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HIGH PRECISION FARMING SYSTEM BASED ON AEROPONICS

Master's thesis

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AEROPOONIKAL PÕHINEV TÄPPIS TAIMEKASVATUSSÜSTEEM

Magistritöö

Juhendaja: Reeno Reeder

Filosoofiadoktor

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Author's declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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19.04.2017

Abstract

Aeroponics is a promising soilless farming method for solving future food crisis. But not much development has been done for consumer market in this field.

This thesis represents the development of a smart aeroponic system capable of providing output data for deep learning and using the process to improve its performance. During the thesis hardware, firmware and software working principles are described and the system is designed.

At the beginning of the thesis a market overview is given about the systems available followed by specifications for the system needed. According to the specifications hardware and firmware are developed. Two modules are designed for illumination and irrigation purposes. Recipe handling and data buffering services were set up.

As a result of this thesis a fully functioning automated aeroponic system was developed with the capability of applying machine learning processes. Still thorough testing and development of the system needs to be done before publishing the project to consumers.

This thesis is written in English and is 38 pages long, including 5 chapters, 29 figures and 3 tables.

Annotatsioon

Aeropoonikal põhinev täppis taimekasvatussüsteem

Aeropoonika on lootustandev mullata taimekasvatussüsteem, mis võiks tulevikus aidata lahendada saabuvat toidukriisi. Kahjuks pole selliseid süsteeme tavakasutaja tarbeks eriti arendatud.

Antud töös käsitletaks sellise targa aeropoonika süsteemi väljatöötamist, mis on võimeline edastama andmeid masinõppeks tarvilikul kujul ning oleks võimeline rakendama masinõpet süsteemi kasuteguri tõstmiseks. Töö käigus antakse ülevaade riistvara, püsivara ja tarkvara tööpõhimõtetest ja koostatakse terviklahendus.

Pärast sissejuhatust antakse ülevaade turul olevatest toodetest ja sealt liigutakse vajalike süsteemi spetsifikatsioonide täpsustamise juurde. Vastavalt koostatud nõuetele töötatakse välja riistvara, püsivara ja tarkvara lahendused. Koostatakse kaks eraldiseisvat moodulit valgustuse ja taimede toiteahela tarbeks. Kasvuretseptide rakendamise ning andmete puhverdamise teenused seadistatakse.

Lõputöö on kirjutatud inglise keeles ning sisaldav teksti 38 leheküljel, 5 peatükki, 29 joonist, 3 tabelit.

List of abbreviations and terms

AC	Alternating current
ADC	Analog digital converter
CPU	Central processing unit
DC	Direct current
DMOS	Double-diffused metal-oxide semiconductor
EC	Electrical conductivity
EEPROM	Electrically erasable programmable read-only memory
EMF	Electromotive force
GND	Ground
GPIO	General purpose input output
HMI	Human machine interface
I/O	Input Output
IC	Integrated circuit
LED	Light emitting diode
MCU	Microcontroller Unit
MIT	Massachusetts Institute of Technology
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
MQTT	Message Queuing Telemetry Transport
NASA	National Aeronautics and Space Administration
PC	Personal computer
pH	Potential of hydrogen
PSU	Power supply unit
PWM	Pulse Width Modulation
RTC	Real Time Clock
TTU	Tallinn University of Technology
USB	Universal Serial Bus
UV	Ultra Violet
VDD	Voltage Drain-Drain

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1 Introduction

United Nations Human Settlements Programme has projected that in next 15 years the urban population of developing countries will double, while the area covered by cites could triple. We need to feed additional 2.5B people living in cities by 2050. [1] Due to limited resources of the planet, growing food demand and changing weather patterns there is a need for the food industry to look into new solutions and change the way safe fresh food is being grown.

Aeroponic research began in the 1920's and progressed steadily as a soilless growing method. In the early stages, researchers grew plants aeroponically using vapour at the plants' roots to deliver nutrients. The types of plants that were used in the 1950's included coffee and avocado plants. It wasn't until 1980, that this new method of growing would be developed into what was coined as "aeroponics".

During the 1990s NASA carried out a series of tests in space and on earth growing biomass with no soil and very little water and this method proved to be very productive. With leaving the roots in the air it improves the root structure of the plants and with the added access to oxygen and CO_2 even faster growth can be accomplished. Nutrients and water are spayed as mist particles to the roots while the backdrop water is constantly cleaned and used again, saving massive amounts of water compared to traditional gardening methods.

Aeroponic growing systems provide clean, efficient, and rapid food production. Crops can be planted and harvested in the system year round without interruption, and without contamination from soil, pesticides or residue. Since the growing environment is clean and sterile, it greatly reduces the chances of spreading plant disease and infection commonly found in soil and other growing media.

This thesis is focused on development of a proof of concept of a high precision aeroponic farming system for small scale farming with the intention of implementing and testing machine learning capabilities.

1.1 Benefits and applications of aeroponics

Aeroponic systems can be stacked up in layers to build vertical farms that take up much less space than traditional farming methods. Since plants are grown in a controlled environment crops can be grown year-round without being dependent on the weather or atmosphere conditions outside. Food can be grown locally near highly populated areas cutting back on logistical costs. Compared to soil based farming aeroponics uses up to 98% less water and 1/3 of the nutrients. With precise climate control the system can also be used in research and pharmaceutical farming.

1.2 Products on the market

Hydroponics is widely used in growing salads, herbs and tomatoes already for decades and is becoming more popular since it enables to cut back on logistic costs and is not dependent on the climate. But the use of the more productive *aeroponic* grow systems has not been developed much for customer sector.

At this point available growing systems that could be maintained in city apartment or balcony are very simple *hydroponic* growing tents or boxes. These are based on timer relays for the nutrient pumps with some added lighting and ventilation and cost 400€-3000€.

Figure 1. Examples of simple hydroponic growboxes

With only timer driven pumps and ventilation cycles the user needs to do much work themselves by measuring the water pH and nutrient levels, maintaining temperature and humidity and also changing the length of the day by setting different intervals for the lights to be turned on and off. By automating these processes and analysing the weather patterns created growing fresh food at home will be much easier and a food computer could become a regular household item like a fridge filled with fresh veggies.

More complex biochambers are available for research and pharmaceutical farming. These systems have more precise environment control capabilities and can also follow given patterns. These systems are at high cost ranging from 10000€-100000€

Figure 2. Examples of research biochambers

There is a need for affordable, efficient and user friendly system to grow food locally anywhere, even in space. As NASA and MIT OpenAg [2] are also working on further developing their systems and sharing their weather patterns, there is possibility in the future to cooperate on the basis of knowledge sharing to benefit all the projects success.

1.3 The Problem

An affordable growing machine will make it possible for everyone to grow their fresh food at home all year. To make the system as efficient as possible implementing machine learning is intended and needs to be taken into account when composing the hardware solution. For deep learning to take place as much parameters of the ongoing processes need to be monitored to get enough feedback for making decisions about process improvements.

1.4 Specification for the System

To make the growing machine as cheap as possible it is wise to use components that are produced in high volumes and are widely used, but to achieve wanted efficiency there is also a need to develop some application specific solutions.

For achieving properly controlled environment and sufficient feedback continuous system monitoring should be done via various sensors.

1.4.1 Data Acquisition

For acquiring data from sensors and interpreting it to upper level analysis microcontroller units will have a key role. There is a need to communicate with different protocols (1-Wire, I2C, Ethernet) and also measure voltages or state-changes on digital sensors.

Parameters needed to be measured:

- Temperature
- Water level
- pH of solution
- EC of solution
- Humidity
- Proximity
- Time

1.4.2 Illumination module

For saving energy and to have proper spectrum of light LED-s will be used in the modules. As ready-made grow LED lamps are quite expensive it is wise to design new stackable light modules for this project. By using carefully chosen LED-s and switching circuit proper light spectrum can be created for every stage of the plants growth cycle. This enables to intensely speed up the growing process. Relation between light spectrum and growing stages can be seen on Figure 3.
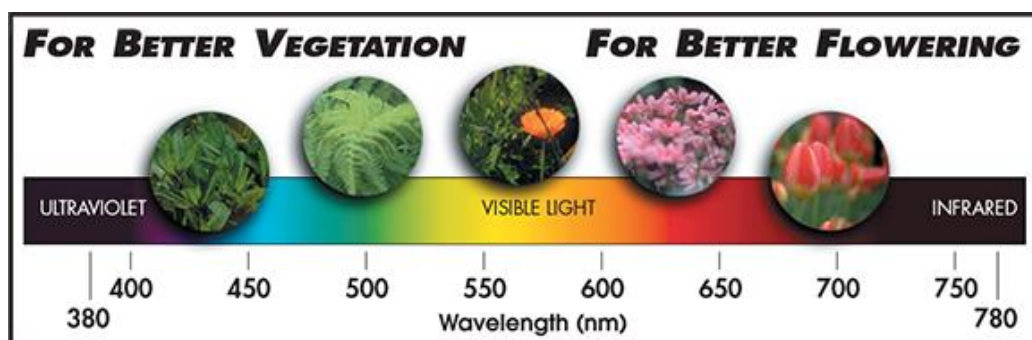

Figure 3. Wavelength importance in growth cycle

1.4.3 Irrigation module

The irrigation module needs a high-pressure pump for delivering water and nutrients to the roots in a form of 5-50 micron sized droplets. Filtering system is needed for maintaining adequate pH and nutrient levels in addition to keeping the environment clean of any contaminants. A precision nutrient pump is needed to balance the pH level and nutrient solution during the circulation of water to and from the roots.

1.4.4 Actuator Control and Power Switching

In actuator control also microcontroller units will play key role of executing the higher level commands for maintaining given weather pattern parameters. Switching lights, water pump, ventilation, pH control, nutrients pumps etc. needs also a properly isolated and protected circuit. Here for more control over vent and pump motor speeds simple relay switching will not work and a better solution needs to be designed.

1.4.5 High Level Control

Here the grow patterns and algorithms are held, data is collected and analysed. By adding deep learning to this layer great advancements can be achieved both in optimizing the power consumption of the unit itself and for plant growth speed and quality.

2 Functional Overview and System Design

This section gives an overview of system functionality and the development of hardware solutions required to achieve given functionality. Grow box is a cyber-physical feedback system. The system divides into three layers as shown on Figure 4:

Functional layer is responsible for data acquisition and control of the physical processes. This layer consists of two separate modules, one for illumination and the other one for irrigation and nutrition of the plants. These modules can be stacked together and configured for bigger growing areas, making the system scalable in size.

Operational layer is responsible for configuring the weather patterns and acts as a buffer to upper layer services. For this purpose Raspberry PI is used but any PC would also work fine if the end user has a lot of space for the system to be installed.

Deep learning layer where all accumulated data is being collected and deep learning process is applied. Here new neurons are being developed and fed back into the operational layer for added accuracy and "smartness" of the system.
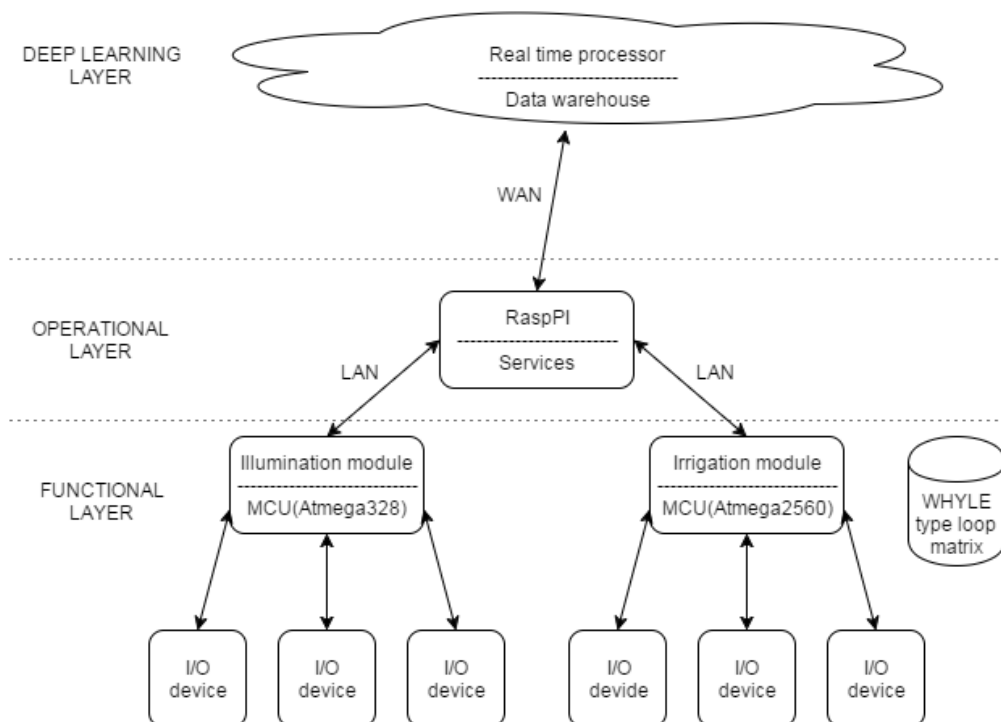

Figure 4. System architecture

2.1 Design of the Functional layer

This section of the thesis gives and overview about the hardware design of the project. To have maximum flexibility and control over the environmental parameters it is needed to compile illumination and irrigation modules. These modules should be capable of working autonomously whit "last known good configuration". For implementing the control and data acquisition processes Atmega328 and Atmega2560 MCU-s have been selected enabling needed I2C, 1-Wire and Ethernet communications and I/O ports with PWM capabilities and ADC-s for precise actuator control and reading sensor data.

2.2 Data Acquisition

Responsible for collecting data and buffering it to upper system layers are the Atmega328 and Atmega2560 MCUs. Sensors used to get readings divide by functionality as:

- Temperature
- Ultrasound
- pH
- EC
- Humidity
- Hall Effect
- Real Time Clock

The measurements are critical for the system to have feedback from the growing environment allowing

2.2.1 Measuring Temperature

Temperature can be measured in various ways including thermocouples, thermistors or digital IC sensors. As in the current application a MCU is the centre piece of data collection a sensor with digital interfacing is a logical choice. DS18B20 [3] sensors are used to monitor the temperatures of incoming, exiting airflow, water and growing area. DS18B20 sensor enables to measure temperatures in the range of -55…..+125 ℃ with measurement accuracy of +-0.5 ℃, providing 12 bit resolution for the readings, meaning in 0.0625 ℃ steps. Fetching the data from sensors is done via 1-Wire bus [4] which is a simple signalling scheme developed by Dallas Semiconductor (now Maxim). The basis of 1-Wire technology is a serial protocol using a single data line plus ground reference for communication. A 1-Wire master initiates and controls the

communication with one or more 1-Wire slave devices on the 1-Wire bus. Each 1-Wire slave device has a unique, 64-bit identification number, which serves as device address on the 1-Wire bus. The sensor can be powered by an external supply on the V_{DD} pin, or can be operate in "parasite power" mode, which allows the DS18B20 to function without local external supply. As in the current application 5 V supply is available from the MCU external power configuration is used as seen on Figure 5 [3].
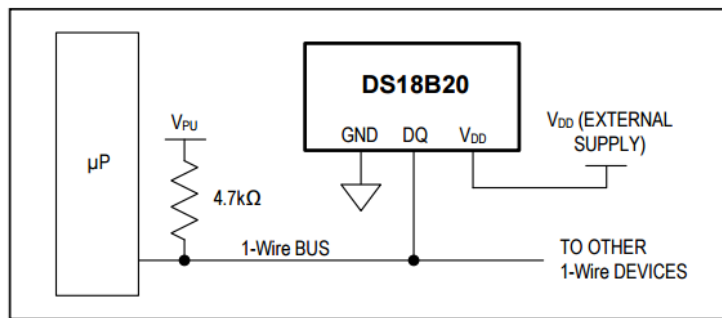

Figure 5.DS18B20 with external power supply [3]

2.2.2 Measuring Water Level

Continuous monitoring of the water level is needed to calculate proper nutrient levels and balancing of pH. For this purpose ultrasonic ranging module HC SR04 [5] shown on Figure 6 is chosen. This sensor enables to monitor the water level without contact to the nutrient solution, it is cheap and widely available. The sensor provides a sensing range of 2 cm-400 cm which suits the needs of measuring water level in a 10cm deep tank with the accuracy of 3mm. For measuring a short 10uS trigger pulse needs to be sent to the module to initiate an 8 cycle burst of ultrasound at 40 kHz and raise of the echo. The range can be calculated from the time interval between the trigger and echoing signals as

$$Distance = \frac{Time * Speed\ of\ Sound}{2}$$

It is also necessary to keep in mind the 30 degree angle of the ultrasound beam when installing the sensor not to get false readings from tank walls. For connecting the sensor to the MCU 4 pins need to be connected GND, +5 V and two digital I/O pins for the Trigger and Echo.

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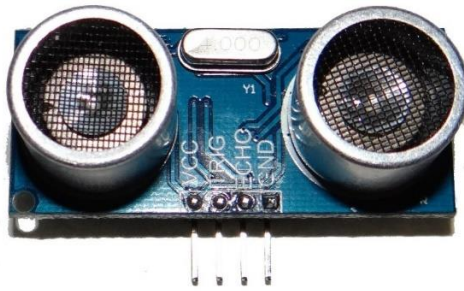
Figure 6. Ultrasonic module HC SR04

2.2.3 Measuring pH

pH refers to the potential hydrogen-hydroxyl ion content of a solution, it is measured on a logarithmic scale of 1-14 with 7 being neutral. Acids are lower than 7 and alkalis (bases) are above 7. Pure distilled water has a balance of hydrogen (H+) and hydroxyl (OH-) ions and is therefore pH neutral (pH 7). Steady measuring the pH of the circulating solution is very important for maintaining acceptable conditions for the plants. When the pH is not at the proper level the plants will lose the ability to absorb some of the essential elements required for healthy growth.

Figure 7. How pH affects nutrient uptake and availability [6]

The pH level is measured with a glass electrode probe [7] which acts as a high impedance voltage source. The potential difference of two e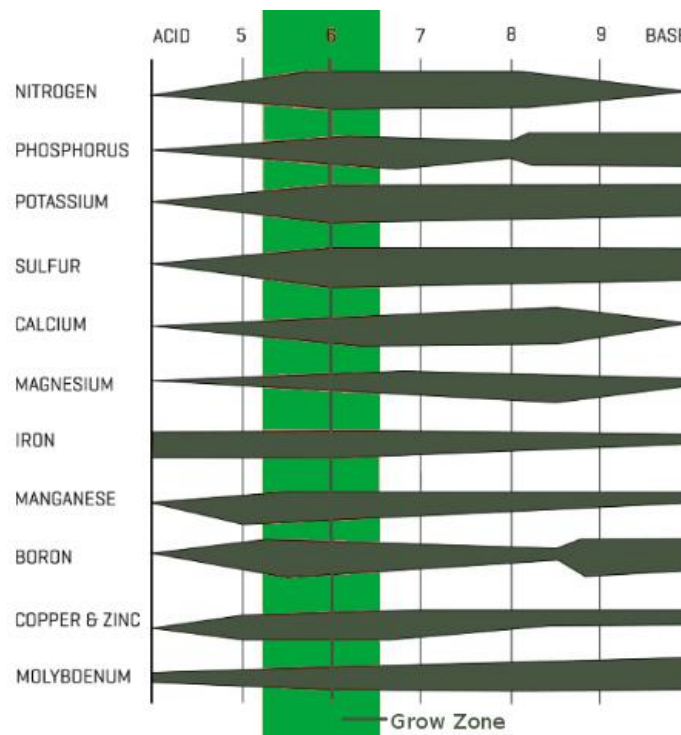lectrodes placed inside the probe is measured. One electrode being submerged in a controlled solution giving a reference and the other electrode being influenced by the solution being measured. The potential of electrochemical cell as a function of concentrations of ions taking part in the reaction is described by Nernst [8] equation :

$$E = E_0 - k \cdot T \cdot pH$$

Here E represents the voltage of the electrode, E_0 – sensor specific constant, k – Boltzmann constant, T – temperature of the solution in Kelvins and pH representing the pH level of the solution measured. This equation makes it possible to convert the difference of electrode potentials into an understandable pH reading.

To get the data readings from the probe a conversion and amplification schematic needs to be added. For this purpose a good and solution has been developed by Sparkyswidgets [9]. The circuit amplifies the signal to be processed by a 12 bit ADC IC that has I2C interfacing for easy data acquisition with the MCU.
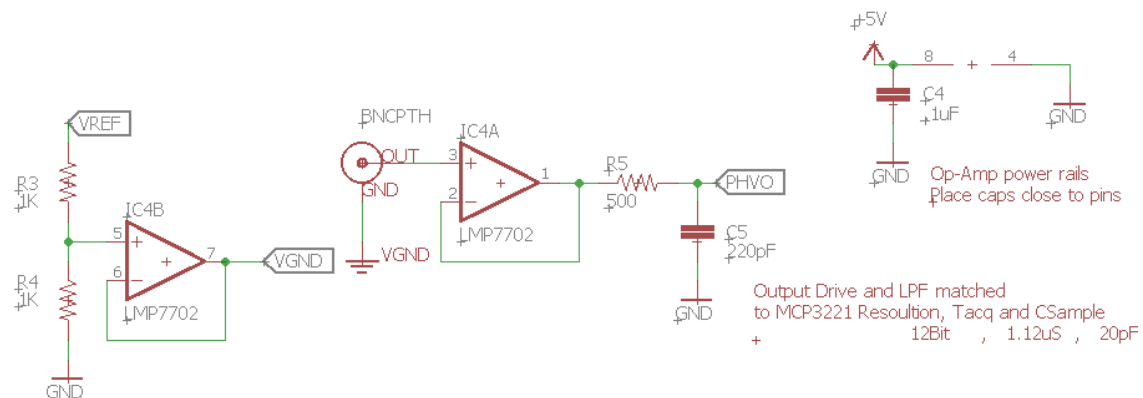
Figure 8. Analog front end of conversion circuit for the pH probe [9]

2.2.4 Measuring EC

In aeroponics all nutrients are made of mineral salts, which are dissolved into water. Different plants grow well at different levels of nutrient strength, and it is important to control this nutrient strength to provide the optimal conditions in the root zone, which in turn allows the maximum uptake of the nutrients into the rest of the plant's cellular

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structure [10]. The strength of the nutrient solution can be measured by measuring the electrical conductivity of the solution.

EC meters consist of two electrodes spaced 1 centimetre apart, which are placed in the solution. When power is applied an electrical current passes from one electrode through the solution to the other electrode and the conductivity of the solution can be measured. Electrical conductivity can be expressed using a number of different units but the international standard is EC, and the unit of measurement is usually milliSiemens/cm.

For the current application a commercially designed conductivity probe [11] is being used, that has platinum coated electrodes to prevent corrosion and make it work correctly longer. For getting the readings from the probe it is necessary to have an excitation circuit shown on Figure 9 with creating alternating current to avoid electrolysis. A Wien bridge oscillator is used to generate +/-5 V excitation sine for the electrodes and a 12 bit ADC with I2C interface MCP3221 [12] is used to make the measurement data easily accessible by the MCU.
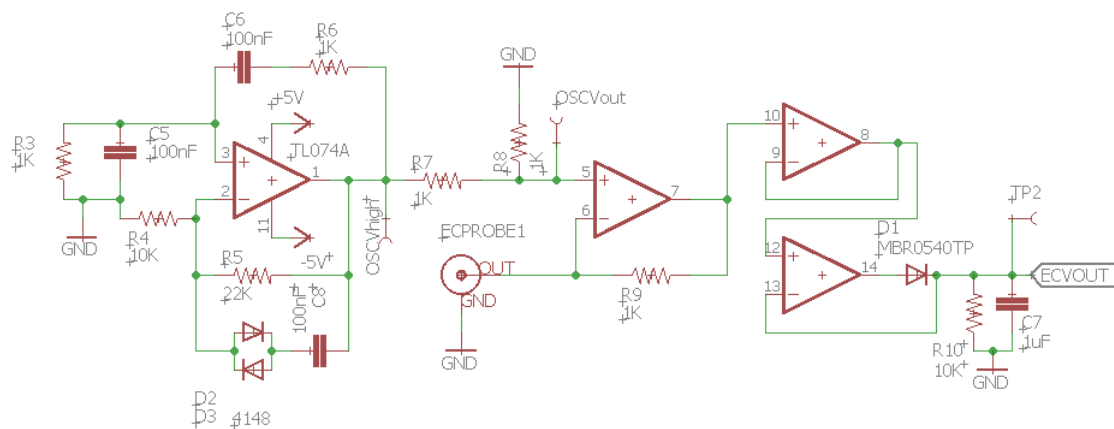
Figure 9. Analog front end of conversion circuit for the EC probe[13]

2.2.5 Measuring Humidity

For measuring humidity DHT22 [14] sensor is used. This sensor includes a resistive type humidity measurement component and an NTC temperature measurement component, and can be connected to a high performance microcontroller. The humidity sensing component has two electrodes with moisture holding substrate between them. As the humidity changes the resistance between the electrodes changes. This change in the

resistance is measured and processed by the IC which makes it ready to be read by a MCU. For connecting GND, +5 V and one digital I/O pin is required. Single-bus data is used for communication between the DHT22 and the MCU.

Figure 10. DHT22 sensor with casing

2.2.6 Proximity Sensing

There is a wide variety of different proximity sensors available on the market including capacitive, inductive, optical, radar, ultrasoni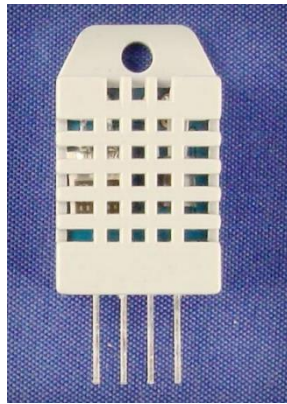c, fibre optics to name a few but most of them are very expensive and too advanced for the current application. In this project proximity sensing is needed for nutrient end stop sensing and this is done by taking advantage of *Hall Effect* [15]. Current consists of the movement of charge carriers. When a magnetic field with a perpendicular component is introduced the carriers experience *Lorenz force* [16]. The magnetic field interrupts the flow of charge carriers pushing the moving charges to accumulate on one face of the material. This leaves equal and opposite charges exposed on the other face where there is scarcity of mobile charges. The separation of charge establishes an electric field that opposes the migration of further charge and so a steady electrical potential is established for as long as the charge is flowing making it possible to measure the proximity of a magnet to the sensor.
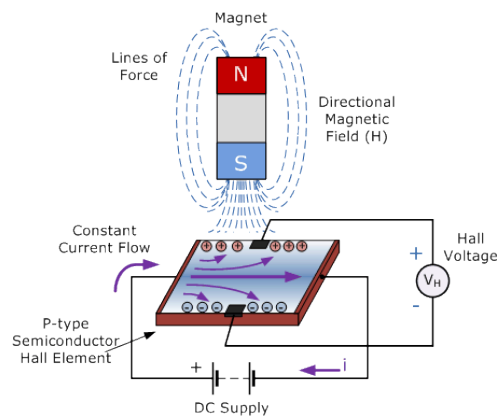

Figure 11. Working principle of Hall Effect sensor

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Hall Effect sensor US5881 [17] is chosen because of low operation voltage 3.5-24 V making it possible to attach it directly to the MCU for getting the readings.

2.2.7 Real Time Clock

For adding a timestamp to all the data sent to upper layers from the MCUs a RTC chip needs to be added. An integrated real time clock circuit DS1307 [18] with the operating circuit shown on Figure 12 is used for this. The chip has an I2C interface that makes data acquisition is very easy.
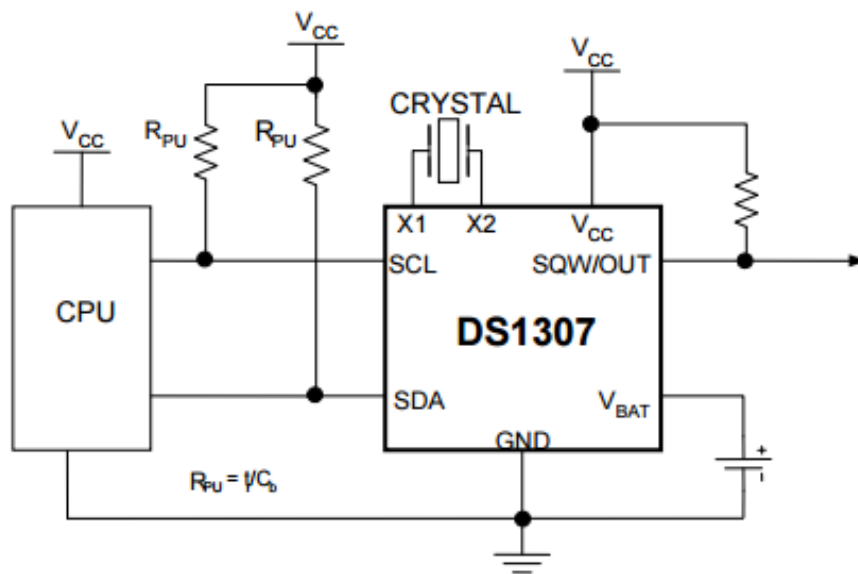
Figure 12. DS1307 RTC operating circuit [18]

2.3 Design of Illumination Module

As high end grow light modules are very expensive ranging from 200-1000 € for a 50 W module and cheaper ones lack digital control capabilities. It is needed to design a new module for this project. As LEDs are more efficient light sources than other options it is decided to go with this solution. To have enhanced control over the vegetation and blooming period it is wise to use LEDs with different light spectrum: red ~650 nm and blue ~450 nm for controlling microprocesses in photosynthesis throughout plant's lifespan.

Figure 13. Chlorophyll production versus light spectrum

Relatively cheap LED strips can be found with a nice aluminium package to help dissipate heat and proper resistors already in place on the strip for current control. The strips chosen are 10 W XJLED grow LEDs that conveniently have the desired blue and red light spectrum available for the price of 20 € for 5 pcs. For one module 5 red and 5 blue strips are used. For powering one module a 10x10 W=100 W 12 V power supply is needed and for digital control a switching circuit needs to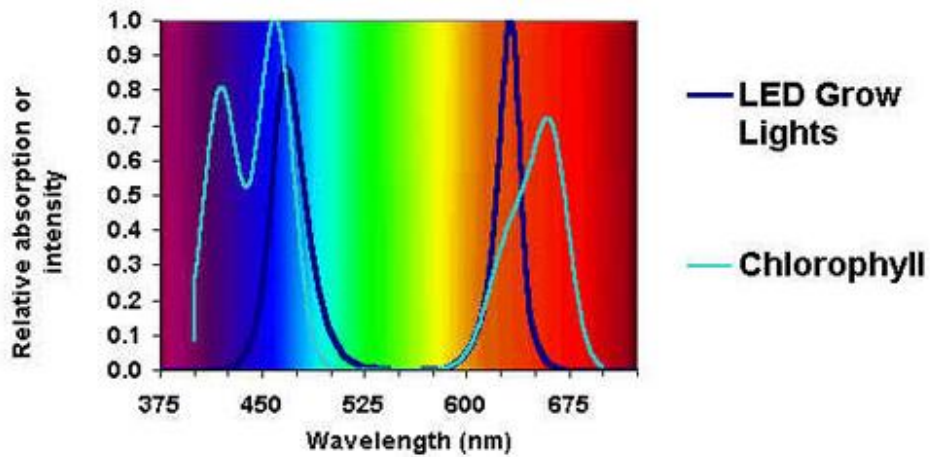 be added. In designing the switching circuit it wise to include dimming capability to better emulate the suns daily cycle and reduce the plants stress in the artificial environment.

For digital control Atmega328 MCU is used making it possible to dim the lights using the PWM output pins and to communicate with higher system layers. Technical specifications of the board can be seen in Table 1.

Table 1. Technical specifications for Atmega328 development board [19]

Microcontroller	ATmega328P
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limit)	6-20V
Digital I/O Pins	14 (of which 6 provide PWM output)
PWM Digital I/O Pins	6
Analog Input Pins	6
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	32 KB (ATmega328P)
	of which 0.5 KB used by bootloader
SRAM	2 KB (ATmega328P)
EEPROM	1 KB (ATmega328P)
Clock Speed	16 MHz

The choice to use a development board comes from the need to update system firmware quite often during testing and having a convenient USB plug for that is very handy. Keeping the MCU board and switching circuitry separate makes it also easy to change the MCU without having to make too many changes on the circuitry. Ethernet shield [20] is added to the board for communication with the upper layer services.
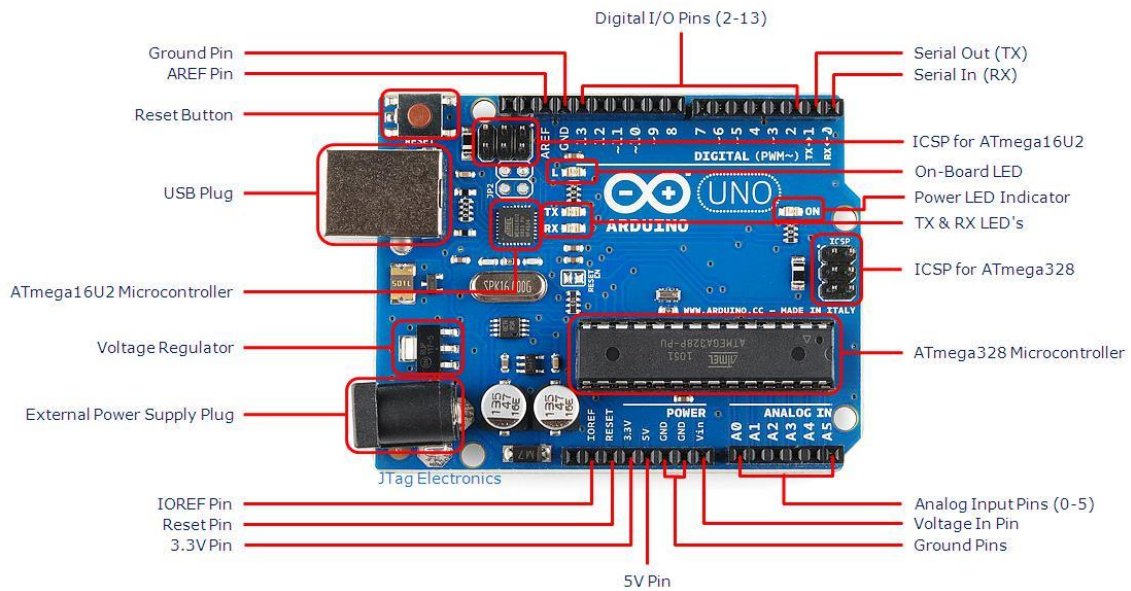
Figure 14. Arduino Uno development board with Atmega328 MCU [19]

As five LED strips will be grouped together it is needed to deliver $\frac{10}{12} * 5 = 4.167\ A$ current to one group. The simplest and cost effective solution for dimming the LED strips with the chosen MCU is to use a MOSFET for the drive circuit. When choosing the right MOSFET for the job it is wise to keep in mind the MCU drive voltage 5 V and the 4.167 A load current needed. An N-channel MOSFET IRL44N [21] is chosen for this.

Calculation of the power dissipated in the MOSFET switching device is needed to be sure the circuit is safe to run. Taken from the datasheet of IRL44N:

Drain source resistance at V_{GS}=5 V drive voltage is R_{DS}= 0.025 Ω. To be safe an extra 20% of resistance is added to the equation R_{DS}= 0.03 Ω.

The thermal power generated in the MOSFET expresses as $P_{loss} = R * I^2$

$$P_{loss} = 0.03 * 4.167^2 = 0.521\ W$$

Thermal resistance for Junction to Ambient is given $T_{\emptyset JA} = 62 \, ^{\circ}C/W$ so the overall heating of the given transistor at maximum load and ambient temperature of $T_{Ambient} = 25 \, ^{\circ}C$ can be calculated as

$$T_{total} = T_{\emptyset JA} * P_{loss} + T_{Ambient} = 92.3 \, ^{\circ}C$$

Maximum working temperature is given in the datasheet as 175 °C but to be safe and protect the MOSFET a heat sink is added to the device.

As the IRL44N is a logic-level gate driven device it is possible to switch it directly with the MCU. Adding a 10 K pull down resistor keeps the MOSFET closed while the MCU is booting and helps to pull down the gate while closing the switch. A 100 Ω resistor is connected in series with the gate for protection of the controller and a flywheel diode is added across the load for MOSFET protection when switching the inductive loads of fan motors.
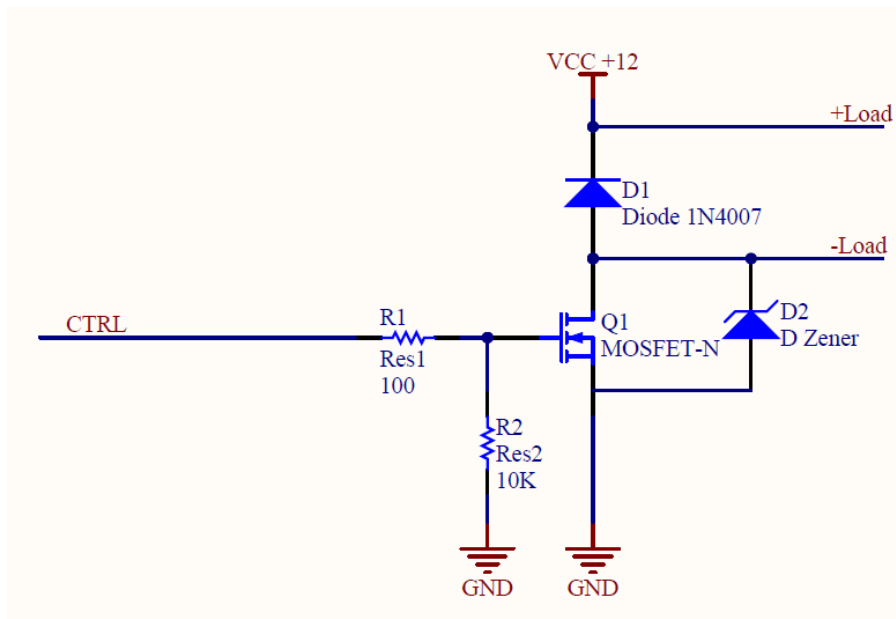
Figure 15. One channel MOSFET switch

To keep the heat dissipated by the high power LED strips under control and to create small vibrations [22] for the plants to grow stronger there are ventilators added for both intake and blowout. Using DC powered fans it is also possible to use a MOSFET circuit for control. As the motor load is inductive, a flywheel diode is connected across the inductive load to dissipate any back EMF generated by the motor when the MOSFET turns "off" and an additional Zener diode connected across the channel of the MOSFET

switch suppressing over voltage switching transients and noise giving extra protection for the device.
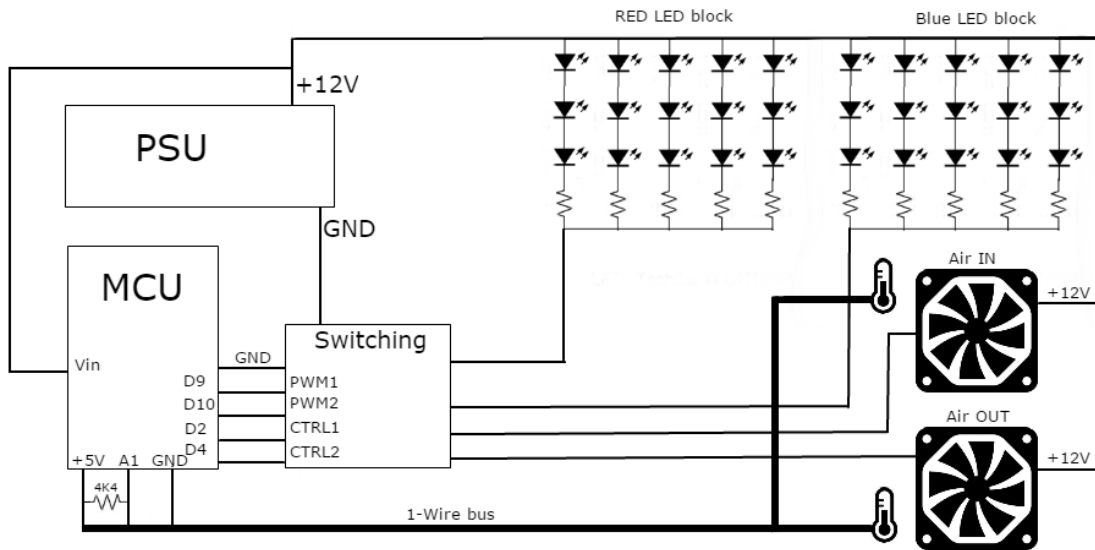
Figure 16. Structural diagram of the illumination module

2.4 Design of Irrigation Module

The irrigation module is responsible for delivering nutrients and water to the plants roots and maintaining a stable environment. For monitoring the parameters of water ultrasound, pH, EC, Hall Effect, Humidity and temperature sensors are used as described in paragraphs 2.1.1-2.1.4.

Figure 17. Structural diagram of the irrigation module

2.4.1 Balancing the Solution

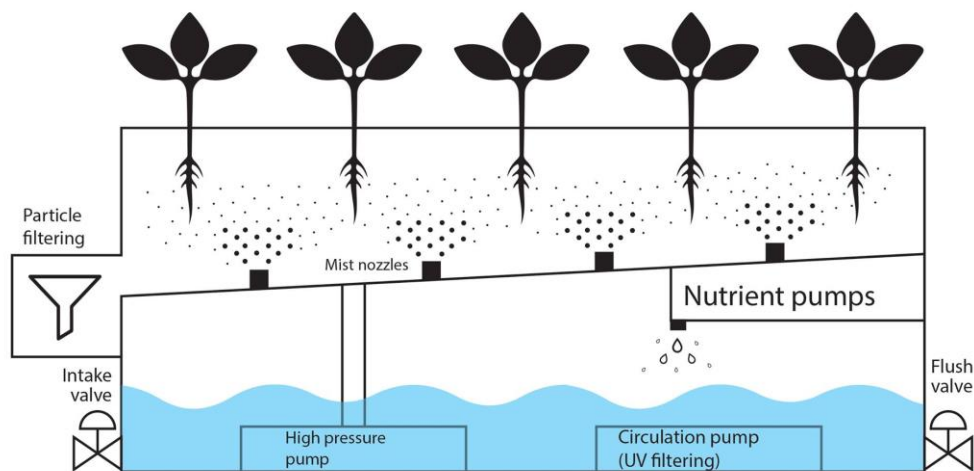Ideally the pH of the solution should be between 5.2-6 at all times and the EC level should be suitable for the current plants being grown [23] for example 0.6 – 1.4 for lettuce or 2.2-2.8 for tomatoes. In the start of growing cycle the nutrient solution reservoir is filled with distilled water.

To keep the solution under control while circulation two feedback loops with sensors and nutrient pumps are employed. To have a very precise balancing of the solutions pH level and adding nutrients a special pump is needed. This precision pump is constructed based on an open hardware idea of a cell struder for 3D printers [24]. This pump works by turning a lead screw with a stepper motor and very accurately moving the syringe pusher attached on the lead screw by a nut. By knowing how many turns it takes to empty the syringe it is possible to easily calculate the amount of liquid extruded by every motor step. Connected to the syringe are two solenoid valves used for allowing to add solution to the tank or refilling the syringe with fresh solution, when refill valve is open the output valve is closed and vice versa. To know when the pump has reached an end point two small Hall Effect sensors are placed on both ends of the duty cycle and are being activated by the neodymium magnets attached to the syringe pusher.

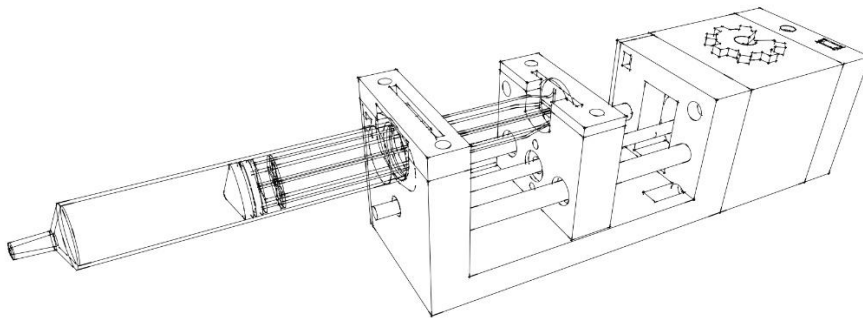Figure 18. Open hardware syringe pump [24]

Frame of the pump can be easily 3D printed and assembled but driving the NEMA23 [25] stepper motors there is a need for a driver circuit. For this purpose A4988 [26] DMOS microstepping driver with translator and overcurrent protection is selected. Heat sing is placed on top of the IC for circuit protection. The application schematic of the driver can be seen on Figure 18.
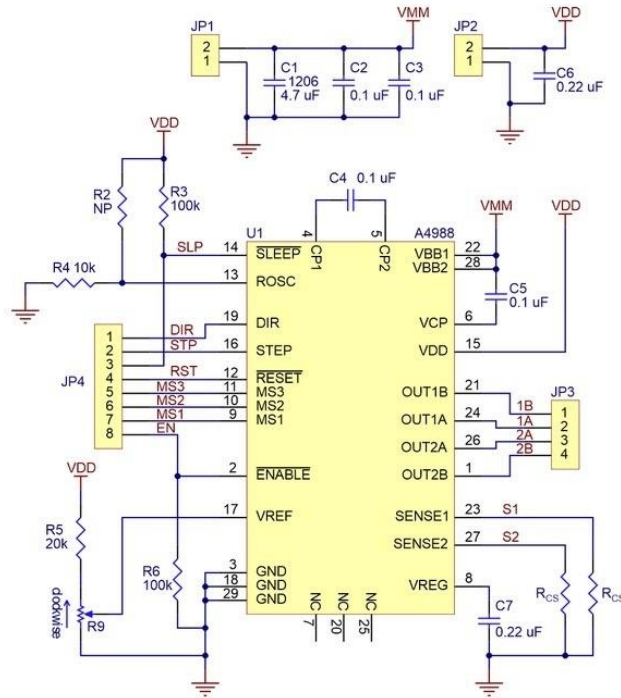
Figure 19. A4988 stepper motor driver application schematic [26]

The microstepping mode is controlled by three MS inputs of the driver [26]. Inputs can be set to low (GND) or high (5 V) according to Table 1. To change the step resolution.

Table 2. Setting step resolution [26]

MS1	MS2	MS3	Resolution
Low	Low	Low	Full step
High	Low	Low	1/2 step
Low	High	Low	1/4 step
High	High	Low	1/8 step
High	High	High	1/16 step

The motor has 200 full steps for one 360 degree rotation. One 360 degree rotation of the lead screw the nut screw is being dislocated 1.22 mm. For achieving the maximum precision 1/16 step mode is selected meaning one rotation will have 200x16=3200 microsteps, bringing the syringe movement accuracy to $\frac{1,22}{3200}$ =318.125 nm. A syringe with an inner diameter of 20 mm is used for moving the liquids. From here the amount of dispersed liquid can be calculated by applying simple geometry for one microstep as:

$$\pi * (0,01m)^2 * 318.125 * 10^{-6}m = 3.142 * 10^{-10}m^3 = 3.142 \text{ µ}l$$

To have full control over the nutrient solution at least 2 pumps are needed. One pump is needed to pull down the pH level as water has a tendency to pH+ over time and the other pump is for adding nutrients.

If the system recognizes that the solution pH or EC levels have passed the point of no return, meaning that adding pH stabilizer or nutrients cannot improve the situation then the tank is flushed by opening the flush valve and fresh neutral water is let in trough the intake valve to mix a new balanced solution. The intake has also the purpose of maintaining sufficient amount of water in the solution tank. Water level is monitored with an ultrasound sensor continuously and water is added accordingly. Although the grow box is almost a closed environment the plants still evaporate a mentionable amount of water trough leaves and body.

2.4.2 Circulation of Solution

To deliver the nutrient solution to the root system it is needed to spray the solution as 5-50 nm droplets for the roots to have maximum access to oxygen and nutrients. This is done with a high-pressure pump [27] pushing the solution trough spray nozzles at 80 psi. The spray interval can vary and in finding the optimum will require the deep learning process to go through some trial and error periods but it should stay around 1 second spray time and 4-15 seconds of drying time for the roots to breathe and grow stronger. The excess solution drips back down and goes through a backflow wool mesh filter where particles are isolated from the solution. In the solution tank there is a second pump for circulating the water. This pump [28] includes a sponge filter and UV LEDs preventing the growth of floating algae, protozoa and bacteria, which results in clear water and healthier environment for the plants.

2.4.3 Digital Control and Switching

For the irrigation module Atmega2560 MCU is chosen to be responsible for fetching sensor data, manipulating the pump cycles and opening/closing solenoid valves for liquid flow. Arduino Mega development board [29] seen on Figure 20 with technical specifications seen in Table 3 is used to ease making the firmware updates while testing software configurations. An Ethernet shield [20] is added to the board for communication with higher system layers.

Figure 20. Arduino Mega development board for Atmega2560 [29]

Table 3. Technical specifications for ATmega1228 development board [29]

Microcontroller	ATmega2560
Operating Voltage	5V
Input Voltage (recommended)	7-12V
Input Voltage (limit)	6-20V
Digital I/O Pins	54 (of which 15 provide PWM output)
Analog Input Pins	16
DC Current per I/O Pin	20 mA
DC Current for 3.3V Pin	50 mA
Flash Memory	256 KB of which 8 KB used by bootloader
SRAM	8 KB
EEPROM	4 KB
Clock Speed	16 MHz

Since the solenoid valves and high pressure pump are driven by 12V DC and current ratings fall in to the range of IRL44N MOSFET capabilities it is possible to use a simple transistor switching circuit with flywheel diode as described in chapter 2.3. For the circulation pump no extra switching circuit is needed because it needs to run at all times being turned off only for maintenance.

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2.5 Design of the Operational Layer

For the operational layer a CPU is needed with enough computation power to handle recipe handling services. Any computer with Ethernet connectivity would basically work but a relatively cheap and very compact minicomputer Raspberry Pi 2 seen on Figure 21, [30] is used for this purpose in the current project.

Technical specifications for Raspberry Pi 2 B

- Broadcom BCM2837 Arm7 Quad Core Processor powered Single Board Computer running at 900MHz
- 1GB RAM
- 40pin extended GPIO
- 4 x USB 2 ports
- 4 pole Stereo output and Composite video port
- Full size HDMI
- CSI camera port for connecting the Raspberry Pi camera
- DSI display port for connecting the Raspberry Pi touch screen display
- Micro SD port for loading operating system and storing data
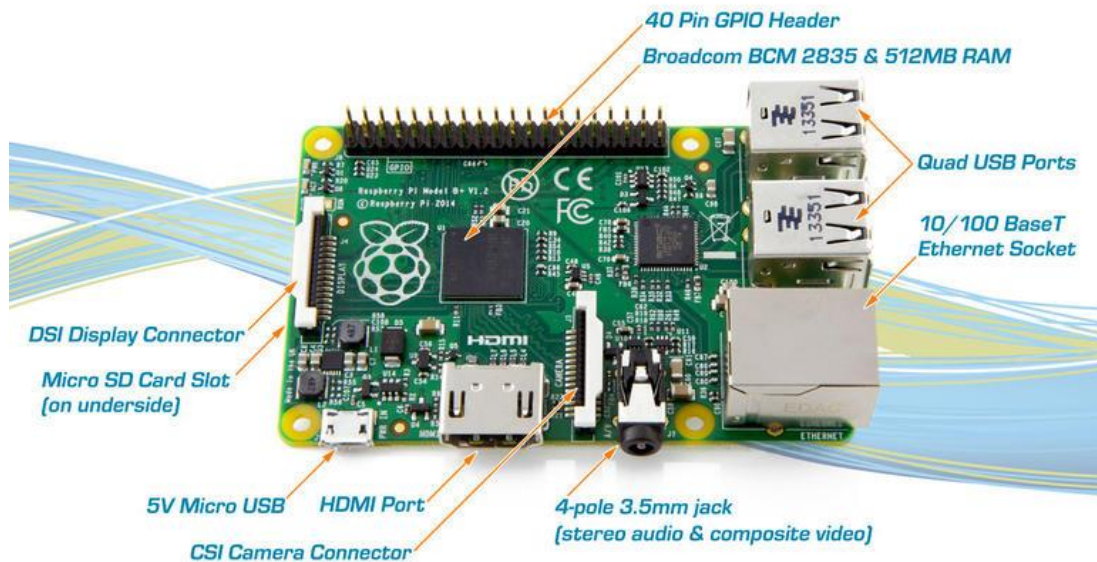- Micro USB power source

Figure 21. Raspberry Pi 2 B board [30]

3 Software Design

This section of the thesis will give an overview of the software part of the project. System software divides into three main parts as the firmware of control MCUs, event services running on Pi and the deep learning algorithms running in the cloud. As for machine learning and data science is a whole separate field of study the development of this software is not discussed very deeply in this thesis.

3.1 MCU Firmware

The MCU firmware consists of device drivers and a conditional loop matrix that is based on the devices connected to a specific MCU. Parameters of this loop matrix can be reconfigured on the fly by upper level instructions such as changing a recipe from the UI or if the deep learning process has calculated better values.

Device drivers

- DS18B20 Temperature sensor Driver
- HC-SR04 Ultrasonic sensor Driver
- MinipH sensor Driver
- MiniEC senror Driver
- DHT22 Humidity/temperature Driver
- GPIO controller Driver
- LED PWM Driver
- A4983 motor control Driver
- RTC Driver
- Ethernet Driver

All the measurement, orchestration and switching processes break down to events. Every time there is a switching or measuring event a publish is made from the side of MCU in the form of [timestamp;key();value()] to MQTT. On the Pi side the received key();value() is propagated through a binary neural network.

When a recipe has an in time changing parameter then the Pi publishes a key();value() parameter list to the MCU. But at the same time all events are processed through a neural network that can recognise environmental patterns and will try to compensate them to achieve the ideal possible conditions.

On the example of pH level control seen on Figure 22 the basic idea how all the processes cycles are run can be explained. A pH measurement event can be triggered by a parameter rule saved in the EEPROM memory, another event function or by a random function request coming from Pi.
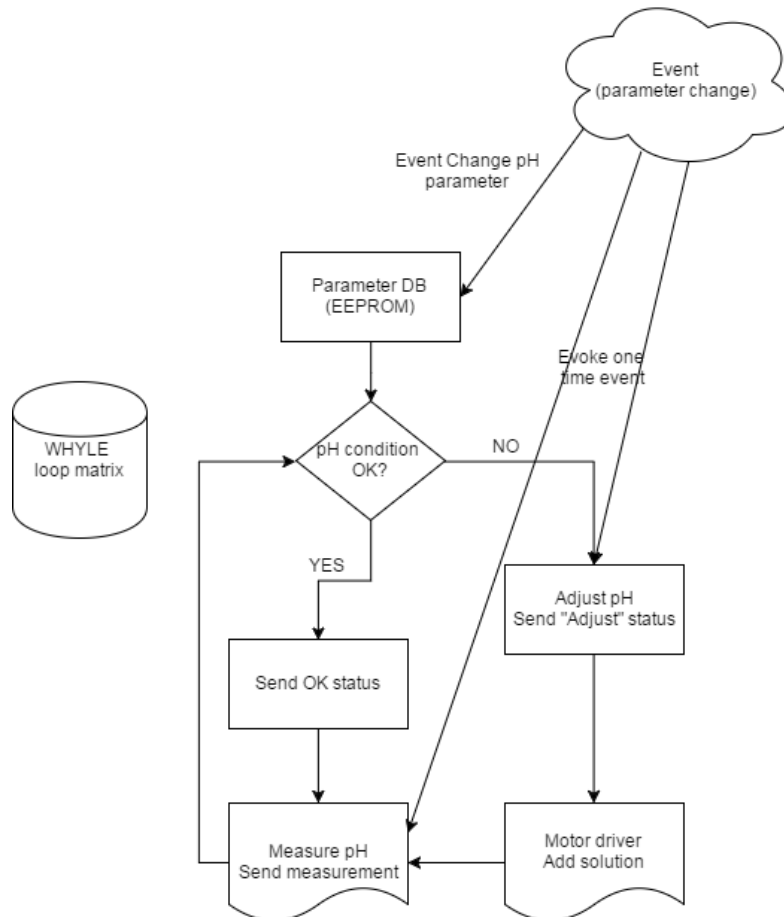

Figure 22. Cycle of pH control and recipe change

3.2 Operational Layer Services

The CPU is running Linux Raspian operation system and facilitating Mosquitto for publish-subscribe data exchange, Postgre database, and application services described on Figure 23.

In a publish-subscribe pattern the senders of messages, called publishers, do not program the messages to be sent directly to specific receivers, called subscribers, but instead characterize published messages into classes without knowledge of which subscribers, if any, there may be. Similarly, subscribers express interest in one or more classes and only receive messages that are of interest, without knowledge of which publishers, if any there are.
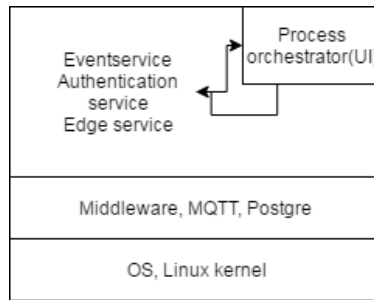
Figure 23. Service integration diagram for Raspberry Pi

3.3 Deep Learning Layer

The deep learning process takes place on a high power server. All the event data generated in the functional and operational layer is transformed into a binary data stream and fed into the learning algorithms, this process is described on Figure 24. There can be thousands of devices sending data and these devices do not need to know of each other's existence. The gathered data goes through extensive analysis. During this new decision functions are being created through the evolution model. These new "smarter" decision functions are fed back to the devices to improve system performance.
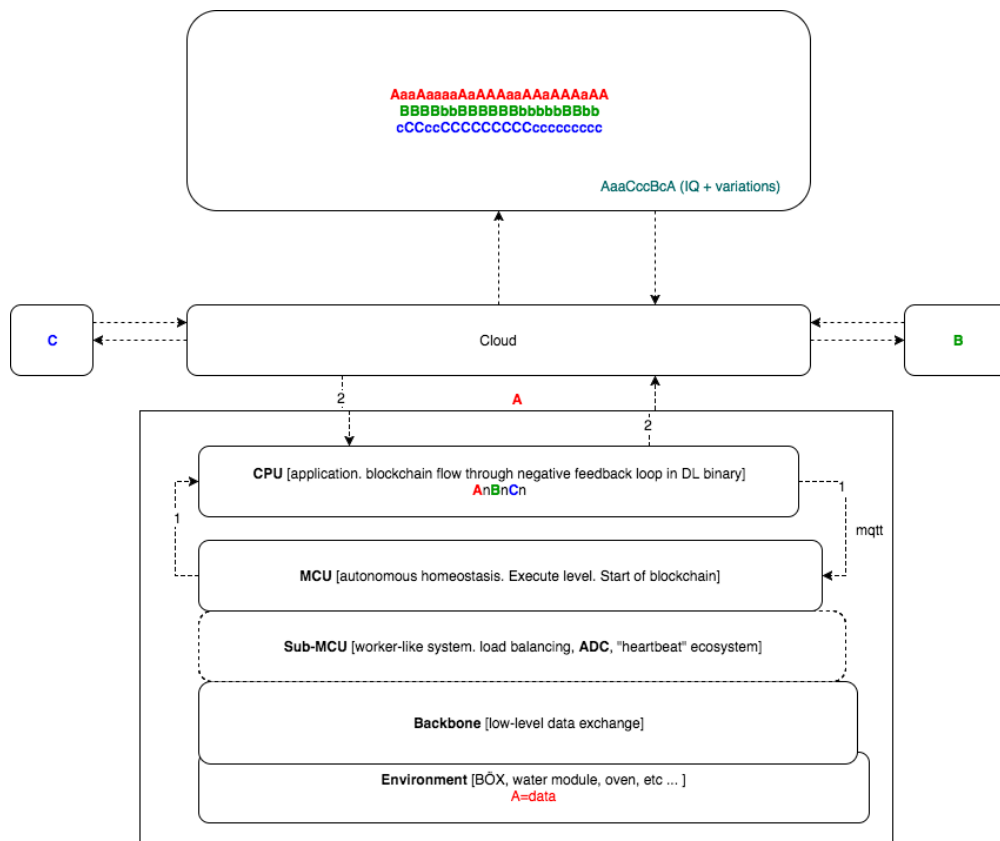

Figure 24. Deep learning data stream diagram

4 Possibilities for Future Developments

As all the components of the system are built to be modular, different parts can be replaced in future versions of the box without changing the basic architecture. Additional sensors can be added to get better overview of the state of the environment and system processes and more actuators added for in-depth parameter control. As the systems level of sophistication increases it might be needed to add more powerful MCUs or use some other platform instead of the Raspberry Pi in Operational layer.

For consumer products additional HMI can be added to the system for maintenance information and recipe change when switching between different plant strains. For this a touch screen [31] could be used displaying system parameters and for input from the user.
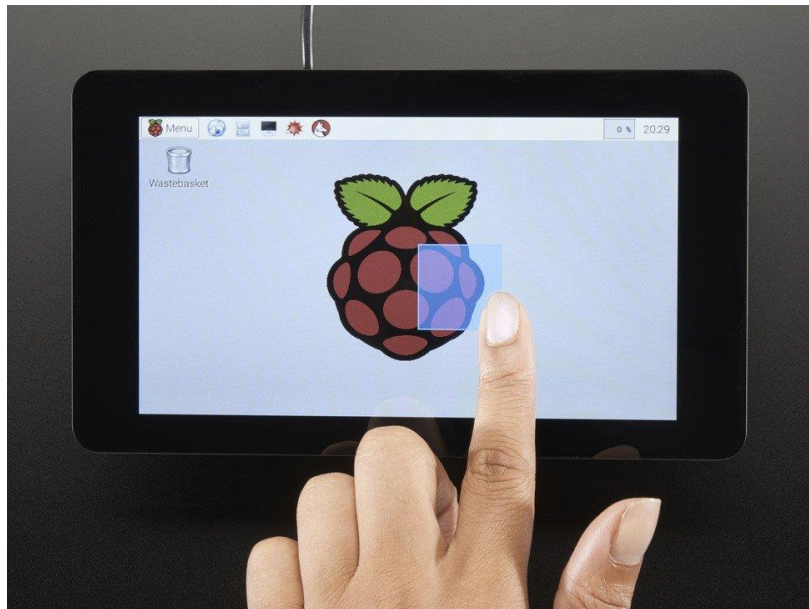

Figure 25. Touch screen for Raspberry Pi [31]

In theory Operational and Deep learning layers could be merged together so the MCU would get the parameter reconfiguring straight from the cloud.

After thoroughly testing the whole system with cloud and deep learning the operational layer software and functional layer designs will be published, making it possible for anyone to build their own farming box. The general idea behind making the software and design publicly available is to incorporate developers and get more data for the teaching/learning of the neural network. Having a lot of data vectors will act as an amplifier for the learning process making it much faster and accurate. These

advancements will help the system gain popularity and applications outside of consumer market and enthusiast circles.

The aim is to reach out to wide range of end users both in consumer and industrial level to have as many variations of biomass growth as possible and in this process teach the "brain" of the system to be a super farmer. As there are several ongoing projects for space exploration [32] the developed system would be a suitable solution for growing biomass on board spaceships on long lasting space travels or bases on other planets.

5 Summary

The purpose of the thesis was to design a proof of concept hardware solution for small scale aeroponic farming with the capabilities of data acquisition and digital control to enable machine learning implementation. A fully functional solution was developed during the thesis. Special hardware and software were developed according to the specifications laid out in the beginning of the design process.

Two hardware modules were created capable of following given recipes to fully take advantage of aeroponic farming potential and giving precise measurements of the ongoing processes in the system for feedback.

The illumination module allows to control the light spectrum and density with digital dimming. Two groups of LED lights red ~650 nm and blue ~450 nm can be dimmed separately from each other to give the right spectrum of light to the plant according to the stage of growth cycle. The module also gives temperature readings of incoming and outgoing airflow back to upper layers. The financial aspect is a bit hard to calculate since some of the components used were recycled from old electronics but if to buy everything the price range of the build would come to around 100 € for a 100 W module what is considerably cheaper than commercial products on the market.

The irrigation module allows to precisely control the nutrient solution pH and EC levels and gives data about humidity, temperature, pH level, EC level and amount of solution in the nutrient tank. The measurement and process data can be compiled into a stream of data for deep learning algorithms to start making estimations and optimizing the workflow of hardware and biomass growth.

As growing plants is a relatively slow process it takes much more than one box to gather enough data for the neural network to show remarkable advancements but this thesis gives a good beginning platform for the realisation of machine learning in food production.

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Appendix 1 – Amplification circuit layout for pH sensor

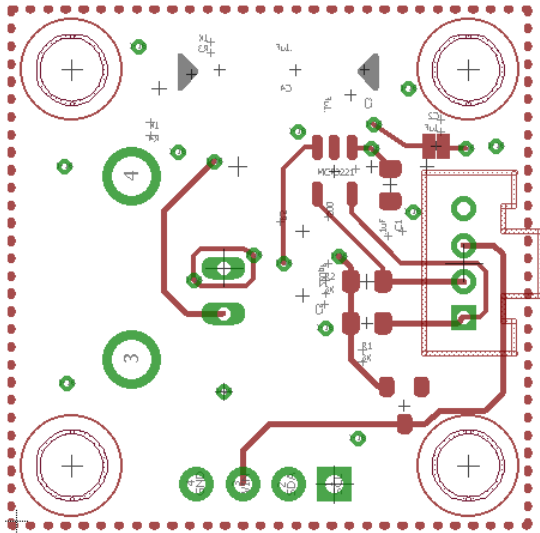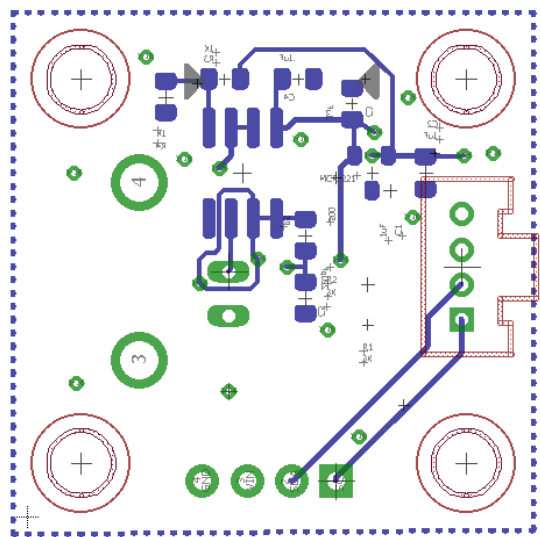Figure 26. Top layer

Figure 27. Bottom layer

Appendix 2 – Grow box

Figure 28. Grow box design

Figure 29. Assembled grow box