

Development of a Remote Control Software Platform for a Plant Factory

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Resumo

À medida que a população em países desenvolvidos se tem vindo a consolidar em centros industriais e ambientes urbanos, a indústria alimentar e agrícola gasta cada vez mais capital na movimentação e transporte dos seus produtos até aos locais de consumo. Adicionalmente, com a concentração de população nestes centros urbanos torna cada vez mais difícil e irrealista alcançar a produção necessária para sustentar tamanha multidão. Uma solução proposta foi a criação de *Plant Factories*, sistemas fechados que utilizam tecnologia com base em controlo de atmosfera e irrigação automática combinado com uma estrutura multinível que permite a criação de flora em várias camadas, multiplicando a quantidade de colheita por unidade de área. No entanto, estes sistemas necessitam de um controlo rigoroso da sua atmosfera e da qualidade do fluido de irrigação e, talvez mais importante de um ponto de vista prático, requerem um investimento inicial bastante avultado. Uma solução oferecida pela *Urban Crop Solutions* são os designados de *Plant Containers*, *Plant Factories* com uma dimensão muito reduzida alojados dentro de contentores navais. Estes sistemas serão mais adequados a negócios de menor dimensão como restaurantes que queiram criar os próprios alimentos. No entanto, de modo a otimizar as dimensões, soluções automáticas de movimentação das plantas no interior serão compactas e de difícil acesso, o que torna manutenção algo complicada. Nesta dissertação uma plataforma de controlo remoto foi desenvolvida que permite a resolução de problemas e a reconfiguração do sistema à distância, assim como a visualização do estado do sistema, com limitações diferentes para o cliente e um técnico de serviço. Este novo programa ajuda na manutenção e monitorização do sistema à distância, diminuindo os custos de manutenção e permitindo um funcionamento mais fiável do produto.

Abstract

As the population of developed countries has been consolidating in industrial centres and urban environments, the food and agricultural industry spends more and more capital on the transportation and movement of their produce to their end destination. Additionally, the sheer number of people in these urban centres means reaching the necessary levels of production isn't feasible or even realistic on a local level. A proposed solution was the creation of Plant Factories, closed systems that employ technology based on atmosphere control, automatic irrigation and a multileveled structure that allows for the growth of flora in multiple vertical layers, multiplying the yield per available area. However, these systems require a rigorous control over their atmosphere, irrigation fluid characteristics and, perhaps most important of all in a practical sense, require an initially high investment. Urban Crop Solutions offers an additional proposal in the form of Plant Containers, a form of Plant Factories with reduced dimensions housed inside naval cargo containers. These systems are more suited to smaller businesses such as restaurants that want to raise their own produce. However, to optimize this reduced size in regard to operational area, automatic solutions to move the plants in its interior have to be compact and of difficult access, which in turn means maintenance is somewhat cumbersome and impractical. In this dissertation a remote control platform was developed that allows for easier troubleshooting and system reorientation at a long distance, as well as the visualisation of the status of the system. This new program helps in the maintenance and remote monitoring of the system, lowering the costs of maintenance and allowing more product uptime.

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Table of Contents

RESUMO.....	III
ABSTRACT.....	V
ACKNOWLEDGEMENTS.....	VII
TABLE OF CONTENTS	IX
TABLE OF FIGURES.....	XIII
NOMENCLATURE	XV
1. INTRODUCTION	1
1.1. History of Plant Factories	1
1.2. Why Invest in Plant Factories?	1
1.3. Futurology: What’s Next for Plant Factories.....	2
1.4. Project Overview and Objectives	2
1.5. Summary and Structure of the Thesis.....	3
2. BACKGROUND STUDY ON PLANT FACTORIES.....	5
2.1. Plant Factories with Artificial Light.....	5
2.1.1. Cultivation room	6
2.1.2. Racks	6
2.1.3. Lighting system	6
2.1.4. Irrigation systems	7
2.1.4.1. Nutrient Film Technique	7
2.1.4.2. Deep Flow Technique.....	7
2.1.4.3. Aeroponics	8
2.1.4.4. Additional hydroponic irrigation systems	9
2.1.5. Atmosphere control.....	9
2.1.6. Sensors.....	9
2.1.7. Additional features	10
2.2. Advantages and Disadvantages of PFAL	10
2.2.1. Advantages	10

2.2.1.1. Resources	10
2.2.1.1.1. Water.....	11
2.2.1.1.2. CO ₂	11
2.2.1.2. Productivity	11
2.2.1.3. Precision Control	11
2.2.2. Disadvantages	11
2.2.2.1. Electrical efficiency.....	11
2.2.2.2. Initial costs	12
2.2.2.3. Operational Costs.....	12
2.2.2.4. Mitigation options.....	12
2.3. UCS' Plant Factory Containers	12
2.3.1. Gully racks	13
2.3.2. Germination rack	13
2.3.3. Ventilation system	14
2.3.4. Elevator	15
2.3.5. Technical Room.....	15
2.3.6. Irrigation system	16
2.3.7. Sensors.....	17
2.4. Growth cycle in a UCS FarmPro Container Unit	17
3. ASSEMBLY, QUALITY ASSURANCE AND TESTING PROCEDURES	19
3.1. Assembly	19
3.1.1. Mechanical assembly.....	19
3.1.2. Irrigation and ventilation systems assembly.....	21
3.1.3. Electrical Assembly	25
3.1.4. Finishing Touches to be realised at the consumer location.....	26
3.2. Quality Assurance and Testing Procedures	27
3.2.1. Lights.....	27
3.2.2. Tackers and Elevator.....	27
3.2.3. Irrigation	28
3.2.4. Sensors.....	28
4. CONTROL SOFTWARE	29
4.1. Remote control software user interface.....	29
4.1.1. Main menu	29
4.1.2. Emergencies Menu	30
4.1.3. Information Screen	31
4.1.4. Recipe Screen.....	32
4.1.5. Mode screen	32
4.1.6. Settings screen.....	34
4.1.7. Service screen	36
4.2 PLC Software.....	37
5. PAST ABNORMALITIES AND RISK FACTORS	39

5.1 Client “Harbour”	39
5.1.1. First Malfunction: Elevator Jammed.....	39
5.1.2. Second Malfunction: Blocked Irrigation	40
5.1.3. Third Malfunction: Pump Failure.....	40
5.2 Client “Port” – Mix Pump Failure	41
5.3 Client “Market” – Filter Error	41
5.4 Multiple Clients – Tacker Malfunction	42
6. DEVELOPMENT OF THE PLC CODE	43
6.1. Key Areas	43
6.2 Elevator	43
6.2.1 Rewriting Harvest Mode.....	43
6.2.2 Service Control.....	44
6.2.3. Consumer Control.....	46
6.2.4. Background check.....	46
6.2.5. Motor Commands.....	47
6.2.6. Mechanical Movement User Interface	48
6.3. Tackers	49
6.4. Irrigation	50
6.5. Lights	51
6.6. Overview Page	51
6.7. Test List	52
7. CONCLUSIONS AND FUTURE WORK	55
REFERENCES	57
APPENDIX A - REWRITTEN HARVEST MODE	59
APPENDIX B – REVISED SERVICE MODE GRAFCET	63
APPENDIX C – REVISED CONSUMER MODE GRAFCET	67
APPENDIX D –FINAL ELEVATOR BEHAVIOR GRAFCET	71

Table of Figures

Figure 1 - Diagram of a basic Plant Factory as seen in Urban Crop Solution’s website.....	5
Figure 2 - A UCS FP lighting system. Note how the first few rows have more LEDs	6
Figure 3 - Visual Representation of a NFT irrigation system (Lu & Shimamura, 2018)....	7
Figure 4 - Visual Representation of a DFT irrigation system (Lu & Shimamura, 2018)....	8
Figure 5 - Visual Representation of an Aeroponics irrigation system (Lu & Shimamura, 2018).....	8
Figure 6 - Gully Rack of a UCS FP with all gullies inserted.....	13
Figure 7 - 3D Schematic of a Container Unit Germination Rack.....	14
Figure 8 - 3D Model of a UCS FP Ventilation Sleeve	14
Figure 9 - 3D Schematic of a UCS FP Gully Elevator	15
Figure 10 - UCS FP Irrigation Drippers	16
Figure 11 - On the left: Elevator Sensors; On the Right: EC Sensor.....	17
Figure 12 - Representation of a UCS FP gully travel cycle.....	18
Figure 13 - An assembled Gully rack inside the container	20
Figure 14 - Empty container with the plastic floor mounted	20
Figure 15 - Metal profiles to help guide condensate towards the plastic floor.....	21
Figure 16 - Close up on the Tacker rail and irrigation gutter	22
Figure 17 - On the left: Automatic Filter; On the right: Basic filter for the backwash	23
Figure 18 - Peristaltic pumps used to mix nutrients and acid into the main tank	23
Figure 19 - Automatic Valves for the gully rack	24
Figure 20 - Close-up of the flow limiters installed on the drippers	24
Figure 21 - Water hose used for Germination rack irrigation and general cleaning.....	25
Figure 22 - Connections for the AC unit, electricity and water intake	26
Figure 23 - Main Screen UI	30
Figure 24 - Emergencies Screen UI.....	31
Figure 25 - Mode select screen UI.....	32
Figure 26 - Irrigation manual control UI	33
Figure 27 - Settings Screen water mixing UI.....	34
Figure 28 - Settings Screen Parameters UI.....	35
Figure 29 - Service Screen UI.....	36
Figure 30 - GRAFCET section highlighting the movement between Top Sensor and Resting position of Harvest Mode 3/4	44
Figure 31 - Prototype GRACFET for Service Mode movement	45
Figure 32 - Code snippet showcasing the manual control of the Tackers	47
Figure 33 - Prototype UI for the Mechanical Control screen	48
Figure 34 - Code Snippet of the Tacker forward movement	49
Figure 35 - UI for the Irrigation control Screen.....	50
Figure 36 - UI for the Lights control screen	51
Figure 37 - UI for the System Overview Screen.....	52
Figure 38 - UI for the Test Checklist screen.....	53

Nomenclature

PFAL – Plant Factory with Artificial Light

PFSL – Plant Factory with Sun Light

NFT – Nutrient Film Technique

DFT – Deep Flow Technique

EFS – Ebb and Flow Systems

DIS – Drip Irrigation Systems

EC – Electric Conductivity

RUE – Resource Usage Efficiency

WUE – Water Usage Efficiency

UCS – Urban Crop Solutions

FP – FarmPro

PLC – Programmable Logic Controller

PVC – Polyvinyl Chloride

RTU – Remote Terminal Unit

QA – Quality Assurance

UI – User Interface

LED – Light Emitting Diode

IEC – International Electrotechnical Commission

SCADA – Supervisory Control and Data Acquisition

ST – Structured Text

GRAFCET - Graphe Fonctionnel de Commande des Étapes et Transitions

UV – Ultra-Violet

Introduction

In this chapter the concept of Plant Factories is introduced along with its range of application and why they are used. It also seeks to justify the need for accurate remote control and many different sets of limitations for different users, as well as a brief report on the results and how they could influence future endeavours.

1.1. History of Plant Factories

The first step towards the creation of Plant Factories was taken in 1949 California, when the first greenhouse with temperature, lighting and atmosphere control was created. Shortly after, companies from Japan, a high-population nation with a diet focused on products derived from agriculture took an interest to the technology and imported these prototypes in hopes to develop them further (Hirama, 2015).

It took until the 70's for a company, namely Hitachi Ltd., to first begin experimenting with a multi-level approach, but the scope was still pretty limited. Shortly after American and Dutch universities have started to take a large surface approach, with natural and artificial light respectively, which lead to the idea of combining both and obtaining the first large scale multi-level Plant Factory in Japan.

Since then, the biggest progresses in the technology have been largely centred around improving the harvest yield, lowering the energy costs and other factors that might affect the production efficiency, utilising different farming methods more suited to automated solutions, namely utilising hydroponic cultures instead of traditional soil farming, and a more tight control over the atmosphere and general environment inside the unit.

1.2. Why Invest in Plant Factories?

With the ever-growing urban consolidation of populations in city centres, the ability to obtain fresh produce faces many increasing costs such as transportation costs (freight transports accounts for 8% to 15% of all traffic in major European cities (Tob-Ogu, et al., 2018)), and as lifestyle choices such as vegetarianism and veganism become more popular among the general population the demand for more vegetables keeps increasing.

1.3. Futurology: What's Next for Plant Factories

In addition, despite yearly world population growth facing a decline in recent years (Population Reference Bureau, 2019), world population is ever growing, in particular in countries like India who mostly consume flora. There is also a tendency for younger professionals to choose careers other than agriculture, especially in developed countries like the ones found in the European Union (Hosnedlová, 2018). All these compounded factors point towards the need to somehow modernise agriculture, and plant factories aim to do exactly that. In particular, plant containers like those manufactured by Urban Crop Solutions offer a compact and space efficient alternative to plant factories, making it ideal to local business that would benefit from fresh greens such as restaurants, laboratories and compounding pharmacies.

In general, plant factories have a much higher resource consumption efficiency compared to greenhouses and especially traditional farms. They also benefit from a much tighter control over its atmosphere and irrigation, and it is also free from the usage of pesticides, herbicides and insect infestation. More attention over the details on the advantages and shortcomings is given in section 2.2.

1.3. Futurology: What's Next for Plant Factories

The future is looking bright for plant factories. Some of the technologies involved in plant factories have already been implemented in NASA projects (Heiney, 2008), and it makes a reasonable assumption that plant container tech would be implemented in future space crafts. Plant factories' biggest upside, high resource usage efficiency, is a big issue when planning for long distance space travel. Being able to recycle water and consume CO₂ are both high importance factors in the act of interstellar travel theorizing. The compactness and space efficiency of plant containers is also appreciated. In fact, progress has already been made to try and incorporate company solutions into future space exploration projects (Vandecruys, 2019).

However not all future is beyond Earth. Plant factories could become a staple in common households if something like a "Plant Closet" (Kozai & Miyaki, 2014) is taken into consideration. Relatively small shelf arrangements with a basic irrigation and lighting systems could eventually be commercially viable to the general audience, and with the faster growth cycles consumers would be able to get frequent harvests.

1.4. Project Overview and Objectives

Plant factories require precise control in many aspects, be it irrigation, lighting control or atmosphere influencing factors such as CO₂ regulation, ventilation or humidity. As such, it is important to have an easy to use monitoring tool to quickly be able to visualize the state of the system and be able to properly assess any error that might occur. While it isn't possible to design a self-repair system with our current technology it would be beneficial to have a manual override control.

The proposed project involves the creation of such tools: a manual override mode for the consumer with certain limitations to stop them from damaging the container unit and a service mode only accessible via service admin password that removes most of these limitations. In addition, sensor information would be displayed in their respective UI. Finally, the integration of the testing checklist into the main program allows technicians to quickly and effortlessly determine the current state of the unit and what kind of adjustments it needs.

In order to achieve such an outcome, an initial study on the ins and outs of plant factories was realised, in particular focusing on the technology they use, their different implementations and possible operations. Then, a more thorough study on Urban Crop Solutions' products, namely the mechanical actuators and the PLC program. Finally, the project was developed as an add-on to the already developed program and tested on a local test unit.

1.5. Summary and Structure of the Thesis

The structure of the thesis roughly follows the project outline. A preliminary study on plant factories is the lead. This includes a study on the common structures between different models, different irrigation models, their advantages and disadvantages and a deeper study onto UCS' own product, the FarmPro Container.

Afterwards, the assembly process of the containers is described, taking special note of components relevant to the objective at hand such as motors and sensors. In the same section it is also given focus to the testing procedures as to shed more light on the reasoning behind the current workable code and notice certain details in the design.

The next step is the analysis of the current program in use. As such, the first step is looking into the user interface, or UI for short, and what options it gives to both consumers and technicians. The actual code is analysed as well as determining the standards in use and the Modbus protocol and programming software used. Before presenting the results of the code, a small exposé on past failure states of the container units is presented. Finally, the final proposed solution alongside its iterations is presented, attempting to properly justify all the choices made in its programming. Each section of the code is given its own subchapter where special attention is given to each section as to properly give a spotlight to and justify each coding decision.

1.5. Summary and Structure of the Thesis

Background Study on Plant Factories

In this chapter a brief overview of the technologies explored in this thesis is provided. As such, Urban Crop Solutions' Farming Containers are explored, most notably the UCS FarmPro Container and the solutions it employs. The general benefits and disadvantages of Plant Factories with Artificial Light in general are also touched on, and how and how much they could be improved moving forward using our current knowledge.

2.1. Plant Factories with Artificial Light

As the name implies, Plant Factories with Artificial Light (from now on referred to as PFAL) are plant factories whose only sources of light are lamps on the inside of the unit, contrasting with Greenhouses and PFSL (Plant Factories with Sun Light). Some characteristics of these units are universal among different providers and are described as follows (Kozai, 2019).



Figure 1 - Diagram of a basic Plant Factory as seen in Urban Crop Solution's website

2.1. Plant Factories with Artificial Light

2.1.1. Cultivation room

The cultivation room must be thermally insulated, airtight and clean. This allows for a greater control of the interior climate, which leads to better yields and avoids contaminations of outside agents like bacteria and parasites. Without these disturbances to take into account the usage of herbicides and pesticides can be avoided, therefore leading to tastier and healthier crops.

2.1.2. Racks

Vertical farming is used to maximize the useable farming area, and as such most farming units employ the usage of multi-layered horizontal racks. These racks contain hydroponic cultivation beds to avoid the usage of terrain, which could easily be contaminated with parasites, bacteria and algae. These layers could be static and accessed manually through a ladder or a lift or automated, like it is seen with certain cyclical solutions.

2.1.3. Lighting system

In between the cultivation levels there should be a lighting unit installed. This lighting unit provides the plants with the necessary and correct amount of radiation. Reflectors could also be installed to maximize the light provided. These also allow the usage of a virtual clock, instead of being subject to nature's 24 hours day cycle (also known as circadian rhythm) it is possible to extend and diminish the duration of artificial days to suit the needs of the cultivated plants.

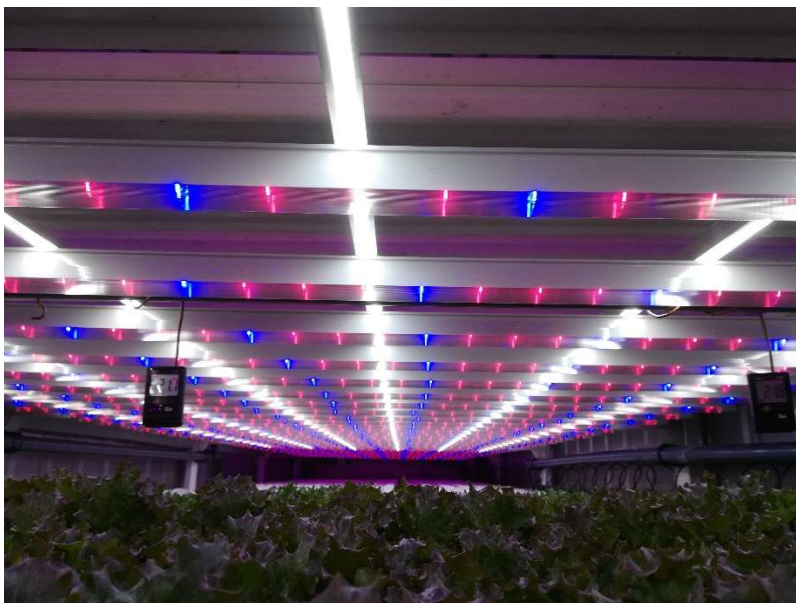


Figure 2 - A UCS FP lighting system. Note how the first few rows have more LEDs

2.1.4. Irrigation systems

The irrigation system needs to supply not only water but also a nutrient solution to the crops. Ideally, this should also be a closed system, and as such requires multiple filters and recycle tanks on top of the expected components such as pressure relief valves and pumps. Additionally, there are many viable irrigation solutions.

While other methods do exist, these are the most commonly used and therefore are the only ones explained for the sake of brevity, based on the description by N. Lu and S. Shimamura (Kozai, 2019).

2.1.4.1. Nutrient Film Technique

In this system a small thin film of nutrient solution is pumped to the rack where due to a small incline, often between 0.5° and 1° but easily adjustable to other values, it naturally flows through the exposed roots without completely submerging them, and naturally trickle down the drain situated on the other end of the rack.

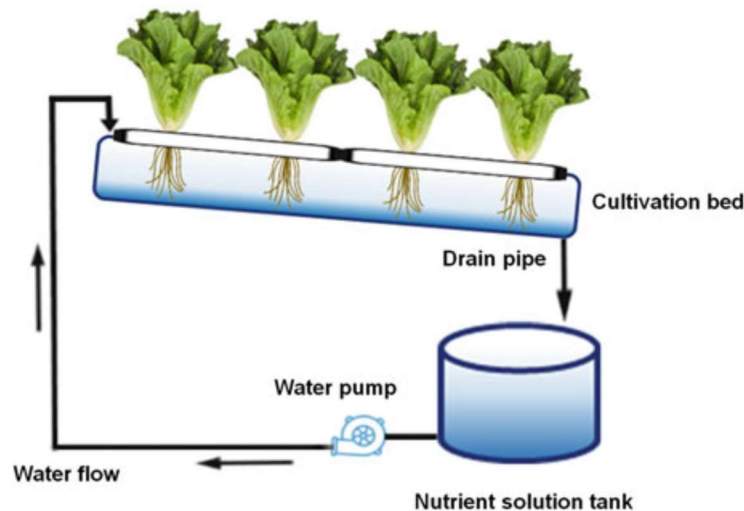


Figure 3 - Visual Representation of a NFT irrigation system (Lu & Shimamura, 2018)

2.1.4.2. Deep Flow Technique

Unlike with NFT, DFT systems submerge the roots completely in the nutrient solution. In this construction the cultivation beds are usually floating in the solution, but they can also be fixed. It still requires constant circulation of the fluid so that the roots can capture oxygen, and some designs even include extras such as multiple intake points per rack or air pumps as to facilitate this procedure.

2.1. Plant Factories with Artificial Light

Despite the similarities to the NFT, this construction provides small yet substantial benefits. In the event of a power outage the plants remain fed for a longer period and it's easier to spot malfunctioning irrigation. However, the system itself is heavier, is less favourable in systems where the cultivation bed is movable due to spilling and if using a floating cultivation bed, the materials used in the floating devices tend to be more conducive to the growth of algae.

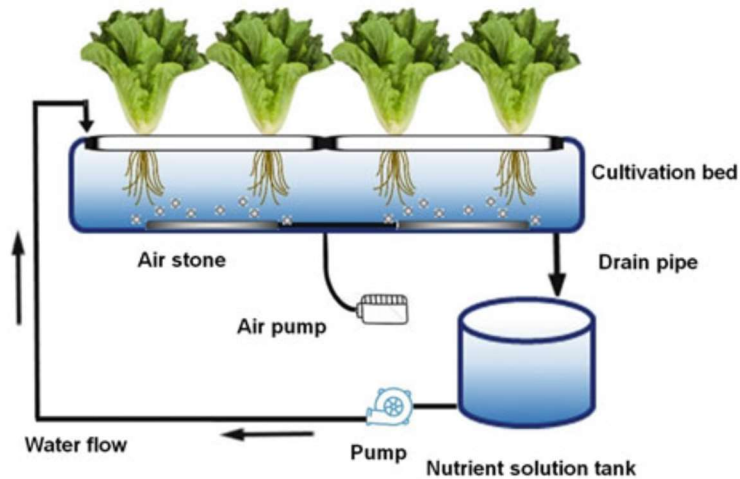


Figure 4 - Visual Representation of a DFT irrigation system (Lu & Shimamura, 2018)

2.1.4.3. Aeroponics

In this construction, the nutrient solution is sprayed onto the roots of the plants, preventing the roots from getting submerged and simultaneously letting them breathe. This keeps the system lightweight but also very fragile, as the spray nozzles are very prone to obstructions, be it the crystallisation of nutrients, algae or other factors. Therefore, a cleaning routine needs to be executed regularly to prevent any gaps in irrigation, especially since with this method the crops are particularly vulnerable to drought periods due to the low amount of fluid provided at a time.

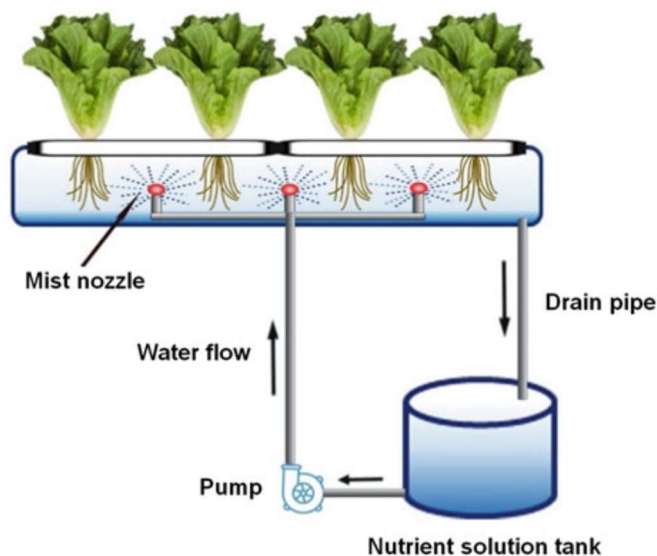


Figure 5 - Visual Representation of an Aeroponics irrigation system (Lu & Shimamura, 2018)

2.1.4.4. Additional hydroponic irrigation systems

In addition to these 3 more commonly used solutions, there are many more techniques used at a lesser rate. These include hybrid systems that attempt to combine the benefits of the NFT and DFT systems, Ebb and Flow systems (EFS) (which use a similar assembly to NFT systems, but employ pots with a rock wool to hold water for longer periods of time), Drip Irrigation Systems (DIS) (used for potted plants to prevent the roots from being soaked in water) and the Wicking System (a system where the nutrient water is absorbed via a wick rope and consequently fed into the plants; unlike any other system this method is devoid of pumps).

2.1.5. Atmosphere control

The atmosphere inside the PFAL needs to be properly controlled to ensure good yield and quality and to prevent outside parasites from infiltrating the system. As such, an air conditioning unit with air filtering is required. It is also ideal that the air flows throughout each rack as to properly oxygenate the crops, ventilate the humidity between the leaves and remove any ethylene that is concentrated around the plant.

Additionally, due to the presence of fluids and variable temperature, it might also be necessary to use a humidifier (or dehumidifier) to control the level of humidity in the unit, as different crops prefer different levels.

Finally, a CO₂ tank is needed to complete the atmosphere control trifecta. This is an essential part due to the crops' consumption of the gas during the photosynthesis process and ensures a good air mixture on the inside.

2.1.6. Sensors

To cap it all off, sensors to monitor temperature, humidity, CO₂, pH and Electrical Conductivity levels are needed. These are connected to the control unit that could either be on-site or on a remote location, connected through the internet. This equipment is essential to maintain a good atmosphere and product quality.

2.2. Advantages and Disadvantages of PFAL

2.1.7. Additional features

Outside of the components in the main unit, there are also auxiliary components used fairly often. These range from automation options like machines for seeding, transplanting, harvest and packaging, among others such as extra rooms for crop trimming and washing and storage of plants, as well as showering and changing rooms for staff.

2.2. Advantages and Disadvantages of PFAL

In this section, the benefits and constraints of PFALs are explored. These range from technological setbacks, like lamp energy efficiency to economic issues or geographic conditions that might affect the viability of this option compared to more traditional methods (Graamans, et al., 2018).

2.2.1. Advantages

This subsection explores the main advantages of PFALs, these residing on the high efficiency of resource use and productivity alongside high precision control over environmental factors.

2.2.1.1. Resources

PFALs have very high Resource Use Efficiency (to be referred to as RUE from now on). RUE is defined by the ratio between the amount of resources utilized in the crops and the total amount of resources supplied to the PFAL. This is due to the insulated nature of the unit, alongside the cyclical nature of the irrigation, which focus the provided resources on the crops and minimizing losses. The formulas to calculate RUE are as seen in formula (1) (Kozai, 2013).

(1)

$$RUE = \frac{F}{S} \text{ or } RUE = \frac{(S - R)}{S}$$

Where

F – Amount of resource used in the Plants

S – Amount of resource supplied to the PFAL

R – Amount of resource considered as Waste

2.2.1.1.1. Water

Additionally, PFAL also have very high Water Usage Efficiency (WUE), due to the high amount of recycled water in the irrigation cycles. Not only that, but since they are isolated units, even condensed water in the Air conditioning units could be recovered and reinserted back into the recycling tanks. PFALs manage to achieve roughly 95% WUE, in comparison Greenhouses only manage about 5%, turning them into fantastic options in areas without a constant water supply.

2.2.1.1.2. CO₂

CO₂ and fertilizer efficiency are also very high due to the insulated environment, and as such the crops absorb the CO₂ generated during the night-time when the photosynthesis starts. The nutrient-enriched water is also filtered and reintroduced back into the main tank, and as such water purges only take place in emergency cases. Efficiency rates range from 80-90%, while Greenhouse rates don't go above 60%.

2.2.1.2. Productivity

PFALs also have very high annual productivity due to the nature of vertical farming. A unit 10 tiers high could reach yields far and above better than traditional farming. The increase in farmable area certainly helps, however the environmental control is probably the greatest factor, as it enables shorter cultivation periods and prevent damage to the crops due to factors like weather and parasites.

2.2.1.3. Precision Control

The high controllability of the atmosphere and general environment has benefits other than increased yield as the crops tend to be of general higher quality both in health and taste. With the right nutrient mixture, it is possible to assure that the plants have better taste and nutritional value. There is also very high reproducibility of farming cycles, since every single resource in the supply chain can be traced to its origin, and as such accurately find flaws or contaminations that might occur.

2.2.2. Disadvantages

In this section, most common PFAL setbacks are detailed. These mostly fall within the economic landscape with a special exception towards the electrical energy required to run the units being rather high and with lower efficiency than its other resources.

2.2.2.1. Electrical efficiency

In terms of resources, by far the biggest weakness of the PFAL is the very low light energy efficiency usage. This is due to the natural low efficiency of lamps in general, but it could be improved by utilising intelligent lighting systems. Additional countermeasures are more insubstantial, such as using/waiting for better, more efficient, lamps to be developed and to use

2.3. UCS' Plant Factory Containers

plants that require less light. In totality the efficiency is only about 3-4% which while better than greenhouses, who don't reach 2%, still leaves a lot to be desired.

2.2.2.2. Initial costs

Worst of all, the biggest setback for the widespread propagation of PFALs is the economic cost. PFALs require a very big initial investment. Most of this investment is related to automation options for the allocation of cultivation beds, harvesting and irrigation. Adding extra towers is relatively cheap compared to the big upfront cost. As such, investors tend to be discouraged. Alternatives such as renting a PFAL exist, but ideally the purchase of a new unit would be the driving momentum behind the technology.

2.2.2.3. Operational Costs

Additionally, the operation costs are high. Electricity cost, labour cost and the depreciation of the initial investment are all concerns as new models are being produced every few months with new technology and improvements. Nutrient mixtures come at a cost, as well as the time and financial investment needed to train a professional team and are contributing factors to the prevention of a faster uptake of PFALs. To remain competitive with other methods it would be needed to reduce the operating costs by at least 30%, and ideally at least up to 50%.

2.2.2.4. Mitigation options

An alternative to mitigate the costs regarding energy supply would be to invest on coupling PFALs with other renewable energy sources, most notably solar. While it would most certainly further increase the initial investment cost, it would vastly decrease the operation costs, and it would further reduce the environmental imprint. In order to reduce the operating costs even more, replacing manual labour with automated solutions for common manual activities such as seeding, transplanting and washing, at the downside of increasing initial investment.

However, to reach this point of automation it would be required a very precise and accurate way to remotely check the status of the system. Unfortunately, this would require a vastly increased number of sensors and surveillance cameras, further increasing initial investment.

2.3. UCS' Plant Factory Containers

UCS' FarmPro is a small PFAL unit, consisting of only 4 vertically stacked layers capable of holding over 40 gullies each. Its premise is to be a form fitting unit, produced at a much cheaper cost than traditional PFALs, providing produce for own consumption and research, among other usage. As such, modifications from bigger, more standard units have been made.

2.3.1. Gully racks

UCS's FarmPro (to be referred to as FP from now on) main defining feature is the rotative gullies that house the crops. The layers 1 and 2 are paired and so are 3 and 4. Layers 1 and 3 are input layers, while 2 and 4 are output layers. There is a sensor in each layer on the user end to detect if there are gullies on both entrances and exits.

On these layers there are tracks that hold a rail of tackers, totalling 2 tracks per layer with a motor for each layer. These move in a seesaw motion, and their purpose is to move the gullies one step forward at a time.

In this section of the unit there is a row of LED lamps for every gully. These LEDs provide the necessary light for the healthy growth of crops and can be dimmed or turned off in a layer wide move. There is an added option for the last few rows of the output layers to also have white light lamps on top of the standard LED set up. These are to provide extra light to the last stage of plant growth should the client wish it so.

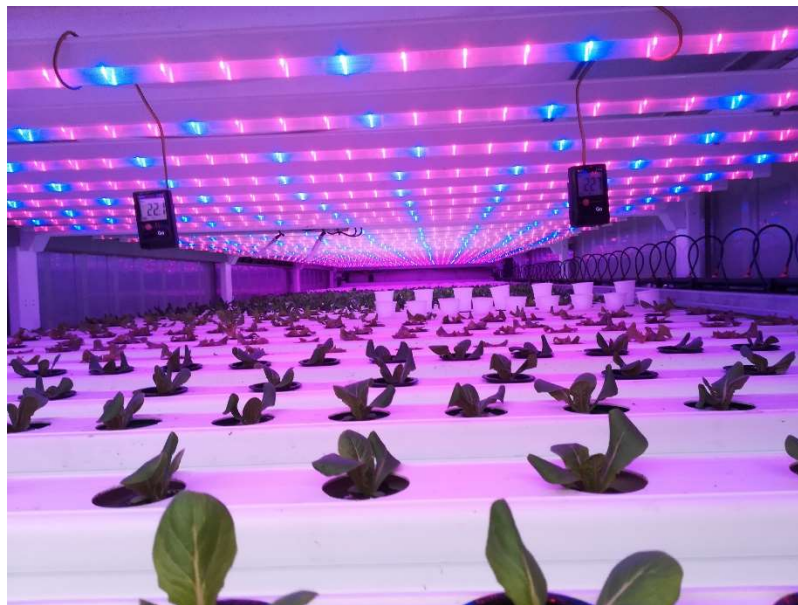


Figure 6 - Gully Rack of a UCS FP with all gullies inserted

2.3.2. Germination rack

Included in the container unit there is a small germination rack. Its size is very reduced, only 4 racks tall and without any automation, whose only purpose is to germinate the seeds that will later be transplanted into the gully racks. There is also no irrigation, but there is a lighting system. The watering is instead done through a hose that is installed nearby.

2.3. UCS' Plant Factory Containers

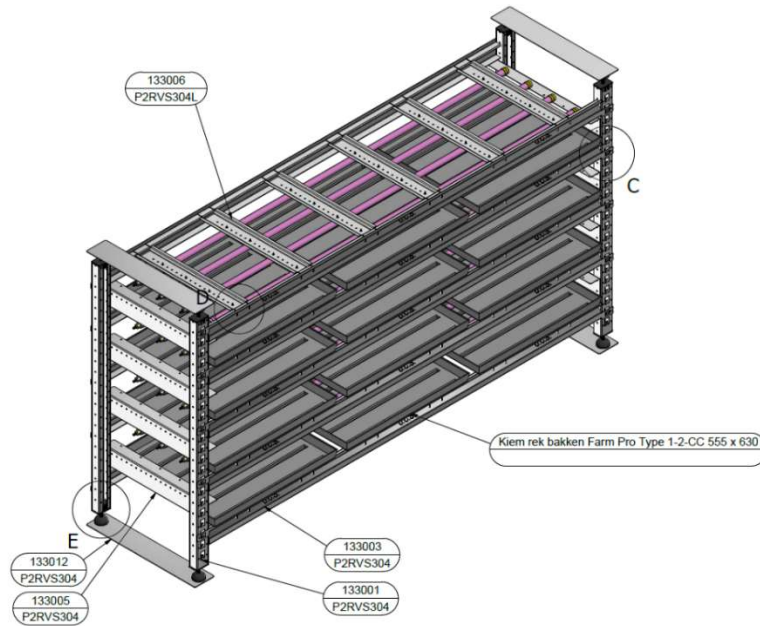


Figure 7 - 3D Schematic of a Container Unit Germination Rack

2.3.3. Ventilation system

Above the germination rack there is an air conditioning unit to help regulate the temperature and atmosphere. This unit also provides an air current for a sleeve that goes through the ceiling on top of the racks into the back, where it expels the air from the back of the unit into the front, making it so the crops are well ventilated and exposed to the correct atmospheric conditions.

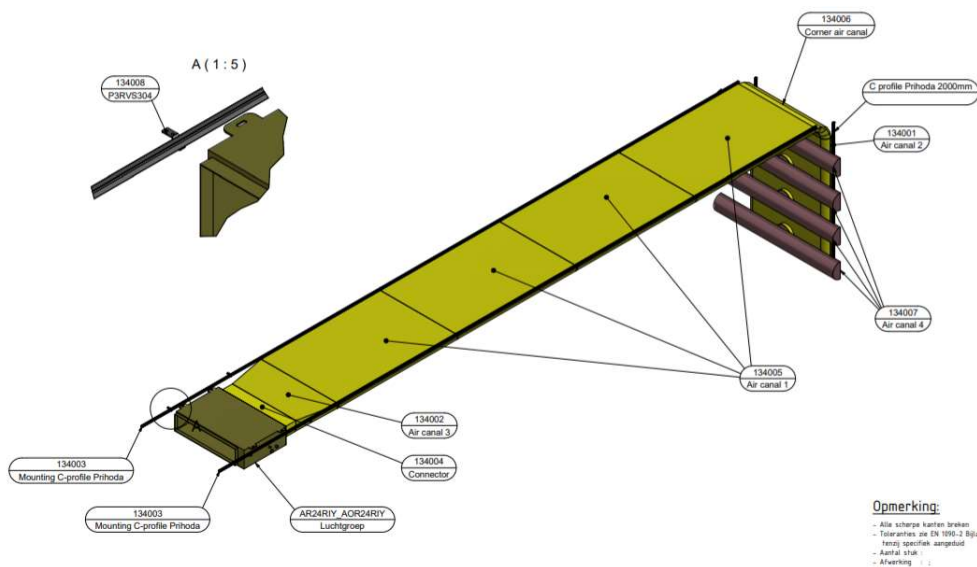


Figure 8 - 3D Model of a UCS FP Ventilation Sleeve

2.3.4. Elevator

On the back of the gully racks there is an elevator whose function is to carry the racks from level 1 to 2 and 3 to 4. It is moved by two chains on each end powered by a motor on top of it. On this elevator there are two prongs where the transported gullies are slid into. The elevator has its reference point at the top of its track and knows it has reached its desired location by sensors placed at each gully rack. Additionally, there is a sensor at the bottom of the track to detect any malfunction that causes the elevator to move lower than expected, as well as a sensor that detects if there is a gully in the elevator.

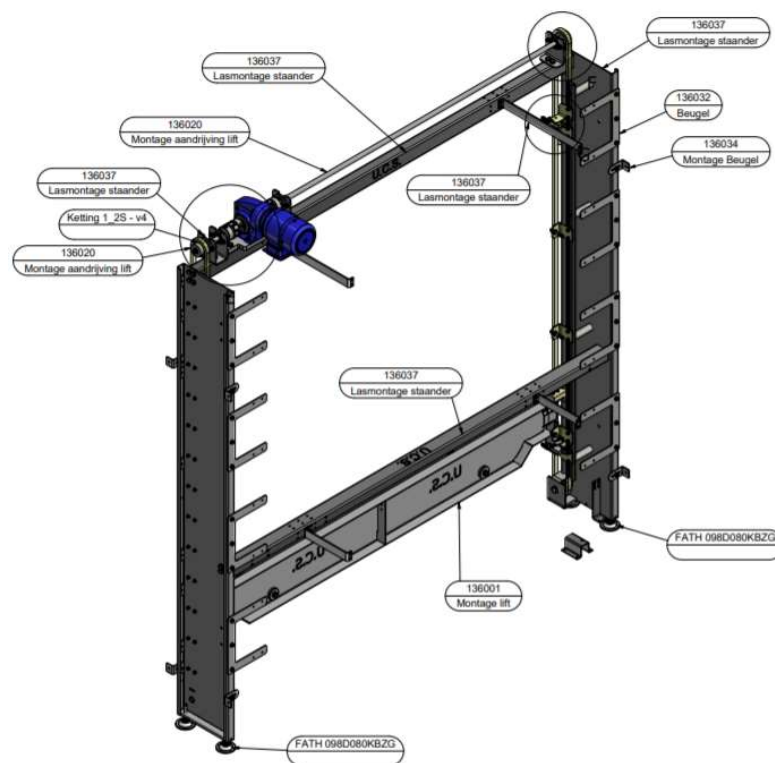


Figure 9 - 3D Schematic of a UCS FP Gully Elevator

2.3.5. Technical Room

At the back of the unit there is a small room that houses the technical end of the assembly. This area contains elements such as the electrical panel, PLC, CO₂ cannisters, Nutrient and Acid Jerrycans. It has certain components from the irrigation system such as the pumps, nutrient water tank, filters and recycling tank. It is also through this room that technical support can access the interior of the container for maintenance.

2.3.6. Irrigation system

UCS's irrigation system starts at the nutrient water tank. This tank mixes the water with the nutrients via peristaltic pumps so the correct dosage can be applied. Similarly, acid could be mixed into the water as to better control the pH levels of the water. Afterwards, the mixture in the tank is pumped via a submerged pump into the feeding pipes.

UCS employs the NFT irrigation technology, each of the feeding tubes has a dripper installed to irrigate the crops on each gully resting position. These drippers consist of a small flow restrictor inserted into pre-drilled holes, with a small tube directing this smaller flow into the gully. This way, the usage of valves for flow control can be avoided and can make the entire row of drippers have the same flow at a low cost. After irrigation the remaining water trickles into a gutter situated on the other end of the gully rack.



Figure 10 - UCS FP Irrigation Drippers

From this gutter the water flows into the recycling tank. Worth noting that the tubing in this section houses a far larger volume than that of all four gutters combined. This is so that it functions as a buffer volume to the recycling tank, reducing its size. The recycling tank connects to the main filter. This component filters the recycled water through two meshes, one for larger dirt particles and one for finer particles. Afterwards the filtered water is reinserted into the main tank.

This filter in particular got a routine to automatically clean its meshes known as backwashing. In this process the water flow is reversed pushing these particles out of the meshes. The water resulting from this operation is drained into a different pipeline. This leads into a different filter with an easily replaceable mesh. This secondary filter collects the dirt filtered on the main filter, and reintroduces the water into the recycling tank, allowing for less water waste.

2.3.7. Sensors

A FarmPro unit makes use of many sensors in order to properly monitor and provide feedback to the control unit. Each layer has a sensor at the user's end so the program can know if there is a gully on either the entrances or the exits of the layers. Additionally, each layer has two proximity sensors on the tacker track, and these provide information on which position the tackers are currently in. Still on the mechanical side, there is another sensor on top of the lift which serves as the lift's reference position and uses it in order to know its position.

There are also sensors for temperature so a proper level can be maintained, and near the main tank there are sensors that check the mixture's electrical conductivity and pH levels.



Figure 11 - On the left: Elevator Sensors; On the Right: EC Sensor

2.4. Growth cycle in a UCS FarmPro Container Unit

Initially, the seeds are placed in the germination rack where they will remain until they grow into seedlings. Once they reach this state, they are manually transplanted into gullies. Once the gully has been sufficiently filled, it is placed into either layer 1 or layer 3. Obviously, these can only be placed if the first position is empty but can only be moved into the cultivation area if the last position of the respective output level (2 and 4, respectively) is empty. One must also press the “harvest mode” button relative to the targeted layer. This function dims the lights and stops irrigation on those levels.

2.4. Growth cycle in a UCS FarmPro Container Unit

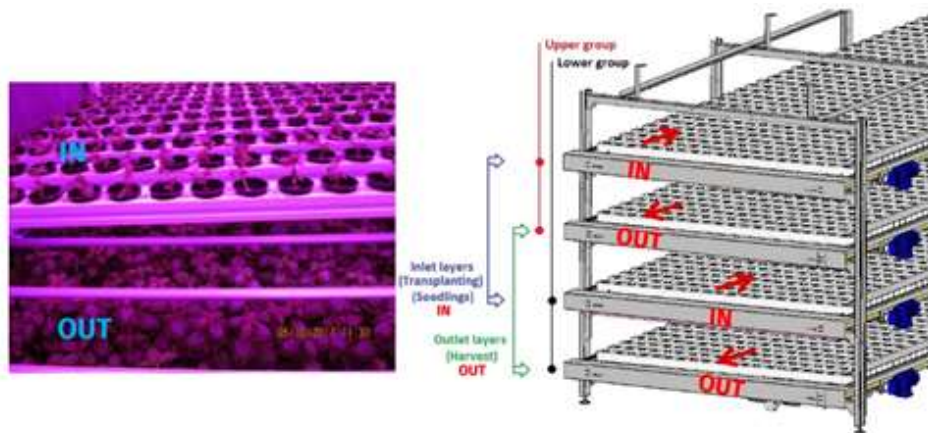


Figure 12 - Representation of a UCS FP gully travel cycle

Once these conditions are fulfilled and the gully placed, the gully request button relative to the layer must be pressed. This button moves the elevator to the receiving position and moves the gullies back one position. After receiving a gully, the elevator moves to the layer right below it, softly lodging the gully on the receiving tracks. After this the bottom track moves forward one step, moving a gully into the output position completing the cycle.

Assembly, Quality Assurance and Testing Procedures

This chapter explores the assembly and testing procedures involved during the manufacturing of the FarmPro container. Special attention is given to the mechanical and hydraulic section of the system since these are the components with a bigger relevance to the main subject of this dissertation.

3.1. Assembly

In this section the assembly of the containers is explored, ranging from the mechanical construction, the irrigation systems and the electrical cabling.

3.1.1. Mechanical assembly

The first step in assembling the container is piecing together the various metallic structures that are housed in the container. These are be the gully rack, germination rack and skid (technical room).

The germination rack assembly is rather simple as it is a stainless steel structure without any irrigation systems interconnecting, as the irrigation in these layers is done manually with a nearby hose. Between each layer there are housings for LED lamps. Additionally, there is the option to mount a small plastic table on top of the topmost layer as an aide for certain actions the work force could perform on the inside.

The gully rack is assembled in various steps. The racks themselves are custom made to have a slight incline between both ends of the gully so there is a steady flow of nutrient water. All levels share the same structure for most of the structure, but levels 1 and 3 have different components at the elevator and user end compared to levels 2 and 4, as to better accommodate the functioning of the elevator and ease of use in the user end, respectively. The motors for each layer are also mounted at this time, alongside with the coupling axis so that each motor can actuate two tacker rails.

3.1. Assembly



Figure 13 - An assembled Gully rack inside the container

The tackers are assembled separately from the racks. These are built in smaller sections to be later assembled together. One section in each layer, both left and right, have a geared section so they can later be connected to the motor. After all the tackers are attached to their respective rail and the geared sections mounted on the respective spots, the tacker rails are ready to be assembled onto the gully rack.

The elevator is assembled alongside its respective motor. The shape of the structure is akin to a portico, with the chain and supporting beams serving as the columns with the motor housed on the top beam. It is also in this structure that the level sensors and the bottom and top level sensors are fixed, alongside the receiver of the photocell. The elevator itself is guided by the supporting beams, and the chains are bolted onto the lift. The protrusions upon which the gullies are transported are bolted onto the lift plate and can have their heights individually adjusted.



Figure 14 - Empty container with the plastic floor mounted

Additionally, a plastic floor is also mounted onto the container, as the original floor is akin to a metal grate. This floor has a drain hole at the back end so that it may drain any excess water that might drip onto the floor. To facilitate this, it is advised that the container be lowered onto a position that very slightly tilts towards the backside, to provide a small but meaningful incline to allow for the excess fluid on the floor to safely leak out rather than be a safety and biological hazard.

There are also some metal profiles to bolt onto the sides of the container. These profiles ensure that any water that could condense on the walls drips onto the plastic floor rather than below it in an attempt to curb fungi growth on the underside of the plastic surface.



Figure 15 - Metal profiles to help guide condensate towards the plastic floor

The metal skid that houses the tanks is also mounted separately and consists mostly of assembling a small steel structure with no features other than housing the water tank, and as such is be given little attention.

After all these separate components are assembled, they are separately and orderly inserted onto the container (post floor installation). First enters the germination rack, to be housed underneath the space allocated to the air conditioning unit. Afterwards, the gully Racks are inserted and aligned with the entrance and activation buttons as to give the end user an appropriate amount of space to work inside the container. Next, the elevator is introduced into the back facing the gully racks. The photocell is also introduced at this moment, but not yet to the precise position it needs to be (a similar situation to the elevator position sensors). The skid or technical room is introduced later and is covered in the irrigation assembly section.

3.1.2. Irrigation and ventilation systems assembly

The first step in the assembly of the irrigation systems is putting together the main tank and lowering it onto the skid frame.

The main tank (there is an option to build two tanks instead to irrigate different layers) is to be inserted onto the skid metal frame and is made of plastic. Inside this tank there are multiple submerged centrifugal pumps that feed various channels in the irrigation system. These are the circulation pump that redirect flow into the irrigation pipes on the four gully layers and the mixing pump that mixes the water every certain time period as designated in the parameters introduced into the control software (if it ran continuously it would raise the temperature of the water) and redirects nutrient water into the UV filter, EC and pH sensors so accurate feedback can be given to the control system to regulate the amount of nutrients and acid to be mixed into the main tank. Below the main tank, underneath the skid, there is a manual valve whose function

3.1. Assembly

is to give the end user the option to manually drain the entire tank, be it for maintenance or simply to refresh the water inside.

Onto the gully rack, opposite to the side where the drippers will later be placed, gutters made from PVC are mounted. These have their exit in the middle of their length with a small incline on the inside to redirect the flow towards it. All these gutter's exit pipes connect to a central pipe that runs underneath the gully rack that connects to the recycle tank. Note that this central pipe has a far larger diameter than what would be normally required. This is so it serves as a buffer for the volume of water that could be held in the recycle tank.



Figure 16 - Close up on the Tacker rail and irrigation gutter

This buffer is necessary because the recycle tank is of a quite reduced size since it has to fit under the skid frame. This tank has 2 level sensors: one that checks the minimum acceptable level and a maximum acceptable level. These two devices give feedback to the system in order to control the frequency of the filtering and recycling cycle. In addition, there is also a filter screwed onto the pipe leading to the pump that feeds the filtering system. This is to prevent larger particles from either jamming the pump or tearing the filter meshes, shortening the number of times these have to be replaced (which is a fairly arduous process regarding the automatic filter).

The filtering system consists of an automatic self-cleaning filter, which cleans the recycled water from the finer particles and reintroduces it into the main tank. This particular filter, after reaching designated pressure differentials, initiates a self-cleaning procedure. During this procedure, the main channel upon which the water flows back into the main tank is closed, and the backwashed water is redirected towards a secondary (ordinary and easy to replace) filter. The water that flows through this section is redirected towards the recycle tank to be later ran through the same recycling cycle.



Figure 17 - On the left: Automatic Filter; On the right: Basic filter for the backwash

There are 3 auxiliary pumps that supply the necessary nutrients and acid to the mixture. These are peristaltic pumps, specially designed so they can provide exact quantities of the pumped fluid to the mixture. The feedback necessary for this procedure is provided by the pH and EC sensors. These are mounted on the skid in such a way so that the end user can have clear access to it and can detect by sight if anything has gone wrong with any of them.



Figure 18 - Peristaltic pumps used to mix nutrients and acid into the main tank

Following the circulation pump line, the automatic valves are housed next to the elevator in between the skid and the gullies. These dictate to which dripper pipe the nutrient water flows into. They also have a manual mode for the cases of maintenance and assembly. In any other case these should be in automatic mode so the control software can actuate them. There are five of these: one for each of the dripper supply lines and one for the main tank water intake.

3.1. Assembly



Figure 19 - Automatic Valves for the gully rack

The dripper pipes are mounted next to the gully racks. There are various connection points throughout the gully rack to make sure that the pipe is not dislocated during the irrigation and transportation process. Afterwards, this line is perforated, and small flow limiters are installed in these orifices throughout the pipe. These make sure each dripper is fed the same flow so that no pressure loss occurs throughout the line in a way that is harmful to the irrigation. Afterwards, small drippers are attached to these flow limiters and passed through a guiding hole, so that it aligns with the gully resting positions. As such, no element in this line has any control or feedback interaction with the software, working purely on mechanical reasoning.



Figure 20 - Close-up of the flow limiters installed on the drippers

Near the entrance to the working area the manual valve on the main tank intake line can be seen as well as a hose connected to the same waterline. This hose's main function is to water the germination rack, but it is also useful for cleaning the work area.

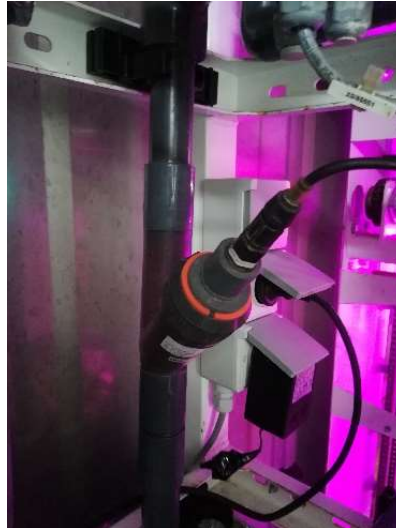


Figure 21 - Water hose used for Germination rack irrigation and general cleaning

Next, the ventilation sleeve is passed over the gully rack and unfurled at the back, resting on top of the racks and behind the elevator. The entry point of the air flow is above the working area in between the germination rack and the gully rack, and the air flows through the sleeve onto the back, where holes redirect the flow towards the crops in the direction of the working area.

Now, Skid with the water tank mounted on top is inserted and connected to the different pipelines, mainly the drain line, pump line and recycle line.

3.1.3. Electrical Assembly

After both the mechanical and irrigation systems are mounted onto the container, it is time to effectuate the assembly of the electrical cabinet.

Mounted opposite of the main tank, the electrical cabinet contains all the different control elements and electrical drivers associated with all the different actuators in the unit. On the same chute the wiring for the control panel at the user end is also be present. This panel includes the emergency stop, Harvest Mode and gully request for both layer couples and the Reset button.

The wiring for the tacker motors runs through the top of the container via a chute. Once at the front, these wires connect to the triphasic motors that perform the tacker movement.

Similarly, all the different pumps need proper wiring, however due to the short distance between the cabinet and the location of the pumps no chutes are needed, and all the wiring is running below the skid.

The automatic valves, automatic filter and peristaltic pumps are connected to the cabinet through a chute that wraps around the top of the main tank containing all the required wiring.

3.1. Assembly

Next, all the sensor equipment including positional, temperature, electric conductivity and pH sensor alongside the photocell are connected to the system via a Modbus protocol, more specifically Modbus RTU.

Once all the wiring has been laid out on each layer's chute and no further action needs to be taken on the area between the gully racks it is time to start connecting the lamps to their respective positions. The technician must enter through the front in-between the levels and start assembling the lamps from the back towards the front. This is because the lamps are the biggest factor contributing towards movement restriction inside the unit, and as such not having this step as the final one would make other operations incredibly cumbersome if not impossible.

Additionally, the lights in the germination racks are also mounted at this point, but this step is not conditioned by the same movement impairing situation and as such it is only done that way as to better organize the workflow.

3.1.4. Finishing Touches to be realised at the consumer location

After completing the construction of the container, it is ready to ship. Do note some final construction solutions, like the door hinges being on the inside and the doorknob being removed: this is so that during the transportation of the container, especially during overseas shipping. This could also lead to further complications like the door or even the wall being damaged as a consequence.

Once the container reaches the consumer location, some precautions need to be made. First, the container needs to be resting at a very small incline with the back area at the lower end. This is so the residual water that might accumulate on the floor can be redirected to the gutter in the back. However, the incline can't be so severe as to impact the flow of the gutters inside the container.



Figure 22 - Connections for the AC unit, electricity and water intake

Outside the container there is a specific area upon which the air conditioning unit is installed. Due to legislation, the company is unable to ship the unit already installed in the container, and the client must procure a unit in his own country.

Once internet, water and electricity have been connected, the consumer with the help of a technician has to do a very basic extra Quality Assurance test so that it can be checked whether anything was damaged during transport. These alongside the QA testing procedures done at the assembly station are covered in the next section.

3.2. Quality Assurance and Testing Procedures

In this section the different testing procedures employed during the assembly procedure are explored in order to make sure that every crucial element in the system is working as intended. This covers the lighting system, mechanical system, irrigation cycles and sensor devices.

3.2.1. Lights

After assembling the container in the assembly facility, it is now time to test its internals to ensure everything is working as intended. The first subject for testing is the lights. Each layer has 5 drivers that activate different sets of lights. Currently it is only possible to dim or turn each layer on and off in its entirety, and one of the goals of this project aims to change that so that each driver can be manually activated.

3.2.2. Tackers and Elevator

Next it is time to test the elevator and tacker system. To do so gullies are introduced in the container utilising the automatic mode for the gully cycle while a technician monitors the movements for any malfunction. The first few gullies on each layer are crucial since they also serve as a test run for the placement of the level sensors on the elevator side. As such, there are many complications that might occur, the most common being the sensors being placed at the wrong altitude and as a result have the gully pushed into the prongs of the elevator, breaking or bending the gully, or have it fall onto the prongs and as a consequence having it fall or tilt, which when during intended use would lead to the collapse of the plants in hard to reach areas. Both of these outcomes result on an empty gully dropped on the floor at best and the jamming and possible ruining of the elevator at it's worse.

3.2. Quality Assurance and Testing Procedures

3.2.3. Irrigation

After the container unit is completely filled with gullies, it is time to test the irrigation circuit. To do such, first a quick inspection is done to assure that all gullies are placed correctly to prevent water from dripping onto the floor.

First the main automatic valve is tested to ensure water intake to the main tank works properly. This action is fairly independent from the rest of the circuit and as such can be performed in tandem with other tasks such as the placement of the gullies. On the same line it is also possible to test the germination rack hose to check for obstructions.

Afterwards the main pump is tested alongside each of the 4 automatic valves. First, each line is connected to a hose leading to the drain gutter present in the facilities. Afterwards, once the main tank is filled to acceptable levels, the main pump is manually activated alongside one of the automatic valves on each layer, making sure that no obstruction is present between the main pump and the common line of the drippers. Once such as been observed, the hose is removed, the exit closed and the main pump is activated again, allowing the technicians to check if any of the drippers are blocked.

Next, the drippers are left running until the recycle tank is filled. When completely filled, the recycle pump and automatic filter are tested by pumping the recycled water back into the main tank via the recycle line. During this step, it is paramount that special attention is given to the recycle pump, making sure it is filled with liquid before it is activated so no air is present, preventing damage and malfunctions. Once both the filter and the pump have been observed to be working as intended, a manual backwashing cycle of the filter is activated to check if said function is working properly.

3.2.4. Sensors

After checking if the main hydraulic circuit is working, it is time to verify the pH and EC sensors. To accomplish so, standard procedure for such equipment is used: for the pH sensor distilled water and the manufactured provider buffer packs are used to properly calibrate it. For the EC sensor mixtures with a known verified EC measurement is done to calibrate it.

After said sensors have been calibrated, a test run of the circulation cycle is performed to make sure no tube is obstructed, and that the circulation pump is operational. Next comes the test of the peristaltic pumps. Each pump is tested individually with the output channel directed to a measurement tube to prove that the requested amount of fluid was provided.

Control Software

In this chapter the current software is explored, both in UI and functionality and the background coding and connections in the device. First, the user interface was examined and studied for the currently available options that could be reused in the new program, in particular the settings screen. Next, the technology behind the code is covered, what language it is written in, what communication protocol it employs and what kind of data processing and display software is in use.

4.1. Remote control software user interface

Utilizing this software, the client or someone at Urban Crops can remotely control and monitor different aspects of the container unit. In this section, the user interface and what it can influence is explored, and the different ways the user can modify the system without needing to have someone at the scene. This information can be found on the user manual, which is also the source for the images (Stubbe, et al., 2019).

4.1.1. Main menu

The main screen consists of key information display and access points to other functions of the program. Immediately one could see the temperature, humidity and CO₂ level displays. The status of the tanks is also available at first sight. This includes their pH levels, their Electric Conductivity and their current water volume. On the bottom above the menu buttons it shown the current LED intensity levels for all 4 gully racks and whether the irrigation for each of the layers is active at the moment or enabled at all.

4.1. Remote control software user interface

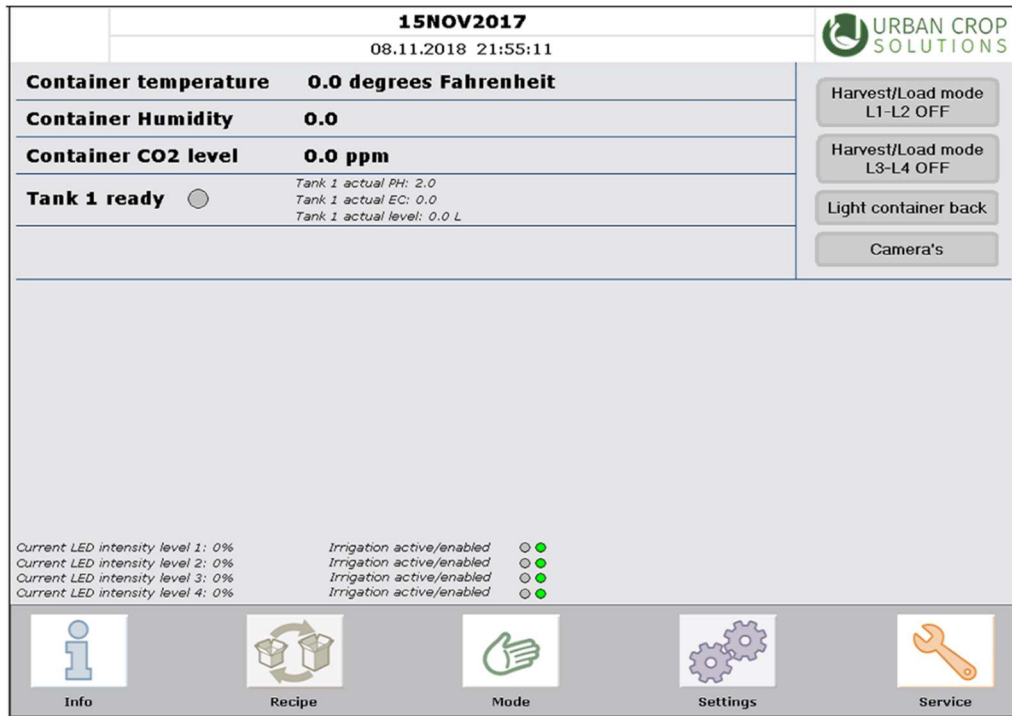


Figure 23 - Main Screen UI

In this same menu there can be found buttons for very simple operations. These are activation and deactivation of Harvest mode for both sets of racks, a remote light switch for the lights in the back of the container and the (optional) live feed camera settings.

From this menu, one can access the Emergencies, Info, Recipe, Mode, Settings and Service menus.

4.1.2. Emergencies Menu

This menu contains indicators of the sources of various errors that might occur. These indicators represent the following errors: Emergency Stop, Open Door Malfunction, Sensor Malfunction, Miscellaneous errors and Motor malfunction.



Figure 24 - Emergencies Screen UI

On the bottom of the screen access the Info, Recipe, Mode, Settings and Service menus can be accessed. If the middle of the screen is clicked the menu redirects to the recent error log, which catalogues errors that have occurred in the last 24 hours. These errors each have a designate code that can be consulted in the user manual, but a small description is also included. By clicking anywhere outside this list, the UI reverts to the main menu.

4.1.3. Information Screen

In this screen it is possible to can check the measurements taken by the sensors in the container unit. In the measurements tab it is shown the same information as the main screen with the Wh consumption added.

The current time on the Date/Time tab is also displayed here, both real and virtual clock and the current date.

Lastly on the Software Version tab the PLC software version can be seen and its serial number. Additionally, the full alarm history log can be seen in this screen, complete with timestamps and the usual error notifications.

4.1.4. Recipe Screen

In this screen, the nutrient recipe to use during production can be selected. It is possible to choose between some pre-programmed recipes or create a custom one. However, since this matter is outside the scope of this thesis, its features will be skipped.

4.1.5. Mode screen

In this screen the functioning of the container unit can be set as either automatic or manual. When in automatic, it functions as set in the programmed PLC routines using the parameters set in the settings tab.

When using the manual mode, it is possible to individually move each of the actuators in the system, however this bears the important detail of being unable to against certain programming restrictions. For example, if a sensor detects a gully on the output position, manual mode is unable to push another gully onto this position via the manual activation of the tackers. This is due to the program being mostly consumer focused and is designed in a way of preventing unintentional damage to the unit.



Figure 25 - Mode select screen UI

In manual mode, the user has access to many menus each controlling a different set of actuators. On the first screen the tacker and lift controls can be seen and interacted with. On the tacker UI see the state of the sensors of each gully. These show whether the tackers are at either end of their courses and if there is a gully on the user's end (there is a sensor on both left and

right of the gully rack). Additionally, there are buttons that allow the user to move the tackers in either direction, up until the end of course.

Next to these the lift control UI can be found. Here it is possible to observe that the lift has 6 proximity sensors: 1 for each layer (totalling 4) and 1 sensor for both the top and bottom position of the lift. Additionally, there is a sensor on the floor that checks if there is a gully present in the lift's course. Finally, there are 2 buttons to manually control the movement of the lift.

The next screen is the gully rack LED control panel. In this panel it is possible to manually turn on and off the entire level of LEDs (it is not possible to turn a single row off). Additionally, it is also possible to control the intensity level of the LEDs. However, it is not possible to change the intensity of a single level individually. Instead, the whole pair has to be changed at the same time (1+2 and 3+4).

Next is the germination rack LED control panel. Here it is possible to change the LED intensity and whether they are active or not but, distinctively from the gully rack LEDs, the intensity of each row can be individually controlled.

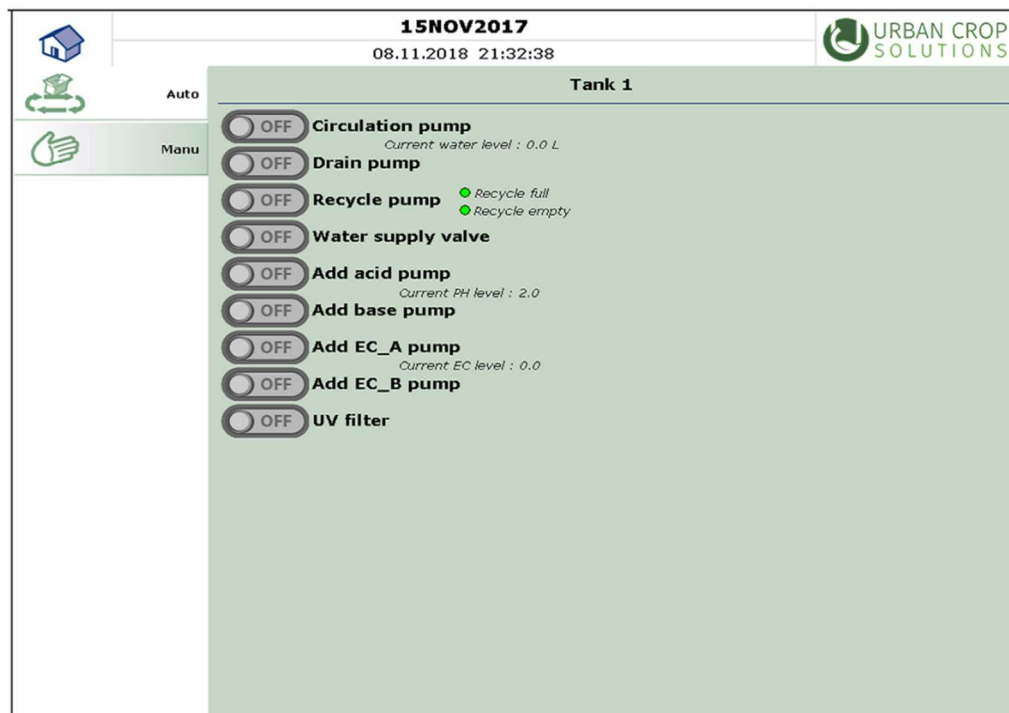


Figure 26 - Irrigation manual control UI

Another manual control screen is regarding the main tank. In this screen the various pumps and valves regarding the water tanks located in the skid can be influenced. It is possible to check the main tank water level and whether the recycle tank is filled or empty and activate the main circulation pump, the drain pump and recycle pumps. Additionally, the peristaltic pumps that provide nutrients and acid to the main tank can also be controlled, and the UV filter and the water supply valves are able to be manually activated, which allows the tank to be manually filled with outside water.

Finally, there are the irrigation control screens. In these screens it is possible to manually control the irrigation valves and the drain pump.

4.1.6. Settings screen

In the settings screen it is possible change various settings regarding virtually every action in the program. These range from parameters such as water levels, pH levels, nutrient concentration to actuator movement speed and activation delays among others.

The first tab in the settings screen is the water preparation settings. In this screen the user is able to change settings such as minimum and maximum water levels, pH setpoint and how much acid should be added at what pH levels measured.

In the irrigation settings screen, it is possible to control the time interval between irrigation cycles, the duration of the irrigation and the delay of activation after LED activation. It is possible to also enable or disable entire levels at once.

Category	Parameter ID	Description	Value
Water preparation	P060	MT1, Minimum water level [l]	50.0
	P061	MT1, Maximum water level [mm]	600.0
Irrigation	P062	MT1, Operational water level [mm]	400.0
	P063	MT1, Circulation time before EC-PH evaluation [s]	20.0
LED lights	P064	MT1, PH setpoint	5.5
	P065	MT1, PH under tolerance [%]	30.0
Para	P067	MT1, EC setpoint	2200.0
	P068	MT1, EC under tolerance [%]	40.0
Takt/Lift	P070	MT1, Alarm Treshold flow rate [%]	5.0
	P072	MT1, add acid time when PH act val above 150% [ms]	4000.0
Climatisation	P073	MT1, add acid time when PH act val between 150-145% [ms]	2000.0
	P074	MT1, add acid time when PH act val between 145-140% [ms]	2000.0
	P075	MT1, add acid time when PH act val between 140-135% [ms]	2000.0
	P076	MT1, add acid time when PH act val between 135-130% [ms]	2000.0
	P077	MT1, add acid time when PH act val between 130-125% [ms]	2000.0
	P078	MT1, add acid time when PH act val between 125-120% [ms]	2000.0
	P079	MT1, add acid time when PH act val between 120-115% [ms]	1000.0
	P080	MT1, add acid time when PH act val between 115-110% [ms]	1000.0
	P081	MT1, add acid time when PH act val between 110-105% [ms]	500.0

Figure 27 - Settings Screen water mixing UI

Next comes the LED settings screen. Here one can enable or disable the usage of the virtual clock, as well as accessing the options for the two pairs of gully layers and the germination racks. In these submenus it is possible to set up the time to switch on and off the lamps, the brightness levels of each level of LEDs (this means even the gully layer pairings can be adjusted separately). Once the changes have been made, they can be enabled with the respective switch. Additionally, one can also introduce settings for the sunset and sunrise. In this new window, the sunset ending and sunrise starting time are defaulted to the off and on times set in the previous menu, respectively. It is then necessary to input the sunrise ending and sunset starting times. A sunrise starts at 5% LED intensity and increases at a constant rate until it reaches the previously assigned LED intensity value at the assigned time, and as expected a sunset works in the same, reversed logic.

In the parameter setting screen it is possible to manually change any parameter available (a full list of parameters and its descriptions are included in the user manual). One can also toggle certain options on and off (these options are also fully listed in the user manual).

In the Tacker/Lift menu the user can manually set parameters related to the tackers and lift. These settings are the speed the tackers have when they move automatically in either direction, the speed in which they move using manual activation. Similarly, the setting related to the lift are the ascension speed, descent speed and manual activation speed.

15NOV2017		URBAN CROP SOLUTIONS
08.11.2018 21:54:21		
Water preparation		Show variables in scroll view
Irrigation	P001 - Lift, Speed up [%]	80.0
	P002 - Lift, Speed down [%]	80.0
	P003 - Lift, Speed manu [%]	80.0
LED lights	P004 - Takt, Speed forward [%]	80.0
	P005 - Takt, Speed backward [%]	80.0
Para	P006 - Takt, Speed manu [%]	80.0
	P007 - LED CLOCK, Hours in one day [1..24]	0.1
Takt/Lift	P008 - LED L1, Brightness Auto [%]	100.0
	P009 - LED L2, Brightness Auto [%]	100.0
Climatisation	P010 - LED L1-L2, Hour on	6.0
	P011 - LED L1-L2, Minute on	0.0
	P012 - LED L1-L2, Hour off	23.0
	P013 - LED L1-L2, Minute off	59.0
	P014 - LED L3, Brightness Auto [%]	100.0
	P015 - LED L1-L2, Brightness Manu [%]	100.0
	P016 - LED L3-L4, Hour on	6.0
	P017 - LED L3-L4, Minute on	0.0
	P018 - LED L3-L4, Hour off	23.0
	P019 - LED L3-L4, Minute off	59.0
	P020 - LED L4, Brightness Auto [%]	100.0
	P021 - LED L3-L4, Brightness Manu [%]	5.0
P022 - LED Seed L1, Hour on	6.0	
P023 - LED Seed L1, Minute on	0.0	
P024 - LED Seed L1, Hour off	23.0	

Figure 28 - Settings Screen Parameters UI

The last menu focuses on climatization settings. In this new window it is possible to set parameters related to the heating and cooling of the interior of the unit. Additionally, it is also in this window where it is possible to change the settings of the CO₂ valve, such as the CO₂ level check intervals, values for the hysteresis of the minimum and maximum CO₂ levels and the time the valve stays open. Optionally, there could be a humidifier/dehumidifier in the system. In such cases, the user could enable or disable them from this screen, on top of its normal settings related to its functioning.

To save any changed setting, one must return to the main menu, where a prompt is given asking the user if he wants to keep the changes made.

4.1.7. Service screen

In the service screen, initially, the user can only change language and shut down the container unit. Should specific, technical passwords be inserted into the activation code, more options within the entire program open up. These include parameters the company doesn't want a client tinkering with, fixed values for each container and the subject of this thesis, a menu that could move all the different actuators without any regard to safety countermeasures to troubleshoot and solve certain malfunctions related to mechanical errors.

Upon entering the admin or technical support activation code a few more tabs appear. These include a date and time tab where these and the virtual clock can be set, along with analogue inputs to relate sensor values to real values (something like analogue value references to actual values such as volume).

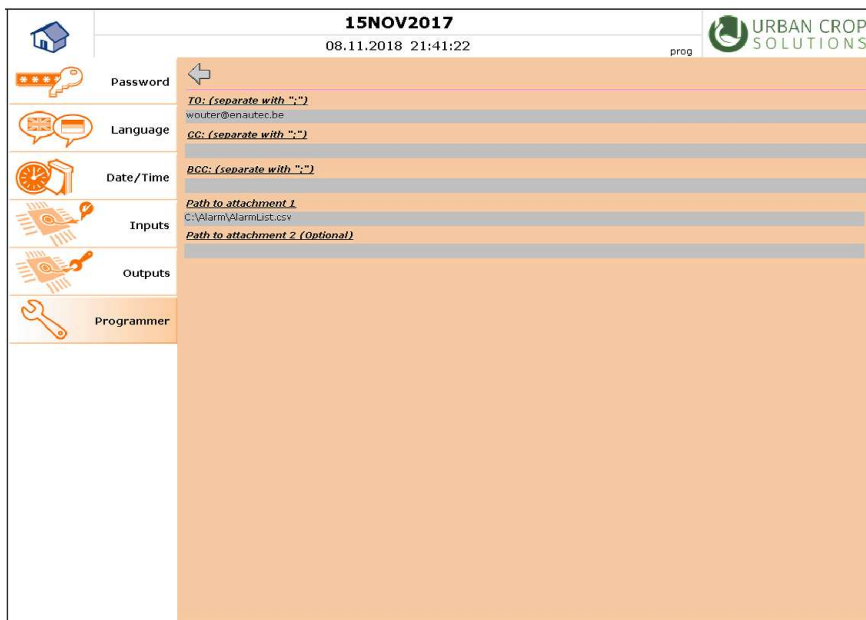


Figure 29 - Service Screen UI

It is also through a newly revealed tab that one can access programmer settings, so collected databases can be sent to remote desktops, be them readings or alarm listings, through email to both the consumer and the company.

4.2 PLC Software

On the back end, to program the PLC it is done utilizing the programming language of Structured Text following the IEC 61131-3 standard. Utilizing Structured Text has the big advantage of the code being more easily readable by people of a different background such as Informatic Engineering, and as such make the interactions between the logic programming of the plc and the HMI integration much easier and more expedient. Additionally, it is easy to use on different software due to it functioning like a high-level programming language.

The software used to program the PLC is Beckhoff's TwinCAT 2. While it is an old program, it is also easily compatible with old operating systems and supporting systems like fieldbuses or SCADA. However, the way the programming is structured in Urban Crop's systems there is no third-party SCADA system, as the visualisations are generated and configured by the PLC itself.

The system uses a Modbus RTU protocol in order to collect and process data gathered from all the various sensors. Modbus RTU is a reliable and robust serial communications protocol that enables the system to gather all the data from the sensors via a master-slave directive and using a RS-485 connection allows for multiple slaves for a single master.

Past Abnormalities and Risk Factors

In this chapter different cases of past malfunctions are analysed, what were their causes, their effects and the ramifications they had in the product design and software programming, alongside the solutions employed on site to resolve the issues. The names and location of the clients were withheld for privacy reasons, and as such they are referred to as code names.

5.1 Client “Harbour”

Client Harbour had multiple malfunctions at different times, each seemingly from a different part of the system, ranging from irrigation issues to mechanical jams and pump malfunctions. Each case was analysed separately alongside their causes and outcomes.

5.1.1. First Malfunction: Elevator Jammed

In this first case it was reported that the elevator tilted during a harvest cycle, jamming the entire system. Once the maintenance crew arrived at the scene it was confirmed that the cause of the jamming was not due to the over extension of the tackers, which would be the most damaging scenario. It was also not caused by a dropped or tilted gully stuck in the chain. Instead, this malfunction was caused by a decoupling of the clutch, which lead to only one chain pulling the elevator. This key factor caused a chain of unfortunate events, being the most damaging one the bending of the supports that connect the chains to the elevator.

Thankfully, the damage didn't compromise the structure or burn the motors, so the damage wasn't critical or particularly damaging to the functioning of the unit outside of the elevator damage, so not many repairs were needed past that. Initially the replacement of the screws and replacing the coupling and the clutch, which thankfully was enough to resume normal functional routine. Due to the nature of the malfunction, no change in the programming and physical build was made.

5.1.2. Second Malfunction: Blocked Irrigation

The same container had another failure a few weeks later, this time the symptom being that the irrigation drippers were having inconsistent flow and at times completely blocked. This was a cumbersome and impractical issue to observe and diagnose since the construction of the container drippers located deeper within the unit are of difficult access due to the gullies and lights.

To properly check the issue, first the gullies were removed via normal gully request. Secondly, the lights were removed from the bottom layer up. This was required so there would be room for the technicians to be able to move and inspect every single dripper individually. Since the gullies were removed the water coming out of the drippers were leaking onto the floor. As it was reported, several of the drippers were indeed obstructed, and were replaced. However, soon after they were blocked again. The line was then connected to a hose and had water pumped into it, to try and expunge any obstruction inside. Even still, new drippers were still getting blocked soon after. A cut of the pipeline revealed a different issue: algae growth on the inner walls of the tubes, blocking the drippers either partially or fully. Algae was also observed on the drain gutter.

Considering the readings for pH and EC were in line with expectations and how there were no signs of outside contamination, the cause of the issue is assumed to have been mishandling of the device by the client, in particular whenever they used empty gullies as a buffer space between larger plants they didn't cover the empty gully holes, exposing the water that runs through the gully to direct light, which lead to the proliferation of algae throughout the system, blocking the irrigation channels and causing multiple plants to die by drought. As a solution, hydrogen peroxide was sprayed to kill the algae in the outer pipelines as well as mixed in the main tank to do multiple cycles of irrigation to cleanse the inner pipeline. The main irrigation channel on each line was also replaced. Upon the completion of the maintenance and refurbishment, this particular issue never rose again.

5.1.3. Third Malfunction: Pump Failure

The third malfunction was noticed when, after a weekend of normal readings and no one present in the installations, an employee arrived at the container and noticed most plants with either severe water deprivation or outright dead. None of the alarms triggered, but first analysis on site showed that the main tank was running low on water, and the recycle tank was overflowing.

Despite the obvious flaw of the alarms not being triggered in this situation, the first priority was to get the irrigation system up and running as to not deprive the plants of more nourishment. The water tank was filled as soon as possible, and the nutrients measured and mixed into the structure, and fed into the irrigation channels, that worked as intended. The draining pipes were also operational. However, upon reaching the recycle tank the recycle pump would not pump the fluid into the filters, however the pump was still working. Closer inspection revealed a piece of fabric, previously used to clean the recycle tank, stuck in the pipe, blocking

the flow of the water but not the functioning of the pump. Upon the removal of this obstruction the system appears to be working as intended and has been functional ever since.

The biggest issue still standing is finding the reason behind the alarms not triggering, as well as the water level not updating in the program as the water level was progressively being lowered. The sensors were all in functional order and were all locally returning results and the local router was also functional. However, the client had not replaced the SD card with a new one sent a few weeks prior, serving as a memory stick for data recording and transmission, causing the data to not be properly communicated to the online services, giving off the illusion that everything was functional and in order. Once a new card was installed no more issues arose.

5.2 Client “Port” – Mix Pump Failure

In this case, all the system optics were in check: sensors for EC and pH were working as intended, and UV light was also perfectly functional, however every planted crop was dying, the symptoms shown being burned roots and dry leaves.

Initially, tests were conducted on the sensors to try and diagnose the problem, but they were well calibrated and indeed the water passing through them had properties within the values read. Additionally, no contamination was found in the main tank.

Next, the pumps were checked, and it was found out that the Mix pump, the pump that redirects the water flow through the EC and pH sensors and UV lamp, was broken. Due to this, there wasn't any flow in the pipes, and the sensors kept reading the same, correct values. This caused a chain reaction where since the pH sensor was reading the solution as too basic and as such kept ordering the acid peristaltic pump to keep pumping acid into the main tank, turning the main tank contents into a heavily acidic substance, resulting in burning the plant's roots.

The obvious solution is to replace the pump, but the issue remains that should this pump ever break again in this or another container there is no way to find out other than checking it in person. To prevent this, future units will house flow detectors at each pump's exit. These emit a signal that is going to be used in the code as a way to notice HQ and consumer when the pump fails. Considering how this change is still not implemented, it is not considered in the code, but it should be noted that it should be relatively easy to add it once the change goes live.

5.3 Client “Market” – Filter Error

Before starting this description, it should be noted that the model in which this error occurred was a slightly different one from the one described earlier. This is relevant since in this unit there wasn't an irrigation loop from the backwash in the automatic filter into the recycle tank, rather the backwash would be flushed into the drain. In this case, a container unit was found to be losing water at an alarming rate. The malfunction was caught early enough so that the lack

5.4 Multiple Clients – Tacker Malfunction

of hydration wasn't impactful to the crops. At first sight, there wasn't any leak in the main tank and corresponding pipes leading into the gullies.

After a presential check by technicians it was found out that due to some error, water was being flushed via filter backwash at an alarming rate. To understand why, an explanation on way the backwash is regulated is due. To regulate when the backwash is activated, the filter measures the pressure between the inlet and outlet pipes. Once the difference reaches the predetermined value (only adjustable manually via a screw in the equipment, similar to a potentiometer) a backwash cycle is initiated, cleaning the filter and, in this slightly older model, flush the water used in said backwash through the gutter.

However, this difference in pressure wasn't due to debris in the filter, but an obstruction in the outlet. Because of it, despite frequent backwashing cycles, the pressure differential was unchanged, which would proceed to proc another backwashing cycle. Each backwashing cycle consumes around 5 litres of water, and with near constant cycles this would drain the recycle tank at an unsustainable rate.

To prevent this, the previously described backwash loop was designed. Water flushed in the backwash cycle would be redirected to a secondary, simple and easy to replace filter and would follow into the recycle tank. Additionally, it was added to the program an error condition for when backwashing is done for extensive periods of time, being the default 30min, which would stop the irrigation and backwashing cycles and generate an alarm.

5.4 Multiple Clients – Tacker Malfunction

In multiple cases there have been reports of critical failures regarding tacker and elevator malfunctions. Most commonly, the tackers would somehow move beyond their natural end of course due to sensor malfunction, or the elevator not recognizing a level sensor and moving beyond it's intended stop, forcing itself down with the tackers and causing a mechanical jam.

This level of malfunction is very hard to predict in an automated system, since it's causes either take root on an incorrect QA testing or, much more commonplace, a faulty sensor that has either stopped working or had its communication with the PLC cut.

This error is by far the most damaging that could occur short of a catastrophic failure and requires heavy maintenance and repair should it happen. The tackers in particular are hard to replace and re-gear should they come completely out of the rail.

Currently the company is in the brainstorming phase trying to resolve this situation. A proposed solution would be to use eccentric motors so that the course of the tackers is fixed, and therefore unable to go off the rails short of some kind of freak accident. Another proposed solution involves utilizing the sensor used for the detection of the backwards limit as a last resort of detecting a failure of the forward limit sensor.

As of the time of writing, no conclusion has been made towards this issue.

Development of the PLC code

In this chapter the development process of the targeted goal is shared, alongside with the different iterations used and final project obtained. Key sections of the code and sequential function chart in the form of GRAFCET are also presented in this section with the diagrams being available in appendix.

6.1. Key Areas

Through the analysis of previous error codes and malfunctions, it is possible to narrow down the most important segments to consider when proposing a solution. As such, three main components were identified as sources of problems and can be easily controlled via software and no added hardware are the elevator, the tackers and the irrigation system. Of these three, the irrigation system could be programmed in relative isolation, while the elevator and tackers movement are somewhat interlinked and therefore need some limitations when operating manually.

6.2 Elevator

The first step to understand the elevator functioning was the observation and analysis of its behaviour. This section explores the movement of the elevator, it's interactions with the level sensors and how it is commanded in Harvest Mode.

6.2.1 Rewriting Harvest Mode

To further facilitate this understanding, the elevator routine for the harvest mode in layers 3 and 4 has been rewritten. Previously, the programmed behaviour would mean that the elevator would reset to the top position every time there was a Gully request. This accrues around 40 seconds of extra downtime per Gully request, which for a full harvest session could be a huge time sink.

The proposed solution would be to have the elevator move to and rest at position correspondent to the Layer 2 Sensor once the harvest mode button for the bottom pair of layers has been pressed. As such, the GRAFCET in Appendix A has been proposed. A snippet of the Grafcet highlighting the new development in the code can be seen in image 30.

6.2 Elevator

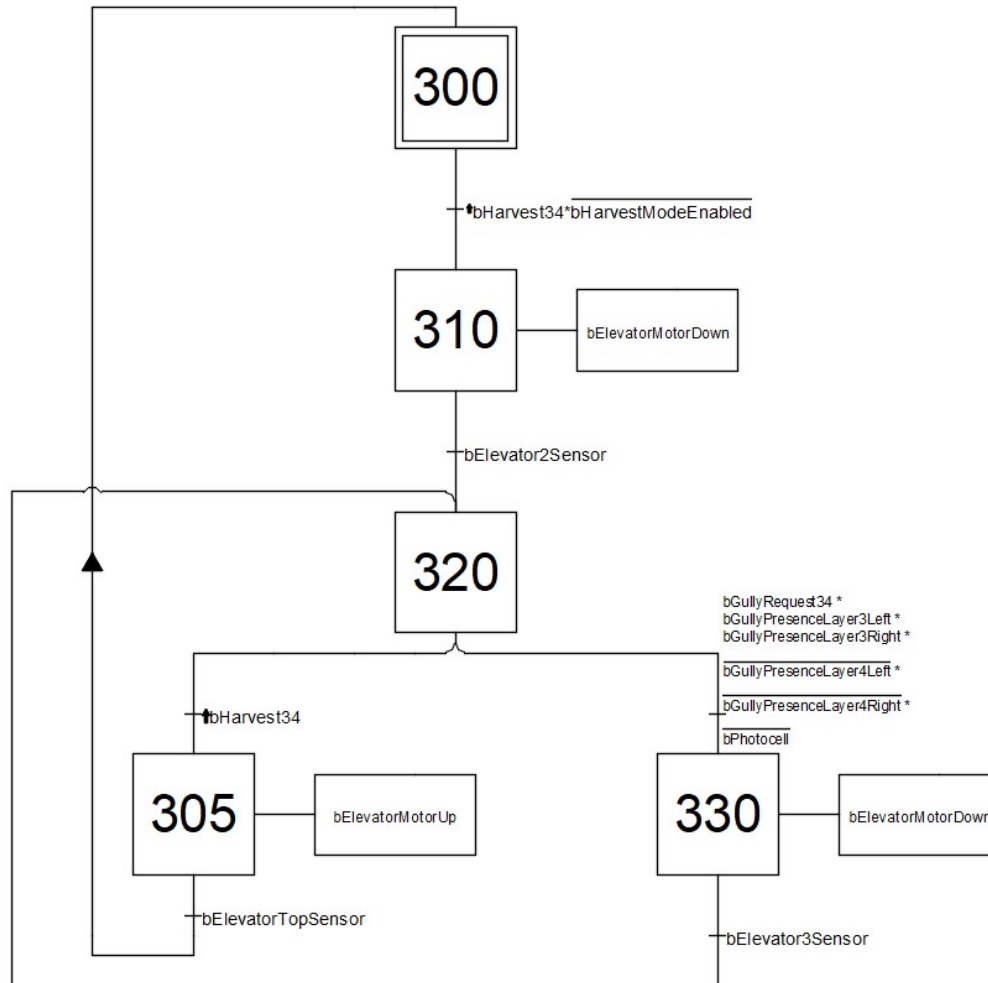


Figure 30 - GRAFCET section highlighting the movement between Top Sensor and Resting position of Harvest Mode 3/4

During normal functioning once the Gully request button has been pressed the programming follows a very strict sequence upon which not more than a single actuator might move at the same time, to avoid unintended collisions between the tackers and the elevator or the collapse of a gully from the elevator. Only once the user has turned off Harvest Mode can he activate it on the other layer, preventing conflicting instructions.

It can be observed that the sensors mostly interact as a way to limit movement and mark the end of specific stages, while the speed of the movement is handled by the parameters within the PLC program.

6.2.2 Service Control

Of the two requested modes of control, Service mode is the simpler one to implement. In this mode most restrictions, be them due to safety or efficiency, applied to the controls the customer has access to are not applied, only keeping the end of course restrictions so a larger accident can be prevented.

Initially, the Grafcet proposed was as seen in Figure 31:

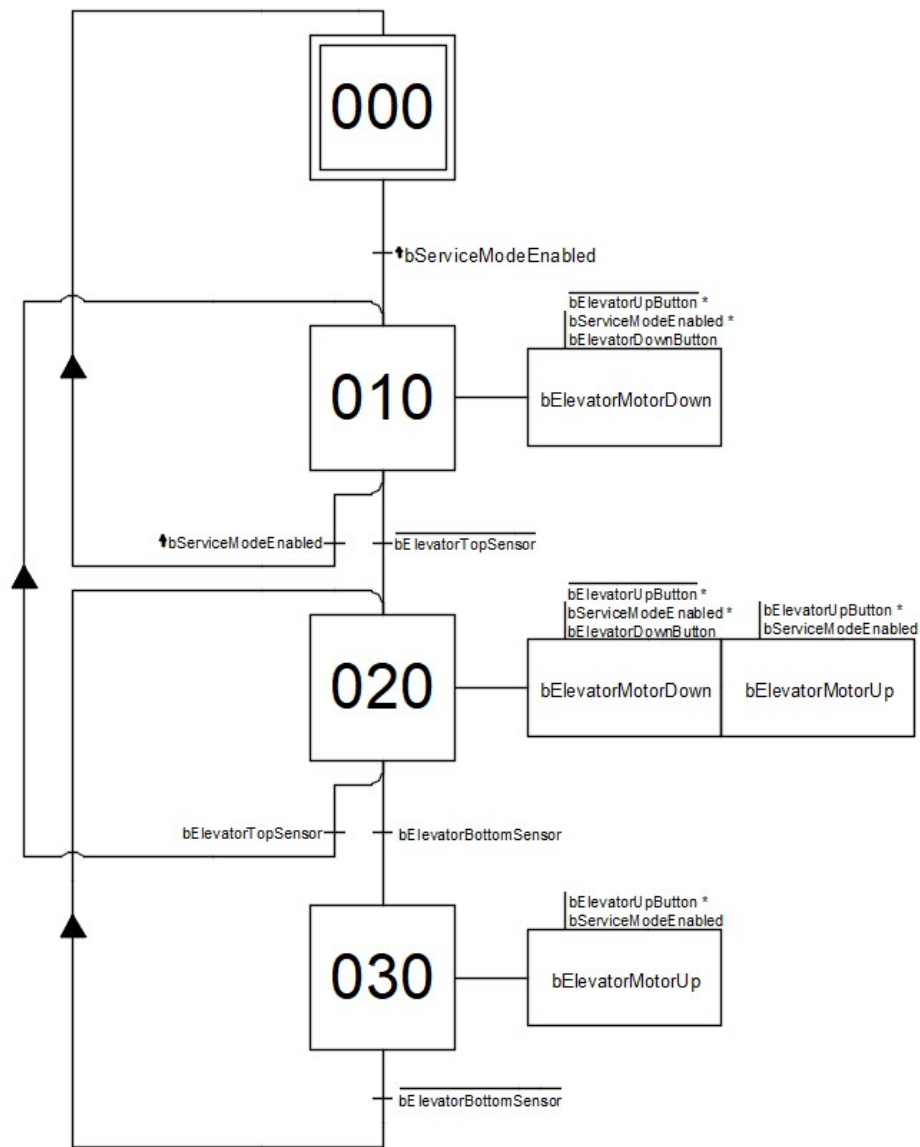


Figure 31 - Prototype GRAFCET for Service Mode movement

As requested, this system only has two restrictions: The top sensor blocks the elevator from going up and the bottom sensor blocks it from descending further. However, certain flaws are evident from the get-go: the manual activation could only be started from the top position, and once it enters the space between the top and bottom sensors there is no internal way to keep track of where it is. Additionally, since to first “activate” the sequence it is needed to press the service button this can lead to problems should the system proc an alarm and stop the gully request midway through.

Considering these factors, the GRAFCET found in Appendix B was drafted.

Utilizing this behaviour, it is possible to always pinpoint where the elevator is at all times, even during sequences such as the gully request process. Furthermore, the service control switch is now relegated to the actions instead of the transitions, allowing for a more immediate and accurate reading of the current position.

6.2.3. Consumer Control

In addition to the end of course sensors, manual control on the client's end should have a couple more limitations compared to the service page. The biggest difference is that should the elevator descend upon a sensor, the movement must stop until the descend or ascend button is pressed again. This GRAFCET is presented in Appendix C.

Some issues were raised, however. Similarly, to the first proposed solution for the service mode, having the manual mode switch be part of the transitions makes this system unable to keep track of the movement of the elevator outside of the mode. It also has the issue of not really being workable in practice, since the stages preventing it from moving aren't momentaneous, with a certain hysteresis existing that could raise issues that could throw off the entire sequence of events. With these issues in mind, a different solution was proposed.

With this new solution the introduction of stages dedicated to the hysteresis of the sensors can be seen, preventing the previously referred possible malfunction. However, due to the nature of the inputs, finding a solution that would track the normal behaviour of the elevator could prove to be challenging. Instead, as is shown in the next sub section, a different draft was proposed.

6.2.4. Background check

Due to all the limitations on the consumer manual mode, having it also track the background movement of the elevator would be too convoluted and messy. Instead, it was proposed the usage of the service mode loop as a method to keep track of the background status of the container.

Since the activation of elevator motor via Service mode is handled by actions within the GRAFCET stages, the stage transitions are ruled by sensors and motor activations therefore having independence from either of the manual activation modes, making it into a perfect background check on the status of the elevator. To integrate the consumer manual mode, it would be as simple as matching the different stages in consumer mode with the correspondent stages in the background check. The proposed GRAFCET can be found in Appendix D.

Each transition between the two stage trees is ruled by the activation of each respective mode button, with priority being given to the Service Mode activation button. This way should there be conflicting instructions control is defaulted to the Service mode. Having this kind of background check loop allows the program to be more precise with the known information of the current elevator position.

6.2.5. Motor Commands

In this section presents a brief overview of the current motor activation code. On top of only being able to be activated on certain stages, it also has a couple of extra restrictions. In Consumer manual mode it cannot be moved should the tackers not be in their backwards position. Otherwise, an accident where the elevator forces itself through a set of extended tackers would be catastrophic. Additionally, should both buttons somehow be pressed at the same time, upwards movement is given priority. Below an excerpt showing the downwards movement is presented.

```

bElevatorMotorDown:=(  bElevatorDownButton
                        AND
                        NOT bElevatorUpButton
                        AND
                        bEnableTest
                        AND
                        bTackerSensorBackwardsLayer1
                        AND
                        bTackerSensorBackwardsLayer2
                        AND
                        bTackerSensorBackwardsLayer3
                        AND
                        bTackerSensorBackwardsLayer4
                        AND
                        (<Grafcet Stages that allow downwards movement>)
                    )
OR
(  bElevatorDownService
  AND
  NOT bElevatorUpService
)
(...)

```

Figure 32 - Code snippet showcasing the manual control of the Tackers

6.2.6. Mechanical Movement User Interface

In order to design a functional user interface for the mechanical control, it is needed to identify not only the necessary buttons but also the necessary indicators of motor movement and actuator positioning. To achieve so, many intermediary stages were proposed. These would be activated based on the last sensor activated and which direction the motor is turning. These stages would be for in between elevator sensors and between the two sensors for each of the tacker sensors. It would also have buttons for Harvest Mode and Gully Requests to test these functions. Note that in the Figure 33 there are buttons to activate and deactivate User and Service mode. In the final implementation, these two are not present and the activation of such modes is ruled by a password in the Service screen of the current program.

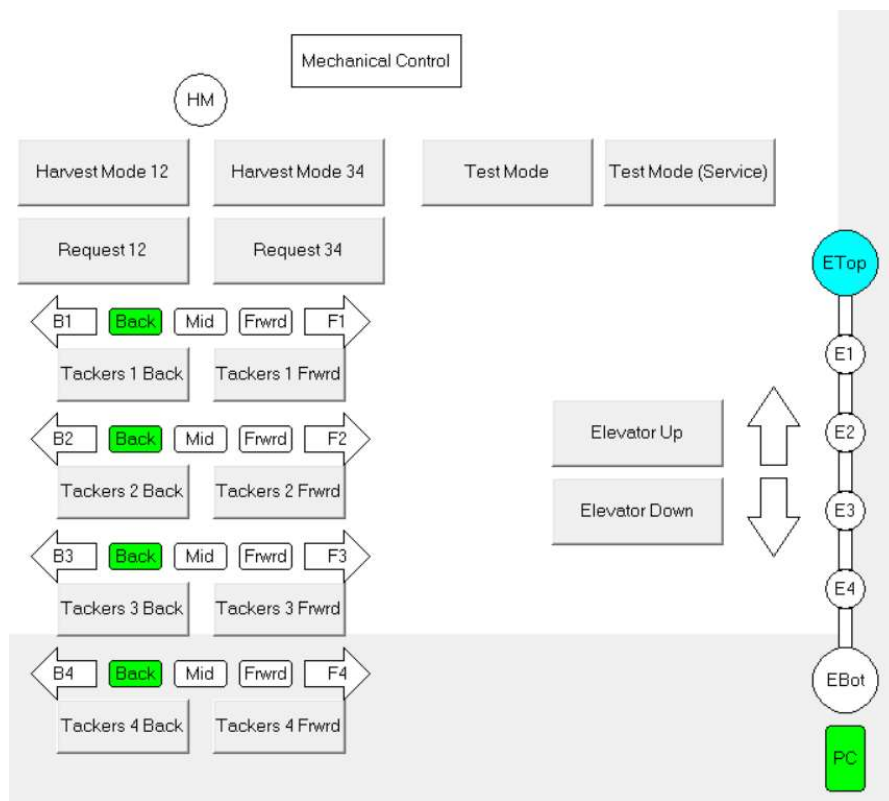


Figure 33 - Prototype UI for the Mechanical Control screen

6.3. Tackers

Tacker movement is much simpler in comparison, as the only restrictions it has is the blocking of any movement beyond the end of course sensors. As such, movement is commanded by the activation of the buttons that enable both manual modes along with the respective Tacker movement button. Should both buttons somehow be pressed at the same time, backwards movement is prioritized. Below is a snippet of code from a forward movement of a single Layer of tackers.

```
bTacker1MotorForward:= (
    (
        bServiceModeEnabled
        OR
        bUserModeEnabled
    )
    AND
    bTackerForwardLayer1Button
    AND
    NOT bTackerSensorForwardsLayer1
    AND
    NOT bTackerBackwardsLayer1Button
)
OR
(...)
```

Figure 34 - Code Snippet of the Tacker forward movement

6.4. Irrigation

Similarly, Irrigation also shares the same functions and limitations between both consumer and Service modes. The only restrictions that apply are that the hydraulic pumps cannot be activated with low water level, preventing air intake that would otherwise damage the pumps. From this screen, it is possible to manually activate all the hydraulic pumps (main, recycle, circulation) provided the previous criteria are met, activate the peristaltic pumps that govern the admission of acid and nutrients into the main tank and operate the automatic valves individually.

In the same menu it is also possible to visualize the current state of the automatic filter, yet it is not possible to manually activate a backwash due to manufacturer limitations placed upon it. The status on the level sensors of the recycle tank and the water level on the main tank can also be seen in this screen.

The readings for EC, Temperature and pH are also displayed here alongside the readings for Humidity. There are also two warning levels for the main tank that show if the tank is overflowing or too empty, which may indicate problems along the water lines.

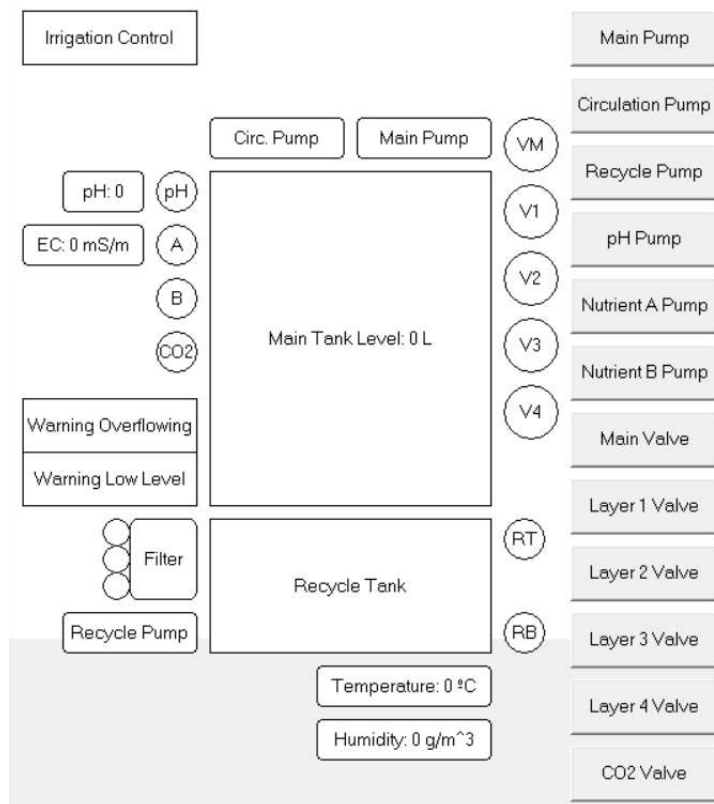


Figure 35 - UI for the Irrigation control Screen

6.5. Lights

As for the lights, the objective is to be able to manually toggle each separate driver individually in both service and customer manual control. Each layer got 5 drivers each controlling 5 lights each, with the germination rack having 4 layers with a single driver each. In the program, this is very simple to implement: Each driver got an associated button to turn on and off with a matching indicator that shows the current state of the lamp, as it can be seen on the UI below.

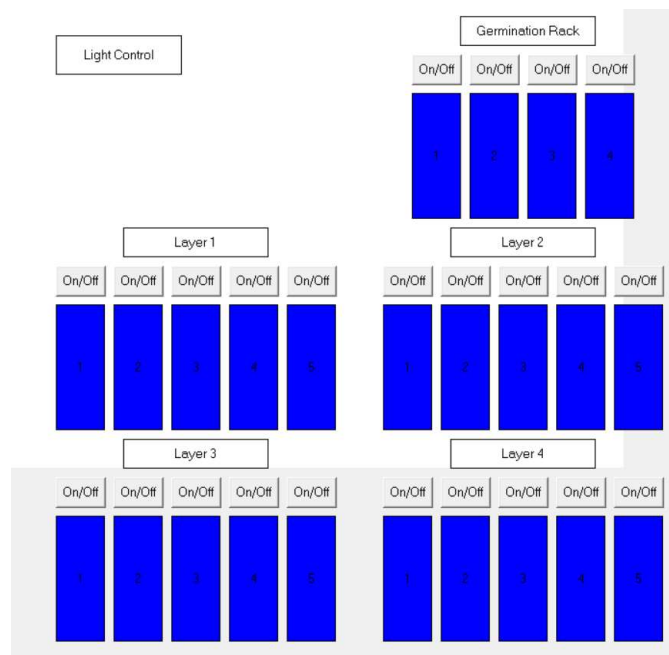


Figure 36 - UI for the Lights control screen

6.6. Overview Page

In order to have a general viewing of the system, an Overview page was designed. In this page one can see the current state of all the recorded information. These would include, from the mechanical side, Indicators for the elevator sensors, Gully Presence sensors, Tacker sensors and Motor activation sensors.

On the irrigation side, it would feature the readings from the pH, EC, Humidity and Temperature sensors, the Main tank water level, the sensors for the recycle tank, the hydraulic valve positions and Pump activation indicators, as well as other miscellaneous indicators such as filter and CO₂ valve status. Finally, it would also feature the current state of all lamp drivers.

6.7. Test List

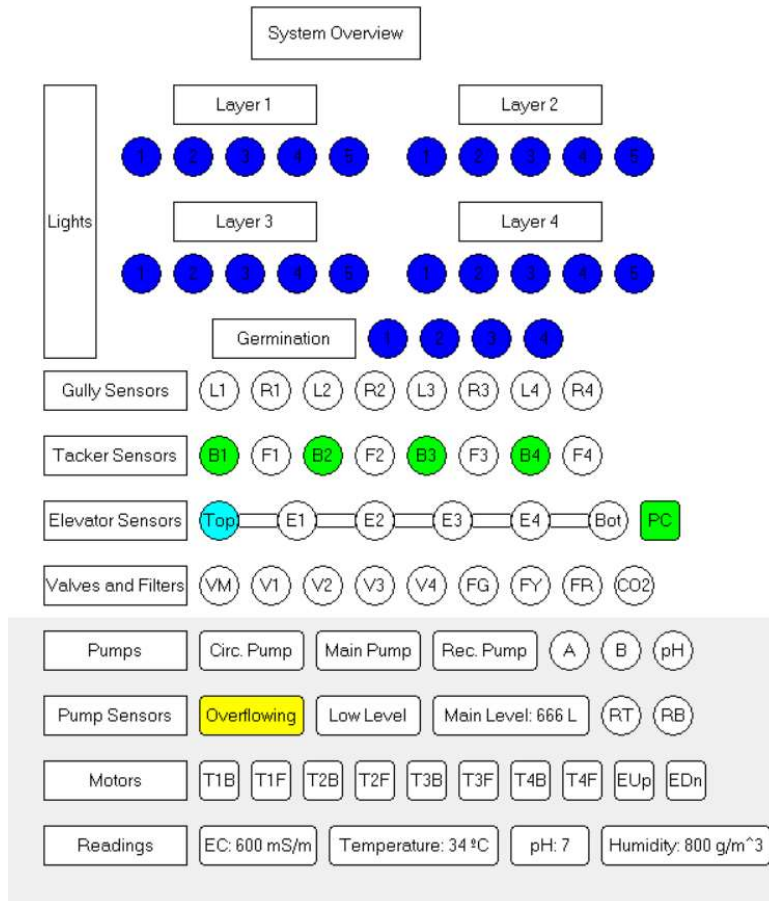


Figure 37 - UI for the System Overview Screen

6.7. Test List

The final item in the program is the integration of the testing procedure checklist into the program itself. This check list must include for each item 3 indicators, one of OK, one for Not OK (NO) and one for Does Not Exist (DNE). Additionally, there should be two more entry data points: Place of Action and Remarks. These would be strings that would detail what went wrong in the testing procedure and at what location could fix such shortcomings.

The main checklist consists of 4 sub-groups: Germination Rack, Gully Racks, Elevator and Skid. Each of these groups could also be divided into 3 subcategories: Electric, Mechanical and Irrigation.

On top of the main categories, the header should include details such as the date of the first test and who tested it, the most recent check and the name of the tester, what container model it is, position of the drain and position and type of connection for both water supply and electricity supply. Finally, there should be a final remarks section at the end to add any additional notes not covered by the checklist.

However, it isn't possible to introduce the entire list in a single page due to the sheer number of variables attributed to each of the input possibilities. To remedy this, the test list is separated into four different tabs, each sharing the same header containing the check data and model type regardless of what tab is active at the moment.

Creation Date	D#2019-12-02	Checked by	Bernardo	
Last Check	D#2019-12-04	Checked by	Bernardo	
1	Container Type	FarmPro 130000		
		OK	NO	
		DNE	Action	
			Commentary	
10	Misc. Checks	Outdoor Unit	Test	Test
		Heat Resistance	Test	Test
		Prihoda Cloths	Test	Test
		Communication Mod	Test	Test
		Drain	Test	Test
11	Just for Collection	Electric diagram in cabinet	Test	Test
		Gutters in front of container	Test	Test
		Door handle disassembled	Test	Test
		Trays germination racks	Test	Test
		spare parts	Test	Test
		cups	Test	Test
12	Final Remarks	TestTestTestTestTest		
		TestTestTestTestTestTestTest		
		TestTestTestTestTestTestTestTestTest		
		TestTestTestTestTestTestTestTestTestTest		
		TestTestTestTestTestTestTestTestTestTestTestTestTest		
		TestTestTestTestTestTestTestTestTestTestTestTestTestTestTestTestTestTest		
		Test		

Figure 38 - UI for the Test Checklist screen

6.7. Test List

Conclusions and Future Work

This dissertation focused on the development of a remote-control software platform for both consumer and technician usage, but it was also a chance to properly explore the technology behind the various iterations of plant factories, as well as their shortcomings when under consumer influence and their market limitations.

First, Plant Factories were described and each of their different systems found in most implementations detailed. In particular, the general advantages and disadvantages when faced with the economic realities of the world were also exposed, revealing that due to the very high upfront cost of a traditional Plant Factory, along with the still relatively high upkeep costs due to electricity usage consumer adoption has been quite slow.

It is then that a sized-down solution by the name of Plant Factory Containers is explored. This smaller, more compact solution was an order of magnitude cheaper than traditional implementations. Using Urban Crop's Solutions FP container unit as a basis, their solutions were studied and explored from the project phase up until the assembly and quality assurance stages.

Next, the current software in use was analyzed in order to find what kind of language it uses, what information it currently displays and what kind of actions one can already do in the current version. Armed with this knowledge, initial GRAFCETs were drafted as to provide a jumping point into the final product.

Then malfunction reports were analyzed, and key weaknesses were pinpointed, and if they originate from software failure, technical malfunctions or customer misuse. With these issues factored in, the final iterations of the code were proposed and eventually approved. The program itself featured a background check loop to always be able to keep track of where the different actuators of the system are, as well as separating consumer and technician control options. A Q&A checklist was also implemented into the program itself so all information about a certain unit can be found within its programming without resorting to external programs.

The code developed in this dissertation has been approved and will be integrated in the next software version that goes live.

However, it is clear this technology is still in its infancy, and it is possible to see that many improvements are still in the horizon. In the solution proposed by UCS FP for example, 5 motors total for the entire container unit seems like it is far from being an optimal solution and could maybe be slimmed down to 3 motors with two adjacent layers sharing the same motor for tacker movement.

Additionally, another possibility could be an easier way to access the interior for maintenance as it is currently very cumbersome. Irrigation systems are also prone to algae, clogging the irrigation drippers, and it would be beneficial to attempt different systems that aren't as susceptible to minor debris as the current solution in place.

Conclusions and Future Work

In terms of economic viability, there are also various points to improve upon. Traditional PFLAs are still too much of an initial investment and container units are too small for larger companies and consumers of produce like supermarket surfaces or larger surface restaurants. A proposed solution could be the purchase of various container units, essentially scaling up in increments. The offset is that this kind of scaling will eventually be outpaced by a full-fledged PFAL, which utilizes space more efficiently and allows for more automation like automatic seeding and harvesting systems. Another limitation is still the upkeep cost. Each unit, be it container unit or PFAL, still consumes a lot of electricity to power its lights and motors. This issue is one that will most likely vastly improve overtime as better, more energy efficient lamps are developed and the systems themselves become leaner.

Despite these setbacks, plant factory container units are poised to carve a niche due to their unique balance between price and size, allowing for smaller initial investments compared to a full-fledged plant factory while still allowing for increased scalability via the purchase of additional containers. While they can still be improved, the solution employed in system's such as UCS' FP are very robust and are already proving to be a viable solution to the struggles of modern farming due to the usage of intricate and compact systems and remote supervision tools such as the one developed in this thesis.

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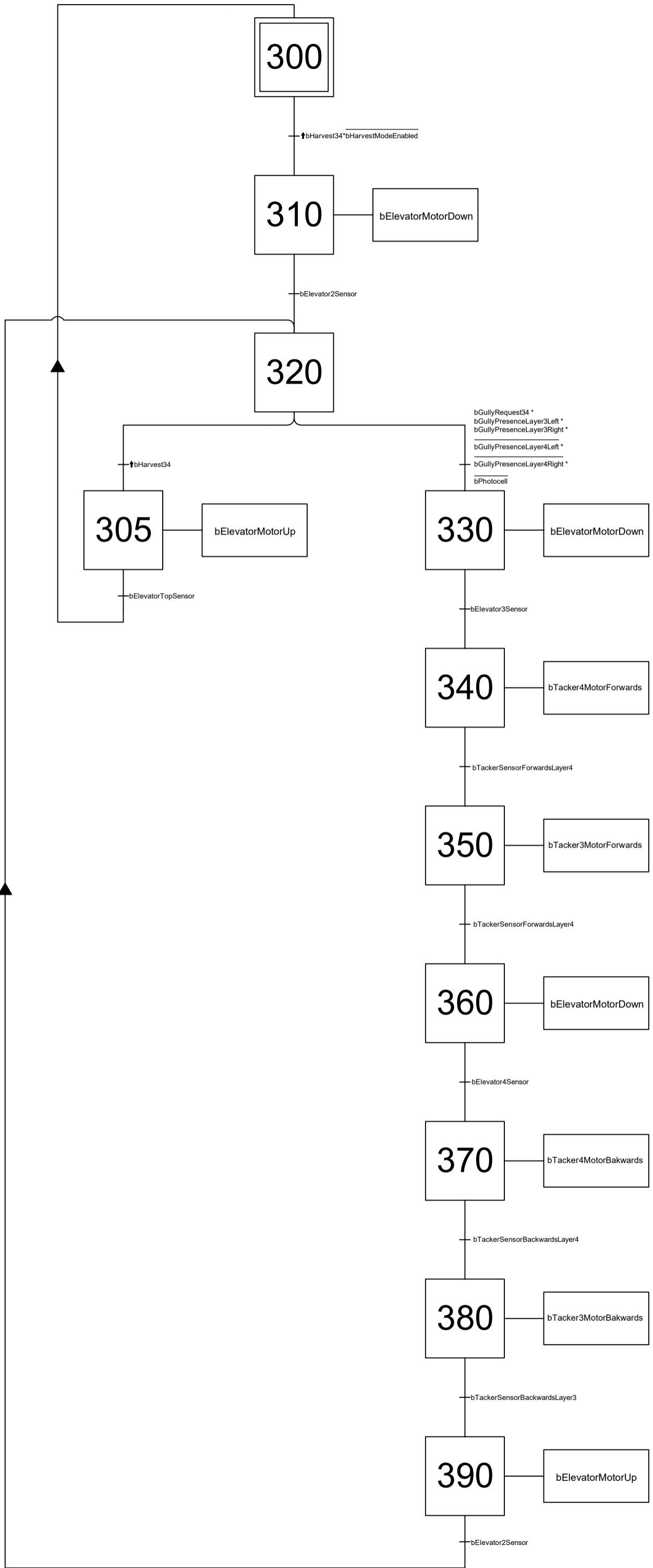
References

Appendix A - Rewritten Harvest Mode

As described in Section 6.2.1., this GRAFCET was created in order to better explore and understand the functioning behind a UCS FP Gully request. In particular, the bottom layers had a long gully request time since the elevator always defaulted to the top position. In order to shorten this delay, an intermediary resting point using the second layer sensor was added between each delay and pressing the harvest mode button again after a request cycle was completed will return the elevator to the top position.

This GRAFCET was designed in accordance to the IEC 60848 standard.

Appendix A - Rewritten Harvest Mode

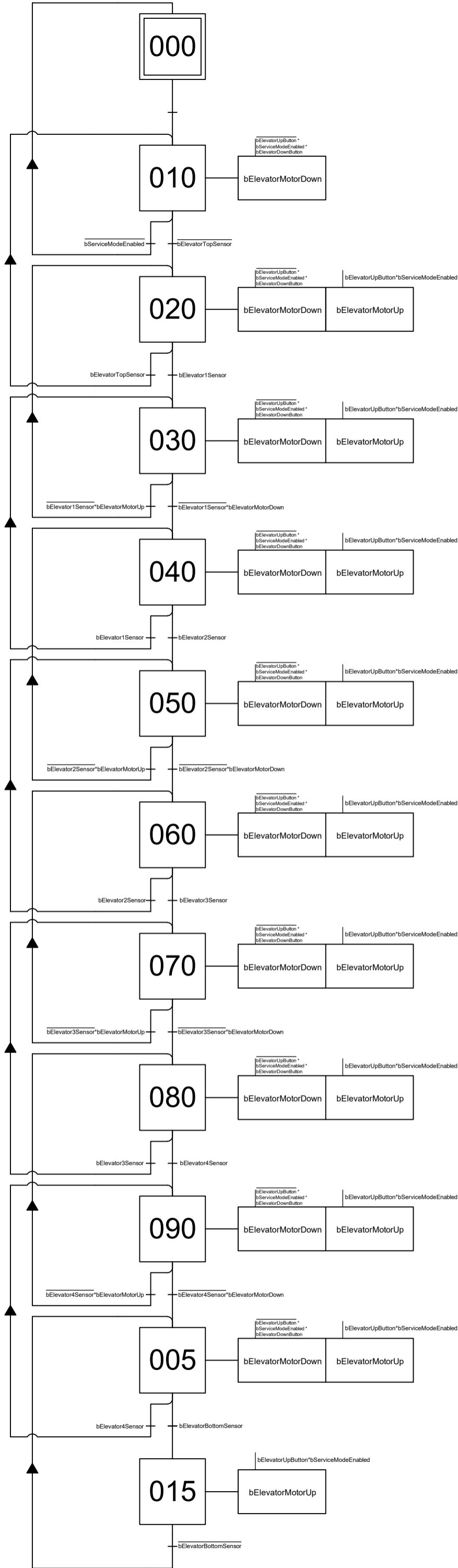


Appendix A - Rewritten Harvest Mode

Appendix B – Revised Service Mode GRAFCET

As discussed in Section 6.2.2., this GRAFCET is the revised version of the behavior of the program while in Service Mode. This includes fixes such as being able to track the position of the elevator during all movements without having service mode enabled.

This GRAFCET was designed in accordance to the IEC 60848 standard.

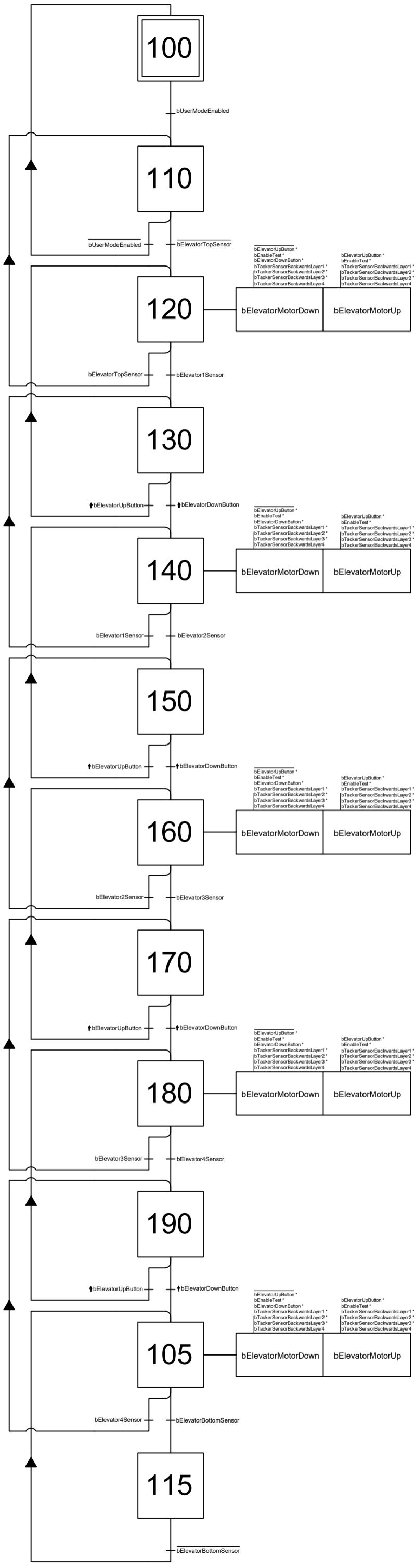


Appendix B – Revised Service Mode GRAFCET

Appendix C – Initial Consumer Mode GRAFCET

As discussed in Section 6.2.3., this GRAFCET describes the initial behavior for the Consumer Mode manual control of the elevator. Note that unlike Service Mode, this one requires another press of the button to move the elevator once it reaches a new layer.

This GRAFCET was designed in accordance to the IEC 60848 standard.



Appendix D –Final Elevator Behavior GRAFCET

As described in Section 6.2.4., this GRAFCET shows the behavior of the elevator utilizing the background check as a way of keeping track of the position of the elevator and having a separate tree for the Consumer Mode, connecting each other at the respective positions.

This GRAFCET was designed in accordance to the IEC 60848 standard.

