/blog/soil-moisture-guide-for-plants-and-vegetables.html. [Accessed: 24-Apr-2023].

D Sample Promotion Brochure

Benefits

Our product offers a wide range of benefits for indoor gardeners of any skill level, no matter how much free time they have. These include:

- Time and effort saving - With The Green Thumb managing watering, your time and energy is freed up!
- Water conservation - The Green Thumb's precise design minimizes water wastage, promoting sustainability with its optimized water delivery.
- Easy installation - Just place the device in the pot, and the sensor and pump hose into the soil.
- Improved plant health - By providing water only when necessary, The Green Thumb avoids underwatering or overwatering your plants!
- Versatility - The Green Thumb can be used with a wide range of plant types, with plants sorted into 4 different water level modes.
- Low-maintenance - The Green Thumb was designed to have as little user maintenance as possible, with busy gardeners in mind.

The Green Thumb truly is the perfect tool for any indoor gardener to eliminate the hassle of manually watering their indoor garden!

THE GREEN THUMB

ENEL 300, W23, LC8-A
Prepared with LaTeX 2_ε and Overleaf
Many thanks to the Szegedi Vox Nova Kórus

The Green Thumb

Moist
Dry

What is The Green Thumb?

Introducing The Green Thumb, an automatic plant watering device created for busy people who can't find the time to care for an indoor garden. Our product monitors your plant's soil moisture, watering it only when needed. With an easy installation, pre-calibrated water level options, and an automatic nighttime shutdown protocol, The Green Thumb is the perfect solution for anyone who wants to garden indoors without the hassle of manually watering.

Moist
Dry
Mode

Testimonial

"I love my indoor herb garden, but with my long, frequent hospital stays, it's become tough to care for it properly. The Green Thumb has completely changed that! It has made my life so much easier, and I can be worry-free, knowing that The Green Thumb is taking care of my plants when I'm away. I highly recommend The Green Thumb to anyone who needs just a little help with their indoor gardens!

- Hector Slacimon, satisfied customer"

The Green Thumb Development Team

Pictured right, from left to right

- Bogdan Bacea
  bogdan.bacea@ucalgary.ca
- Ziad Shamma
  ziad.shamma@ucalgary.ca
- Bihan Wanni Arachchige
  bihan.wanniarachchig@ucalgary.ca
- Austin Nguyen
  austin.nguyen1@ucalgary.ca

How it Works

Using a moisture sensor (pictured right) and an AVR128DB28 microcontroller, The Green Thumb detects when the plant's soil isn't moist enough. When this happens, the peristaltic pump (pictured below) runs, watering the plant. Another microcontroller manages the dial, which allows you to set a specific plant watering type from four pre-calibrated options.

A daylight detector disables the device at night, indicator LEDs inform you about the soil moisture status, and a speaker plays a tune when the water container level is low. Finally, when watering, a blue LED blinks, as an extra touch to let you know that The Green Thumb is doing its good work!

Figure 8: "The Green Thumb" promotional brochure

E Sample Sustainability Promotion Poster

Figure 9: “The Green Thumb” sustainability promotion poster

F Sample User Interview

The interviewer is Bihan Wanni Arachchige, one of the developers of “The Green Thumb.” The interviewee is Bianca Wanni Arachchige, a young and busy student who has an attachment to a small potted lemon tree.

Q: Can you tell me about your manual watering experience with this lemon tree?
A: I usually water it once a week, but some weeks I forget to do it, and also sometimes I don’t have the time. I think once the soil was very dry for almost a month, so I water it a lot and then the soil gets too wet. I don’t really know how much water it needs to be honest.

Q: Do you feel confident in knowing when the lemon tree needs water?
A: Not really. Sometimes the soil feels dry at the top, but when I poke my finger in, it’s wetter than I thought it would be. The water tray under the pot doesn’t really fill up with a lot of water too, so I’m not sure. Also, when I put lots of water to make up for missing a week or two, I kinda just give it extra water, since I’m not really sure how much I extra I need to put.

Q: Do you ever worry that you might overwater or underwater your lemon tree?
A: Yes, I worry about it sometimes. I don’t want to underwater it because then it will die, but it will also die if I overwater it. I try to water it properly, but I’m not sure if I’m doing it right.

Q: Have you ever underwatered or overwatered this plant?
A: I have underwatered and overwatered it before, for sure. When I forget to water for a week or two, the soil gets too dry. There have been times where I think I definitely watered it too much and the soil looked like mud.

Q: How do you currently monitor the moisture of its soil?
A: I have a moisture sensor in the soil there, but I don’t really use it. I mostly rely on how the soil looks and how long it has been since I last watered to help me judge that.

Q: What are some things you like about your current moisture sensor?
A: I like that the sensor gives me some info about the soil, even if I don’t really understand it. I kinda just leave it in there and it does its thing. Sometimes I look over at it and it reminds me to water the lemon tree.

Q: What are some things you dislike about your current moisture sensor?
A: I don’t really understand what the 0-10 numbers on the front mean. I get that 5 means more wet than 4, but I don’t really understand what each one means, and I don’t really know which one is the right level for my lemon tree. The sensor isn’t helpful to me.

Q: What are some features you would like in a soil moisture sensor that this one doesn't have?
A: I think it would be great if the sensor gave some clear information about the soil water level. Maybe like percentage or something like that. It would also be cool if it could tell me when to water too. Like a little light or a sound or something like that.

Q: Would you be interested in a device that automates watering your plant? It would sense the moisture of the soil and water based on that reading.
A: I think that would be useful, it would save me the time of watering. It would need some way to set how moist the sol should be, instead of one soil moisture fits all plants.

Q: What features would you like to see in such an automated watering device?
A: It should have a way to adjust the moisture that the plant soil will be at. Also I think it would be good if it told me when it was going to water, and maybe show the moisture of the soil somehow. If it's automated, it should be easy to use as well.

Q: How much effort are you willing to put into maintaining an automated watering device?
A: I don't really want to be constantly thinking about a device like that if it's meant to do things automatically. If I need to constantly do work on it, what's the point? I'm fine with replacing the battery and all that when I need to, but it would be good to just set it and forget it.

Q: How important is the device's aesthetic design to you for an automated watering device?
A: It would be nice if it was visually appealing, but I don't really want it to overshadow my lemon tree. I would rather it worked before it looked good, if that makes sense.

Q: Any concerns with using an automated watering device on your lemon tree?
A: How will it be watering things? Will it be from a container on the device, or does it need to be connected to a water line? How will I know when to refill that, if it is a container? Also, how will the device make sure that underwatering and overwatering aren't a problem?

Q: Thank you for your concerns, we will definitely keep those in mind! I do not currently have answers to those questions. Do you have any final thoughts on the topic?
A: Well, I'm definitely interested in this automatic watering device thing. I hope it would be able to help me take care of my lemon tree!

G Sample Feedback Form

Date: April 15, 2023 ENEL 300
User Name: Bianca Wanni Arachchige W23
Developer Name: Bihan Wanni Arachchige LC 8-A

Feedback Form

Product: The product in question for this feedback form is the moisture sensor that the user currently has implanted in the soil of her lemon tree.

Questions:

1. How satisfied are you with this product overall?
   - ☐ Very Satisfied
   - ☐ Satisfied
   - ☑ ~~Neutral~~
   - ☐ Unsatisfied
   - ☐ Very Unsatisfied
2. How likely are you to recommend this product to others?
   - ☐ Very Likely
   - ☐ Likely
   - ☐ Neutral
   - ☐ Unlikely
   - ☑ ~~Very Unlikely~~
3. How easy is it to use this product?
   - ☐ Very Easy
   - ☐ Easy
   - ☐ Neutral
   - ☑ ~~Difficult~~
   - ☐ Very Difficult
4. How well does this product meet your needs?
   - ☐ Very Well
   - ☐ Well
   - ☐ Neutral
   - ☐ Poorly
   - ☑ ~~Very Poorly~~
5. How frequently do you use this product?
   - ☐ Daily
   - ☐ Weekly
   - ☐ Monthly
   - ☑ ~~Occasionally~~
   - ☐ Never
6. How would you rate the quality of this product?
   - ☐ Excellent
   - ☐ Good
   - ☑ ~~Average~~
   - ☐ Below Average
   - ☐ Poor

Date: April 15, 2023
User Name: Bianca Wanni Arachchige
Developer Name: Bihan Wanni Arachchige

ENEL 300
W23
LC 8-A

Feedback Form

7. What do you like the most about this product?

I like the fact that this sensor gives me at least a little bit of information about the moisture of my lemon tree's soil. It helps me avoid underwatering and overwatering. Sometimes though I don't really check it at all, and I water it based on the soil's appearance, or if I feel like it has been a bit too long since I last watered. I check it sometimes when that happens, and it's nice to have that extra reassurance.

8. What do you like least about this product?

I don't really like how there's no explanation about what the 0-10 scale on the sensor means. I understand that a 10 is moister than a 9, but how much is that really? I think that different plants require different amounts of water, but I don't really understand how the numbers on the scale relate to those.

9. In what ways could this product be improved to help you better?

I think this moisture sensor could be improved by adding some sort of watering alert or something. That way, I wouldn't really have to worry about the specific number on the scale, and I wouldn't have to guess every time I water my lemon tree.

H Moisture Sensor Testing Log

Date: April 10, 2023
Start Time: 7:45 PM
End Time: 8:45 PM
Tester Name: Bihan Wanni Arachchige

ENEL 300
W23
LC 8-A

Moisture Sensor Testing Log

Test Description:

- Place a recorded volume of potting soil in a plastic container, then add a volume of water to the soil according to the desired testing volume percentage. For example, if the desired testing percentage is 50%, and the recorded volume of potting soil used is 500 mL, then 500 mL of water should be added
- Mix the soil and water well, then place the moisture sensor inside the mix, ensuring that soil covers 75% of the sensor's resistive contacts
- Using Scopy and the ADALM 2000, provide 5V to the appropriate ports on the sensor, using the ADALM power supply
- Using the Scopy and ADALM voltmeter, measure the voltage output from the sensor. Wait 30 seconds after turning on the power supply to allow the output to stabilize. Record this value.
- Repeat for different testing percentages.

Testing Results:

Soil Sample	Soil Volume (mL)			Water Volume (mL)			Sensor Output (V)		
	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
Control (no water added)	300	300	300	0	0	0	0.133	0.145	0.151
10% water by volume	300	300	300	33	33	33	0.545	0.549	0.547
20% water by volume	300	300	300	75	75	75	0.569	0.576	0.572
30% water by volume	300	300	300	129	129	129	0.599	0.603	0.609
40% water by volume	300	300	300	200	200	200	0.617	0.621	0.622

Date: April 10, 2023
Start Time: 7:45 PM
End Time: 8:45 PM
Tester Name: Bihan Wanni Arachchige

ENEL 300
W23
LC 8-A

Moisture Sensor Testing Log

Tester Observations:
During testing, the upper portion of the moisture sensor felt hot to the touch. It would be best to implement some feature which only turns on the sensor when needed, instead of keeping it on all the time. The device should check for moisture infrequently.

Tester Conclusions:
For our purposes, this moisture sensor will only be used in soil with a moisture level of 10%-40% water by volume. Taking the average of these values should be sufficient in determining appropriate sensor values to trigger our device at:

- For “5%-15% moisture” mode, trigger the device at 0.547 V read from the sensor
- For “16%-25% moisture” mode, trigger the device at 0.572 V read from the sensor
- For “26%-35% moisture” mode, trigger the device at 0.604 V read from the sensor
- For “36%-45% moisture” mode, trigger the device at 0.620 V read from the sensor

I Schematic

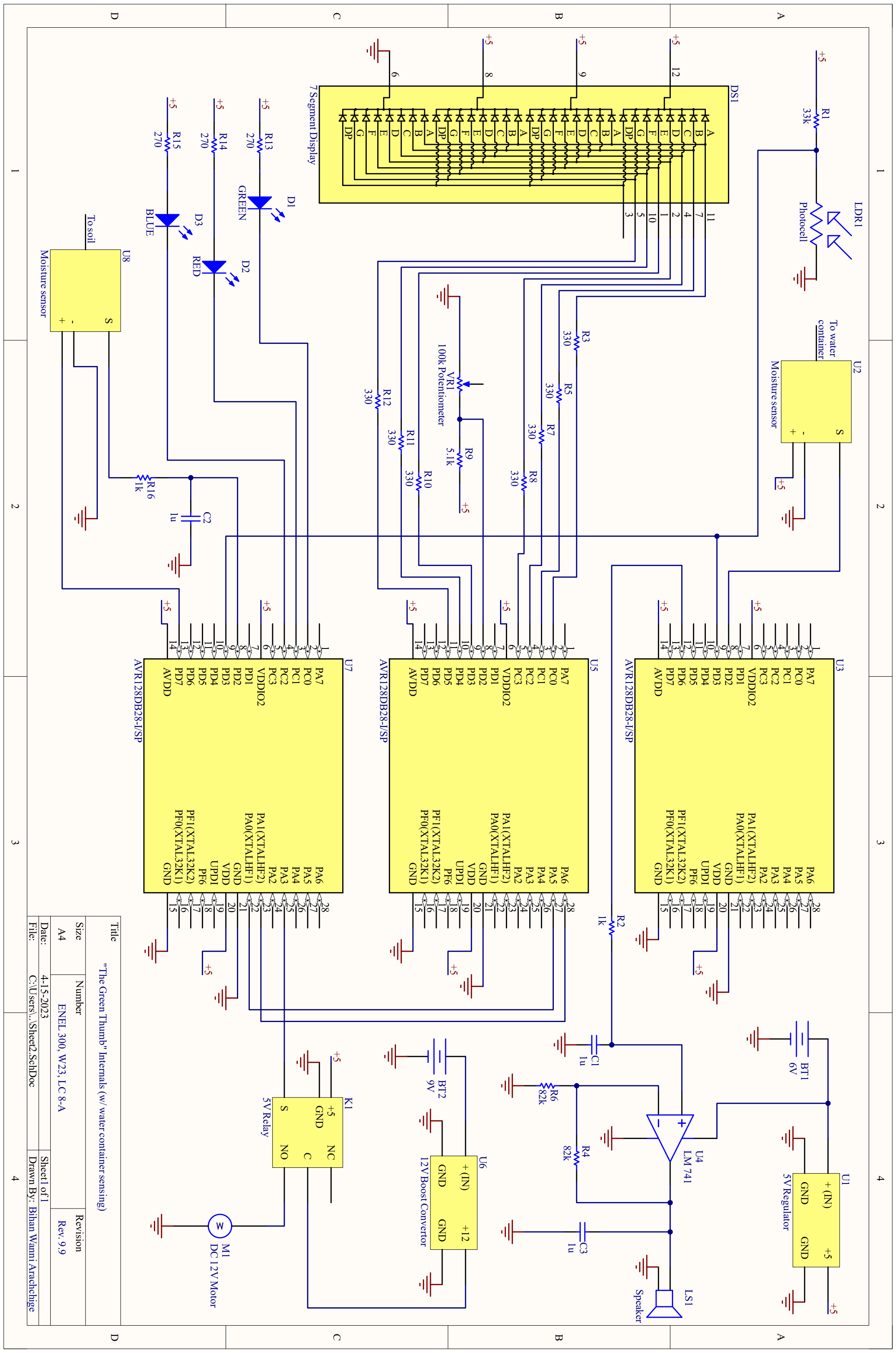


Figure 10: "The Green Thumb" internal circuit schematic

J Source Code Listings

```c
/*
 * primary.c
 * Author: Bihan Wanni Arachchige
 */

#define F_CPU 4000000UL
#include <avr/io.h>
#include <util/delay.h>



int moisture_check() {
    PORTD.OUT &= 0b01111111;
    PORTC.OUT |= 0b00000111;
    PORTA.OUT &= 0b11110111;
    int time_to_water = 1;
    for (int i = 0; i < 2; i++) {
        PORTD.OUT |= 0b10000000;
        int plant_type = ((PORTA.IN & 0b00000011) > 2) ? 3 : (PORTA.IN & 0b00000011);
        int ref = 450 + (20 * plant_type);
        _delay_ms(10000);
        if((ADC0.INTFLAGS & 0b00000001) == 0b00000001) {
            int result = ADC0.RES;
            if (result > ref)   {
    PORTC.OUT |= 0b00000111;
                PORTC.OUT &= 0b11111110;
                time_to_water = 0;
            }
            else {
    PORTC.OUT |= 0b00000111;
                PORTC.OUT &= 0b11111101;
                time_to_water = 1;
            }
        }
        PORTD.OUT &= 0b01111111;
        for (int j = 0; j < 65; j++) {
            _delay_ms(1000);
        }
    }
    return time_to_water;
}



int day_check(void) {
    AC1.DACREF = 36;
    int day = 1;
    if((AC1.STATUS & 0b00010000) == 0b00010000) {
        day = 0;
    }
    else {
        day = 1;
    }
    AC1.STATUS |= 0b00000001;
    return day;
}
```

```c
void water(void) {
    PORTA.OUT |= 0b00001000;
    PORTC.OUT |= 0b00000100;
    for (int i = 0; i < 20; i++) {
        PORTC.OUT |= 0b00000100;
        _delay_ms(250);
        PORTC.OUT &= 0b11111011;
        _delay_ms(250);
    }
    PORTA.OUT &= 0b11110111;
    return;
}



int main(void) {
    // input pins: PA0, PA1, PD2, PD3
    // output pins: PA3, PC0, PC1, PC2, PD7
    PORTD.DIRCLR = 0b00001100;
    PORTD.DIRSET = 0b10000000;
    PORTC.DIRSET = 0b00000111;
    PORTA.DIRCLR = 0b00000011;
    PORTA.DIRSET = 0b00001000;

    // Enable AVR interrupts, enable more control over AVR
    CCP = 0xd8;
    SREG = 0b10000000;

    // Initialize analog comparator 1
    AC1.CTRLA = 0b00000111;
    AC1.MUXCTRL = 0b00001011;
    VREF.ACREF = 0b00000101;
    AC1.INTCTRL = 0b00000001;

    // Initialize analog to digital convertor
    VREF.ADC0REF = 0b10000101;
    ADC0.INTCTRL = 0b00000001;
    ADC0.MUXPOS = 0x02;
    ADC0.CTRLC = 0x00;
    ADC0.CTRLA = 0b00000011;
    ADC0.COMMAND = 0x01;

    PORTC.OUT |= 0b00000111;

    while (1) {
        if(day_check()) {
            int time_to_water = moisture_check();
            if (time_to_water) {
                water();
            }
        }
        else {
            for (int i = 0; i < 60; i++) {
                _delay_ms(1000);
            }
        }
    }
}
```

Listing 1: Source code for primary microcontroller

```c
/*
 * File:   secondary.c
 * Author: Ziad Shamma
 */


#include <avr/io.h>

int main(void) {

    // Enable global interrupts.
    SREG = 0b10000000;

    // Set the ADC reference level to VDD.
    VREF.ADC0REF = 0b10000101;

    // Enable the ADC interrupt.
    ADC0.INTCTRL = 0b00000001;

    // Select PD2 (AIN2) as the ADC input.
    ADC0.MUXPOS = 0x02;

    // Select minimum clock divide.
    ADC0.CTRLC = 0x00;

    // Select single ended mode, 12 bit resolution and free-running modes.
    ADC0.CTRLA = 0b00000011;

    // Start conversion.
    ADC0.COMMAND = 0x01;

    //set pinS PA5 & PA6 as output pins
    PORTA.DIRSET = 0b01100000;

    //set pins PC0-PC3 & PD3-PD5 as output pins for LED Display
    PORTC.DIRSET = 0b00001111;
    PORTD.DIRSET = 0b00111000;

    while (1) {
        //empty while loop to check if the INTFLAG register was set
        while(ADC0.INTFLAGS == 0b00000000) {}

        //clear the INTFLAG register after checking
        ADC0.INTFLAGS = 0b00000001;

        // if the voltage is < 1V (option 1 (00))
        while(ADC0.RES < 819) {
            PORTA.OUT = 0b11111111;
            PORTC.OUT = 0b00000110;
            PORTD.OUT = 0b00000000;
        }

        //check and clear INTFLAG register
        while(ADC0.INTFLAGS == 0b00000000) {}
        ADC0.INTFLAGS = 0b00000001;
```

```
        // if the voltage is >= 1V and < 2V (option 2 (01))
        while((ADC0.RES >= 819) & (ADC0.RES < 1638)) {
            PORTA.OUT = 0b10111111;
            PORTC.OUT = 0b00001011;
            PORTD.OUT = 0b00101000;
        }

        //check and clear INTFLAG register
        while(ADC0.INTFLAGS == 0b00000000) {}
        ADC0.INTFLAGS = 0b00000001;

        // if voltage is >= 2V and < 3V (option 3 (10))
        while((ADC0.RES >= 1638) & (ADC0.RES < 2457)) {
            PORTA.OUT = 0b11011111;
            PORTC.OUT = 0b00001111;
            PORTD.OUT = 0b00100000;
        }

        //check and clear INTFLAG register
        while(ADC0.INTFLAGS == 0b00000000) {}
        ADC0.INTFLAGS = 0b00000001;

        // if voltage is >= 3V (option 4 (11))
        while(ADC0.RES >= 2457) {
            PORTA.OUT = 0b10011111;
            PORTC.OUT = 0b00000110;
            PORTD.OUT = 0b00110000;
        }
    }
}
```

Listing 2: Source code for secondary microcontroller

```c
/*
 * File:   tertiary.c
 * Author: Bogdan Bacea
 */


#include <avr/io.h>

unsigned short nSmp = 20;
unsigned short wave[] = {127, 166, 202, 230, 248, 255, 248, 230, 202,
       166, 127, 88, 52, 24, 6, 0, 6, 24, 52, 88};
unsigned short n = 0;

void notes(int length, int note) {
    while (RTC.CNT <= length) {
        DAC0.DATAH = wave[n];
        n = (n+1) % nSmp;
        while( TCA0.SINGLE.CNT <= note);
        TCA0.SINGLE.CNT = 0;
    }
    n=0;
    RTC.CNT = 0;
}

void offdelay (int length) {
    while(RTC.CNT <= length) {
        DAC0.DATAH = 0;
    }
    RTC.CNT = 0;
}

int main(void) {
    // input pins: PD2
    // output pins: PC0, PC1, PC2
    PORTC.DIRSET = 0b00000111;
    PORTD.DIRCLR = 0b00000100;

    // Enable global interrupts.
    SREG = 0b10000000;

    // Set the ADC reference level to VDD.
    VREF.ADC0REF = 0b10000101;

    // Enable the ADC interrupt.
    ADC0.INTCTRL = 0b00000001;

    // Select PD2 (AIN2) as the ADC input.
    ADC0.MUXPOS = 0x02;

    // Select minimum clock divide.
    ADC0.CTRLC = 0x00;

    // Select single ended mode, 12 bit resolution and free-running modes.
    ADC0.CTRLA = 0b00000011;

    // Start conversion.
    ADC0.COMMAND = 0x01;
    PORTC.OUTSET = 0b11111111;

    // -- Clock Configuration --
```

```
// Set internal clock frequency to 4 MHz.
CCP = 0xd8;
CLKCTRL.OSCHFCTRLA = 0b00001100;
while( CLKCTRL.MCLKSTATUS & 0b00000001 ){
    ;
}

// divide by 16 -- 250000Hz
TCA0.SINGLE.CTRLA = 0b00001001;

//select 32KHzclock
RTC.CLKSEL = 0b00000000;

//Divide by 2048 - T = 0.0625s
RTC.CTRLA = 0b01010001;

TCA0.SINGLE.PER = 0xffff;

//(Timerspeed/freq)/20

unsigned int A5 = 13.907;
unsigned int A4 = 28.409;
unsigned int B4 = 25.310;
unsigned int C5sharp = 22.548;
unsigned int D5 = 21.283;
unsigned int E5 = 18.961;
unsigned int F5sharp = 16.892;
unsigned int G5 = 15.944;
unsigned int G5sharp = 14.90;

unsigned int sec0_11250 = 1.7*1.8;
unsigned int sec0_1875 = 1.7*3;
unsigned int sec0_0750 = 1.7*1.2;
unsigned int sec0_16875 = 1.7*2.7;
unsigned int sec0_28125 = 1.7*4.5;
unsigned int sec0_225 = 1.7*3.6;
unsigned int sec0_150 = 1.7*2.4;
unsigned int sec0_300 = 1.7*4.8;
unsigned int sec0_375 = 1.7*6;

// Set PD6 to be the DAC output and enable the DAC.
DAC0.CTRLA = 0b01000001;

// Configure to use VDD as the reference level.
VREF.DAC0REF = 0b10000101;

while (1) {
    if (ADC0.RES <= 2703.36) {
      //1st bar
        //first note
        notes(sec0_11250,A5);
        offdelay(sec0_1875);

        //second note
        notes(sec0_0750,E5);
        offdelay(sec0_0750);

        //third note
        notes(sec0_0750,D5);
        offdelay(sec0_0750);

        //fourth note
```

```
            notes(sec0_16875,C5sharp);
            offdelay(sec0_28125);

            //fifth note
            notes(sec0_0750,C5sharp);
            offdelay(sec0_0750);

          //2nd bar
            //first note
            notes(sec0_0750,D5);
            offdelay(sec0_0750);

            //second note
            notes(sec0_0750,E5);
            offdelay(sec0_0750);

            //third note
            notes(sec0_0750,F5sharp);
            offdelay(sec0_0750);

            //fourth note
            notes(sec0_0750,G5sharp);
            offdelay(sec0_0750);

            //fifth note
            notes(sec0_225,E5);
            offdelay(sec0_225);

            //rest
            offdelay(sec0_150);

          //3rd bar
            //first note
            notes(sec0_11250,F5sharp);
            offdelay(sec0_1875);

            //second note
            notes(sec0_0750,E5);
            offdelay(sec0_0750);

            //third note
            notes(sec0_0750,D5);
            offdelay(sec0_0750);

            //fourth note
            notes(sec0_11250,C5sharp);
            offdelay(sec0_1875);

            //fifth note
            notes(sec0_11250,C5sharp);
            offdelay(sec0_1875);

          //4th bar
            //first note
            notes(sec0_11250,B4);
            offdelay(sec0_1875);

            //second note
            notes(sec0_11250,C5sharp);
            offdelay(sec0_1875);

            //third note
```

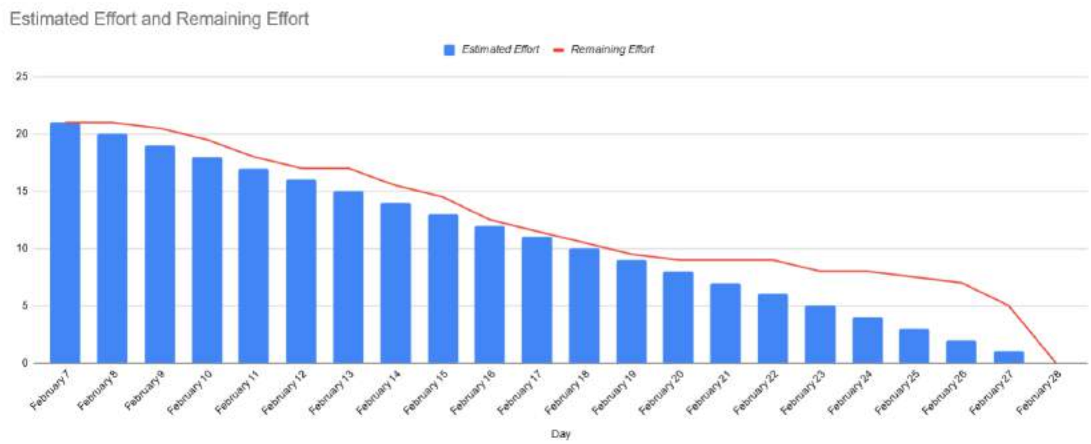
```
      notes(sec0_150,D5);
      offdelay(sec0_150);

      //rest
      offdelay(sec0_300);

    //5th bar
      //first note
      notes(sec0_11250,A5);
      offdelay(sec0_1875);

      //second note
      notes(sec0_0750,E5);
      offdelay(sec0_0750);

      //third note
      notes(sec0_0750,D5);
      offdelay(sec0_0750);

      //fourth note
      notes(sec0_225,C5sharp);
      offdelay(sec0_375);

    //6th bar
      //first note
      notes(sec0_0750,C5sharp);
      offdelay(sec0_0750);

      //second note
      notes(sec0_0750,D5);
      offdelay(sec0_0750);

      //third note
      notes(sec0_0750,E5);
      offdelay(sec0_0750);

      //fourth note
      notes(sec0_0750,F5sharp);
      offdelay(sec0_0750);

      //fifth note
      notes(sec0_150,D5);
      offdelay(sec0_150);

      //rest
      offdelay(sec0_300);

    //7th bar
      //first note
      notes(sec0_0750,F5sharp);
      offdelay(sec0_0750);

      //second note
      notes(sec0_0750,E5);
      offdelay(sec0_0750);

      //third note
      notes(sec0_0750,D5);
      offdelay(sec0_0750);

      //fourth note
      notes(sec0_0750,C5sharp);
```

```
            offdelay(sec0_0750);

            //fifth note
            notes(sec0_0750,B4);
            offdelay(sec0_0750);

            //sixth note
            notes(sec0_0750,C5sharp);
            offdelay(sec0_0750);

            //seventh note
            notes(sec0_0750,D5);
            offdelay(sec0_0750);

            //eighth note
            notes(sec0_0750,F5sharp);
            offdelay(sec0_0750);

          //8th bar
            //first note
            notes(sec0_0750,E5);
            offdelay(sec0_0750);

            //second note
            notes(sec0_0750,D5);
            offdelay(sec0_0750);

            //third note
            notes(sec0_0750,C5sharp);
            offdelay(sec0_0750);

            //fourth note
            notes(sec0_0750,B4);
            offdelay(sec0_0750);

            //fifth note
            notes(sec0_300,A4);
            offdelay(sec0_300);
        }
    }
}
```

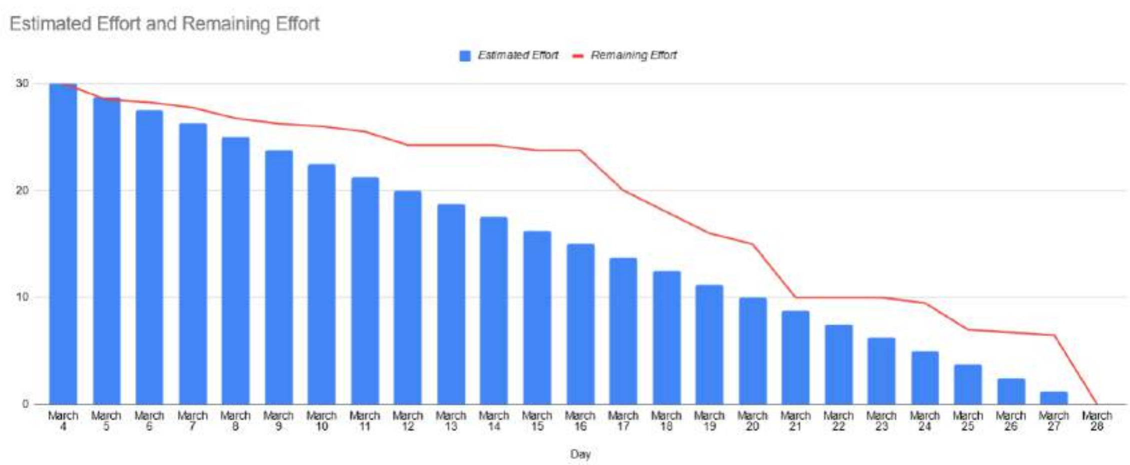
Listing 3: Source code for tertiary microcontroller with day_check() not included for brevity

K Burn Down Charts

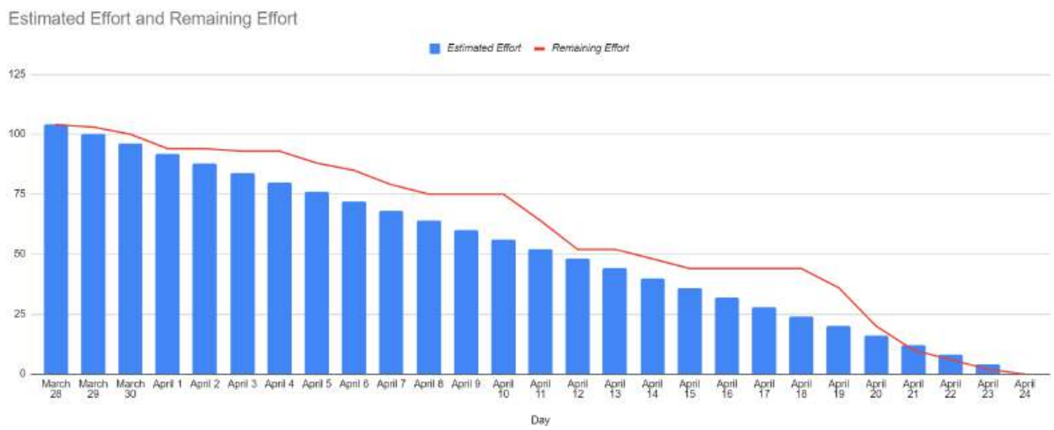
Sprint 2:



Sprint 3:



Sprint 4:


Estimated Effort and Remaining Effort
Estimated Effort
Remaining Effort
125
100
75
50
25
0
March 28
March 29
March 30
April 1
April 2
April 3
April 4
April 5
April 6
April 7
April 8
April 9
April 10
April 11
April 12
April 13
April 14
April 15
April 16
April 17
April 18
April 19
April 20
April 21
April 22
April 23
April 24
Day