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SELF-AWARE AQUARIUM CONTROL SYSTEM

Master’s thesis

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Ph.D.

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TALLINNA TEHNIKAÜLIKOOL
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ENESETEADLIK AKVAARIUMI JUHTSÜSTEEM

magistritöö

Juhendaja: Kalle Tammemäe
Ph.D.

Tallinn 2019

Author’s declaration of originality

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

Author: Gunnar Kotkasets

06.05.2019

Abstract

This thesis introduces the design of an experimental self-aware freshwater aquarium controller. The goal is to implement a computing system with a limited awareness capability and develop self-decision-making logic on a sensor-actuator network. The development methods in current thesis are based on the results of a questionnaire composed for fresh and marine water aquarists exclusively for this research. The most suitable environmental perception system for such platform is introduced, designed and partially built for proof of concept. ARM Cortex-M4F microcontroller-based unit uses several sensors to perceive environment microclimate changes and necessary actuators to keep them under control, being mostly independent from the human operator presence. Such a system can perceive the environment in different parameters, validate their credibility and verify measurements that may lead to an inaccurate representation of an environment. Health of the environment microclimate is evaluated with different sensors that are continuously monitoring parameter values. With the collected dataset, it is possible to create a representation model of the environment's microclimate. The main issue with the ARM Cortex-M4F microcontroller based environmental perception sensor-actuator network system is finding suitable algorithms and choosing a level of self-awareness. It has been shown, that the selected approach for such system is successful – results of the environment monitoring and controlling algorithms are proven, and further improvements may significantly add more independence to this system.

This thesis is written in English and is 57 pages long, including six chapters, 27 figures and 28 tables.

Annotatsioon

Eneseteadlik Akvaariumi juhtsüsteem

Käesoleva projekti eesmärgiks on luua iseendast ja ümbruskonnast teadlik olev akvaariumi juhtsüsteem, mis suudab hoida veeparameetrid stabiilsete ja sobivatena seal pesitsevate elusorganismide jaoks. Valitud meetod sellise juhtimissüsteemi ehitamiseks näeb ette küsimustiku koostamist hobi ja professionaalsete akvaristide jaoks ning erinevate müügil olevate akvaariumikontrollerite uurimist. Tulemusena ehitatakse eksperimentaalne eneseteadlik akvaariumi kontrolleri juhtplatvorm.

Antud lõputöö eesmärgiks on uurida väliskeskkonna ja süsteemi enesetajumise ning kontrollimise võimalusi. Eneseteadlikkuse mõõtme saavutamiseks on kasutatud stiimuli ja eneseväljenduse mudelit (vaata joonis: Figure 15: System integration to self-awareness model), mis on saavutatud reaalses süsteemis tarkvaraliselt.

Lõputöö eesmärgi saavutamiseks on uuritud arvutusliku eneseteadlikkuse saavutamist arvutisüsteemides, on uuritud kuidas ehitada teadlikkuse loogikat nii, et seda saaks taaskasutada teiste parameetrite ja süsteemide peal tervikuna. Ümbruskonna ja iseenda tajumiseks ning kontrollimiseks kasutatakse sensoreid ja täitureid, mida ühendab mikrokontroller.

Tulemused näitavad, et teadlik süsteem suudab dünaamilisemaid väliskeskkonna parameetreid jälgida ja kontrollida paremini kui klassikaline elektromehaaniline süsteem. Lisaks suudab süsteem jälgida sisemiste sõlmede korrasolekut ja hinnata seeläbi enese tervislikku seisundit.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 57 leheküljel, 6 peatükki, 27 joonist, 28 tabelit.

List of abbreviations and terms

Aquarist	Fish keeper – human who keeps fishes in the tank of water
Brackish water	A mix of fresh water and salt water found in estuaries [1][1]
COR	1Link Controllable reverse direction flow pump
DIY	Do it yourself (self-made equipment usually)
Freshwater	Water salinity concentration, usually less than 1%
gH	General hardness – concentration of Mg^{2+}, Ca^{2+} ions.
GPIO	General-purpose input/output
HAL	Hardware Abstraction Layer
IDE	Integrated Development environment
IFTTT	web-based service to create conditional statements – applets.
kH	Carbonate hardness – bicarbonate HCO_3^- and carbonate CO_3^{2-} ions that buffers in the water to prevent the pH dropping.
NO_2	Nitrite ion is the toxic by-product for fishes of the nitrifying bacteria Nitrospira.
NO_3	Nitrate is a toxic nitrogen by-product for the fishes.
OEM	Original equipment manufacturer
ORP	Relative "purity" of aquarium water.
PAR	Photosynthetic active radiation.
pH	Power of hydrogen
PO_4	A Phosphate is a chemical derivative of phosphoric acid.
Radion control lightning	Programmable LED light module for Neptune Apex System
RO	Reverse osmosis. A method of purifying water
ROM	Read-only memory
Saltwater/marine water	Water salinity concentration is usually 3-5% salt.
UML	Unified Modelling Language
UPS	Uninterruptible power system
WAV	1Link Controllable wave making pump

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1 Introduction

An aquarium is a transparent tank of water where fish or other creatures live, and plants are kept [2]. Fish keeping is mostly relaxing hobby which does not take much time in the daily schedule but needs relatively strict discipline from a keeper. Fish keepers, also identified as “aquarists”, can be divided into three main subjects according to fish species, categorized by the type of water [3]. Today's typically managed disciplines are fresh, marine and brackish water aquariums.

In-home, the most common closed tank ecosystem is freshwater aquarium because of its undemanding conditions. Everyone can start basically with minimum knowledge or no experience with freshwater fish keeping. Beginners just must keep in mind to change water in regular basis and keep the temperature consistent. Providing enough (intensity and quality) artificial light is necessary when growing plants, also feeding the fishes should not be forgotten. More specific needs and requirements occur with marine type aquaria, known as saltwater fish keeping. Some may find the saltwater ecosystem more beautiful for an eye to watch because of the colourfulness and more exotic fishes and plants. Saltwater aquaria are also harder to keep – the salinity of water and temperatures which are usually colder from household conditions, require better cooling system. Most aquarists (especially inexperienced) are not aware of the third type: brackish water [1]. Some species naturally live in river estuaries and willingly prefer saline water instead of fresh (with salinity 0 – 0.5ppt) or ocean water (salinity over 30) [4].

As the Author of the thesis (hereinafter Author) is a fish keeper, he understands how much all the hobby aquarists love to take care of their aquariums. Fish-keeping consists of number of daily to monthly routines like feeding fishes, changing the water and using different aids to keep the aquarium visible. The history of using automation for maintaining different aquarium routines has been actual since the beginning of aquariums. Fish-keepers use everything to make the environment in a tank safer for living and ensure that everything is under control whether they are around or not. Inventing new features for controlling or monitoring the microclimate of fish tank is the fish-keepers enthusiasts’ playground. In the contemporary world using rigid automatics is standard. Working solutions have proven themselves, but there is always room for improvement for more fail-safe and why not, significantly smarter systems.

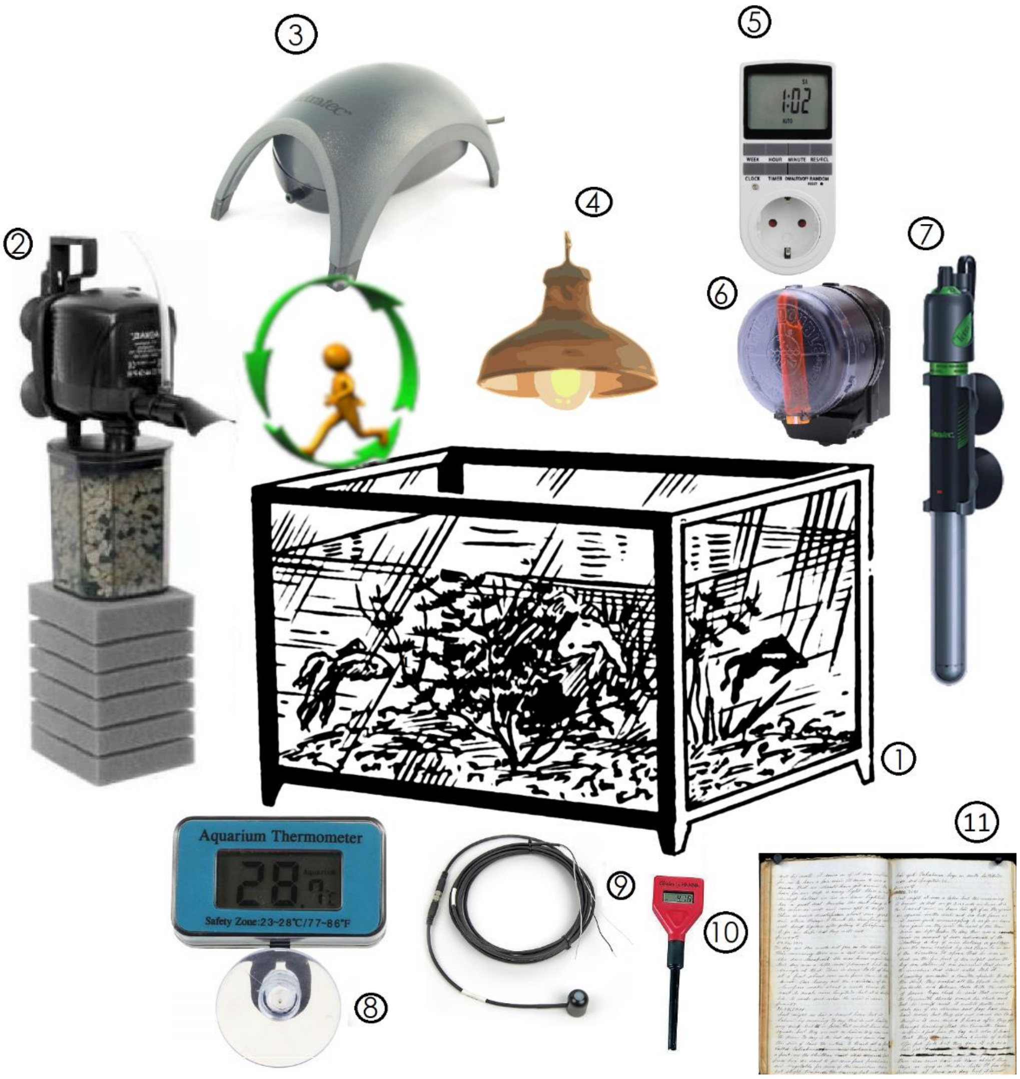

Figure 1: Regular hobby fish-keeper (human in loop) setup based on chapter 2.1

Standard rigid automatics do their job well, but aquarists still feel the lack of functionality to change the environment of the aquarium safer and make fish-keepers' life more peaceful. Instead of keeping static log book over parameters, manual maintenance cycle and keeping track of system parts wearing level, would be nice to replace all that with automatically collected dataset, automatic maintenance cycle and automatic system overhaul diagnostics. Based on the author's experience and fish-keepers feedback from the questionnaire (see. Chapter 2.1), brief classical overview of used equipment is shown in Figure 1.

Microcontrollers have brought us into a new era which gives further advantages in monitoring and controlling systems. Over the decades, massive development has been done with systems that can complete repetitive tasks with more performance and better accuracy. However, in the dynamically changing environment, there are multiple parameters which are related to each-other with relatively complex chemical and physical laws. Same applies to aquarium ecosystem. Traditional sensing and controlling verification methods are static and remotely unreliable and need smarter approach. Computing power has tremendously increased over the time and energy consumption has also decreased. Today's systems can handle large amount of data which has led information technology to a whole new level where new paradigms have been born. Awareness over private and public consciousness expands opportunities like measuring system depreciation and predicting failures in an early stage, or even perceive changing dynamics in environment microclimate.

Table 1: Equipment description (Figure 1)

1. Aquarium tank for aquatic environment keeping 2. Filtering system for clean and flowing water 3. Aerator system for dissolved Oxygen (O2) in water 4. Light for growing plants in an aquarium 5. 24H electromechanical timer for turning on/off lights day and night mode, but also for fish feeder and other equipment (if not included with the product)	6. Automatic fish feeder 7. Heater-thermostat for keeping temperature fixed 8. Thermometer for monitoring the current temperature 9. PAR meter monitoring photosynthetically active radiation to evaluate light source quality for plant growing 10. pH meter to assess the power of hydro-gen in water 11. Aquarium log book (environment parameters, device replacement dates, notes)

Embedded systems have wide application usages integrated more and more into today's world. IEEE article “Self-Aware Distributed Embedded Systems” declare that such systems are now being successfully deployed in environmental monitoring of natural phenomena as well as for in e-commerce, physical security, and other applications [5]. However, they claim that the complexity of growing sensor and actuator networks in embedded systems add a new layer of uncertainty - increasing risk of failure, which may result in system damage or even disaster in the environment that is being monitored.

Today, different approaches are used to design such applications for pervasive monitoring of the environment. Traditional sensors and actuators systems have a fixed pre-configured calibration and are usually not scalable. Problems may arise when monitoring environment parameters are relative in time and surrounding conditions, but the system is not aware of it. For example, in natural water, body concentration of free dissolved non-compound oxygen present in water (or other liquids) is fluctuated daily and seasonally, depending mostly on light and temperature, as well as other linked parameters. It is one of the critical parameters in assessing water quality for aquatic life [6]. Such parameter values are not fixed and depend on many other related parameters, which is why embedded computer systems come into the game.

Self-expressive level of embedded distributed system is limited with hardware and software capabilities. Self-awareness is not singular, in other words all or nothing phenomena. Instead, it can explain the spectrum of awareness levels [7].

1.1 Problem Definition

This thesis is an experimental project for improving the existing concept of an aquarium controlling devices setup. Improvement is expected to reduce the need for human involvement and increase a reasonable level of self-decision making by the distributed embedded sensor-actuator network controller. Human-in-loop as an operator raise the problem with its inability to look after living pets in the tank 24 hours a day and 7 days a week. The goal is to improve an integrated solution to keep an eye of an aquarium ecosystem and control it independently, keep its parameters stable under any circumstances with or without a human factor and distribute all the information to the operator.

THE MAIN TASK FOR THIS PROJECT is to design a self-aware monitoring and controlling system basis for fresh water aquarium that could be extendable to marine water aquarium. Such sensor-actuator network system should be able to execute self-test for abnormal system behaviours and discover unexpected environment deviations. Clear relations must be designed between monitoring sensor data and controlling peripheral actuators per parameter and system as a whole. System sensor-actuator network must be capable of avoiding aquarium environmental disasters which can be caused by either malfunctioning component in the system or unexpected environmental forces.

THE MAIN TASK FOR CURRENT THESIS is to investigate and provide a basis for aquarium environment monitoring and controlling system-on-chip sensor-actuator network. The first goal is to develop a system which can keep chosen water parameters stable over the time in normal conditions based on initial data. The second goal is to introduce system self-stimulus and self-expressive behaviour. For example, peripheral devices expected and actual power consumption is compared to discover anomalies and life in tank is maintained during the time when system is not functioning properly. The chosen base for embedded computing hardware ensures the resources to implement all expected functionality with necessary input and output ports and has resource to update or optimize existing features alongside with new developments. This project’s solution uses an ARM Cortex-M4F based MCU. Controller for this environmental perception system was chosen by considering the balance between limited budget and enough computing power.

1.2 Concept of Self-aware Aquarium Control System

The main purpose of the project is to gain a certain degree of autonomy for aquarium controlling mechanism. The goal of self-aware aquarium control system is to supersede operator roles (human factor) with modest level of self-awareness using opportunities that on-board computer system’s hardware and software co-existence offer us. The complete system should handle all the environment monitoring tasks and make optimization decisions based on the collected and analysed environment dataset. Designed system should take over routine maintenance tasks - reducing human interference and excluding irregular human activities.

Balanced microclimate keeps itself in good wealth, but every natural water body ecosystem always depends on external forces like temperature, quality of light and exchanged water. In addition, artificially created and controlled ecosystem depends on false expectations, undetected sensor reading errors or actuators failures and therefore on misbehaviour of the whole system. The intelligent control system is required to cut those threats down.

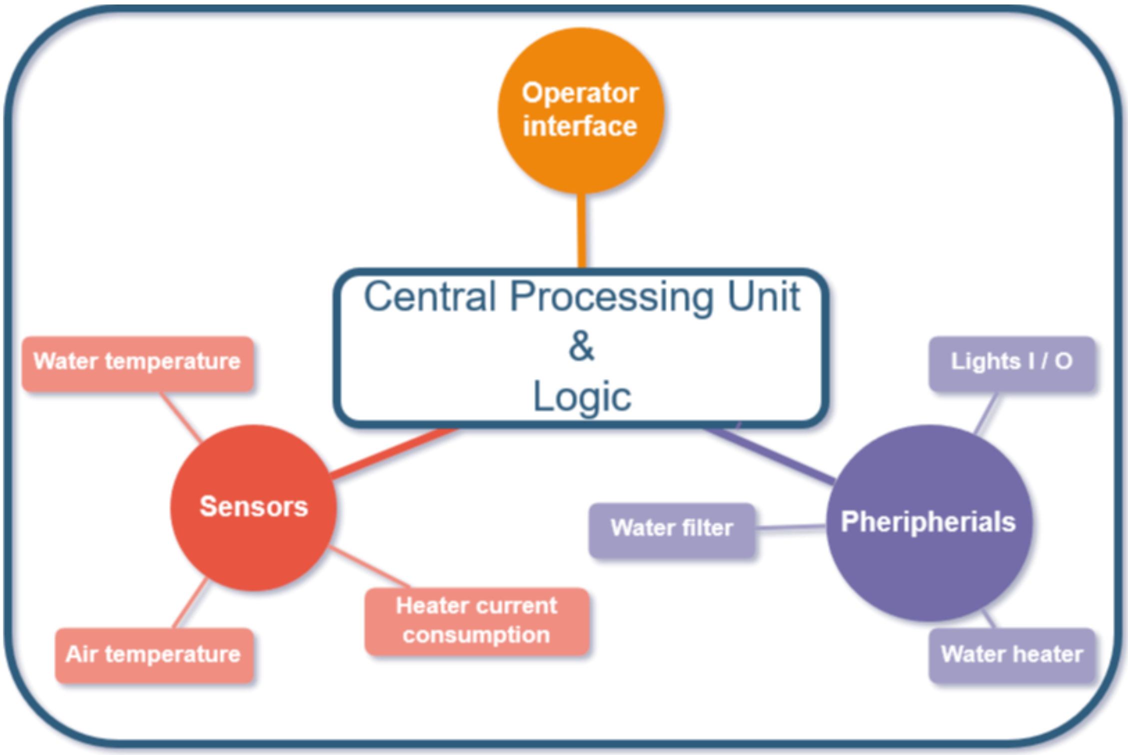

Figure 2: Conceptual architecture

The idea is to achieve a capability to collect all environmental and system internal parameters centrally, starting with critical parameters. Each parameter value is taken in routine check and compared with allowed range and relations to others. To simplify proof of concept, only the most critical flow is played through. The initial parameter monitoring-controlling choice has been made based on the feedback of the questionnaire, critical importance for the microclimate and implementation simplicity for proof of concept.

According to Figure 1, simple assumption can be made to design conceptual architecture (Figure 2) by categorising equipment into groups. There are mostly two types of equipment in Figure 2 – actuators that influence aquarium parameters and sensors that monitor real time parameters value. Central embedded controlling system ties together the whole system and interacts with operator panel.

1.3 Thesis Organization

Main tasks are defined in Chapter 1, addressing main problems and brief purpose of conceptual architecture idea. The goal of this project is to research, design and implement a base level of self-aware distributed embedded sensor-actuator network controller for aquarium.

Chapter 2 is dedicated to hobby and professional aquarists' real use-cases and expectations for aquarium controller systems. Analysing the questionnaire's feedback data by aquarists and researching the advantages and disadvantages of the existing products offered on the market. Several estimations are made in this chapter to construct an effective model for final platform.

Chapter 3 introduces briefly the research of self-stimulus and -expressive computing system and defines modest self-awareness level for current project. The principles from computational system self-awareness are equated to Ulrich Neisser's human self-awareness model [7]. The main task for this section is to approach ways how to integrate self-awareness with rigid automatics.

Chapter 4 investigates different possible modelling solutions based on questionnaire and analysed data of market product research from chapter 2. In addition, extending concept with chapter 3 about definition of self-awareness and its levels, binding it with electromechanics for the final and possible solution.

In Chapter 5, minimum basis of real design for self-aware aquarium computer is introduced in detail. Chapter focuses on building real system proof of concept that will confirm main statements of the hypothesis and result in experimental trials that will show if the system is worth to implement as whole.

Chapter 6 concludes implemented work so far and points out emerged problems, details that need possible improvement and presents future development ideas.

2 Domain analysis and Market demand

There is plenty of information about fish keeping in printed form and on the internet. Communities and forums share experiences and know-how about fish keeping. Information is relatively widely available in different languages and difficulty levels. Starting from setting up small freshwater fish tank, ending with complex custom-built aquarium systems and introduction to physical and chemical parameters maintaining healthy microclimate underwater world – all kind of information is available.

To come to conclusion about real life problems and bottlenecks, special aquarium equipment and maintenance questionnaire is composed for this thesis. Questionnaire was distributed in Estonian aquarium hobby forum[1] and Estonian aquarium maintenance companies.

The purpose of the questionnaire was to become aware of the current situation about the usage of aquarium automatic systems today. All respondents own at least water heater with thermostat and if not more than simple electronic relay timers that turn on and off lights twice a day. However, thirty to forty years ago even the simplest automatic devices were not available in mainstream, not to mention wide selection of measuring equipment.

2.1 Fish keeper's questionnaire

Despite sending questionnaire to all target groups, only hobby fish keepers were clearly interested in result and answered kindly to all questions and even made their own suggestions in the comment area. Unfortunately, none of the professional aquarium maintenance companies responded. The Author concluded that the companies were not interested in being a part of the research. Hopefully after this thesis, the research results and prototype evoke more interest.

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[1] http://foorum.akvarist.ee

2.1.1 Target group

In Figure 3, hobby fish keepers divided themselves into two main types of disciplines out of three. From all fish-keepers, the popularity of fresh water discipline is 77% and saltwater 23%. Brackish water was not mentioned, but there were also hobby enthusiasts who own both types of aquarium disciplines – around 8% of all fish keepers.

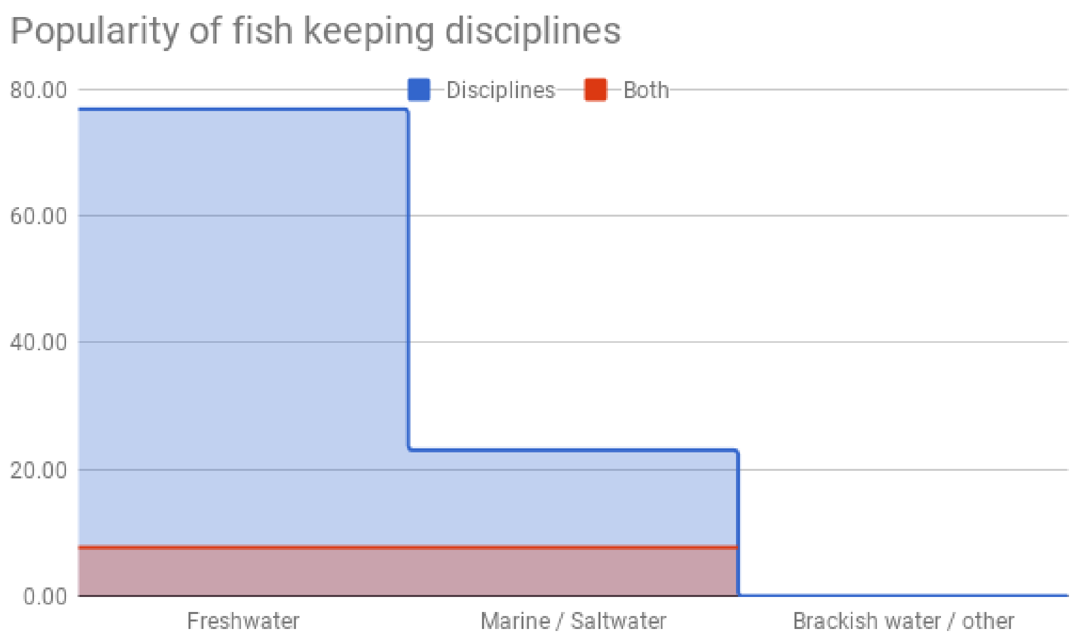

Figure 3: Types of fish keeping disciplines

It is worth to mention that brackish water fish keeping is playing between fresh and saltwater and adds additional complexity to keep the required ratio of mixing marine salt with fresh water. For obvious reasons no one mentioned themselves as brackish water discipline keeper because there is a grey area between both. However, aquarists understand that some of the species need more salinity water e.g. Mollies[1]. Simple solution for that is that if they own such fish species in their fresh water tanks, is mostly to add salt by experience and common sense or calculate salt amount scientifically and measure it manually occasionally.

1 http://badmanstropicalfish.com/brackish/brackish.html

2.1.2 Popular automatics modules and aquarium control systems

Another classification from questionnaire divided fish-keepers into four identifiable groups (Figure 4) when using automatics. Difference formed in complexity of behaviour when using automatics (Table 2) and the count of different parameters that are being monitored.

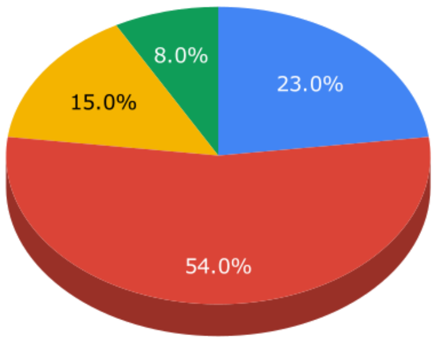

Figure 4: Popularity of used automatics grouped by complexity

Table 2: User group description by used automatics

Basic equipment (54%)	Simple solutions (23%)	Branded controllers (15%)	Central aquarium CPU system (8%)
Fish keepers own more equipment than controlling lights and keeping fixed water temperature with heater. In addition, they are using DIY and well-known aquarium brands equipment (e.g. Aquael, JBL, Hydor, Tunze) for example CO_2, O_2 diffusers or automatic food feeders. Also, simple digital sensors used e.g. temperature, PAR meters.	Fish keepers answered that they prefer controlling everything by themselves and use preferably indispensable solutions for controlling and monitoring. Two parameters were mentioned: automatic water temperature and enlightenment controlling. For water temperature there are pre-set-able fixed-point thermostatic water heaters and for light has electron-mechanical 24h timers.	In addition, from all respondents special integrated aquarium parameter controllers are used (e.g. Figure 9: JBL controller for maintaining CO2 and pH). Single parameter control boxes are available widely for many aquarium brands: JBL, Aquael, Hydor, Tunze or Aqua Medic.	Using advanced configurable and extendable central sensor and actuator functionality. Only one brand was mentioned - **GHL Profilux** which advertises itself as an aquarium computer.

2.2 Aquarists' real expectations and problems

Probably the most important goal of the study of used equipment questionnaire was to find out aquarists' real concerns, problems and expectations for building better system for keeping aquariums. Questionnaire was constructed to ask fish-keepers which functionality they lack in automation or needs to be improved. Do they need remote control and notification system? Same questions were asked also about parameters that they need to measure. Combining those two lists together with some additionally specified questions should give clear overview of needs and requirements.

2.2.1 Results of aquarium control functions automation based on questionnaire

Below is a summary of peripherals (Figure 5, Table 3) that are already automated or need improvement for remote controlling or for remote information sending (e.g. notifications, warnings, alerts).

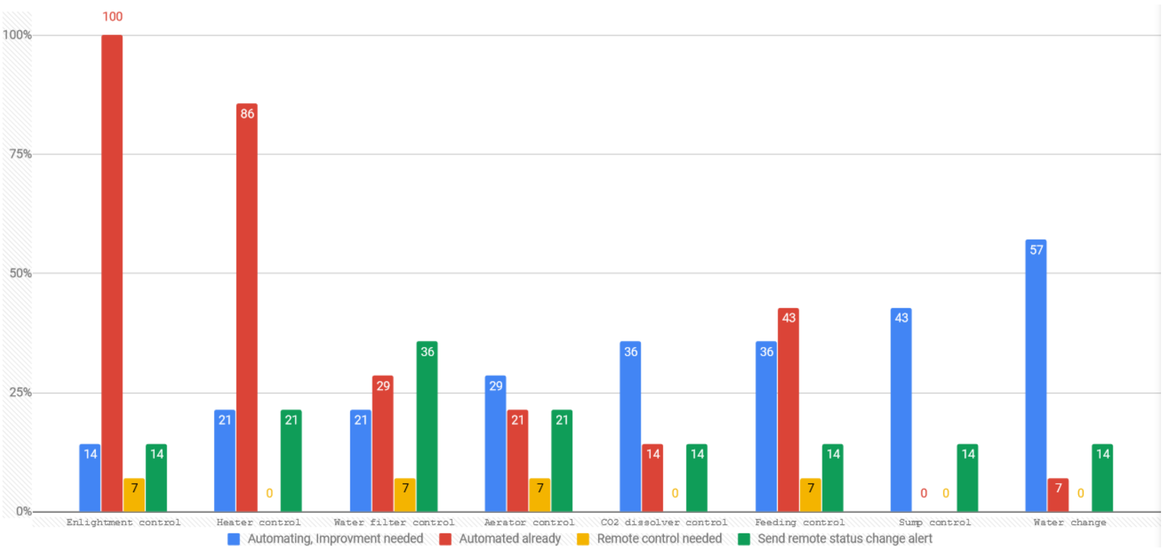

Figure 5: Actuator automation questionnaire feedback status

Table 3: Actuator automation questionnaire feedback status

	Automating, Improvement needed	Automated already	Remote control needed	Send remote status change alert
Light control	14%	100%	7%	14%
Heater control	21%	86%	0%	21%
Water flow/filter control	21%	29%	7%	36%
Aerator control	29%	21%	7%	21%
CO2 dissolver control	36%	14%	0%	14%
Fish feeding control	36%	43%	7%	14%
Sump control	43%	0%	0%	14%
Fresh water change	57%	7%	0%	14%

Most automated devices by the fish-keepers are:

- Enlightenment control
  - 100% automated by the fish-keepers
  - 14% looking for improvements
- Heater control
  - 86% automated by the fish-keepers
  - 29% looking for improvements or still need automating
- Fish-feeder control
  - 43% automated by the keepers
  - 36% looking for improvements or still need automating

Least automated devices with most wanted ratio:

- Fresh water change
  - 7% automated by the fish-keepers
  - 56% would like to have an automated version
- Sump control / Water filter (Sump would replace simple water-filter system)
  - 0% / 29% automated by the fish-keepers
  - 43% / 21% would like to have an automated version or improvement
- CO2 dissolver / O2 dissolver (aerator)
  - 14% / 21% automated by the fish-keepers
  - 36% / 29% would like to have an automated version or improvement

About 30% of the respondents also requested additional features that should be automated when designing such system. It is an interesting fact that additionally suggested features that were separately described in comments field match with improving part's percent from the table. Biggest contrast to highlight is that light is automated 100% by everyone, but still 14% would like to improve it. 86% believe that their water filters are enough automated, but still need improvement. The list below describes briefly what can be improved in detail.

Aquarists would like to see "next generation" aquarium controllers:

- Enlightenment improvement
  - Astronomical calendar, sunset and sunrise functionality, thunderstorm simulation
  - Measure PAR (Photosynthetic Active Radiation) because this parameter is important for growing plants, rather than measuring light intensity or spectre after all.
- Water filter, aerator, heater, water level improvement
  - Battery backup adding

2.2.2 Results of the aquarium measurement parameters automation based on the questionnaire

Below is a summary of parameters (Figure 6,

Table 4) that are already measured or need improvement for remote view.

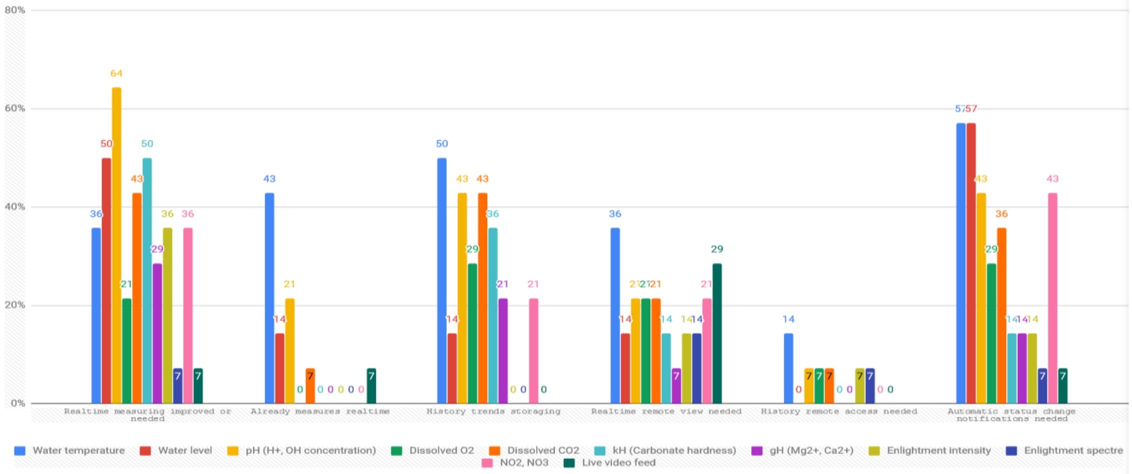

Figure 6: Parameter monitoring automation status

Table 4: Parameter monitoring automation status

	Real-time measuring improved or needed	Already measures real-time	History trends storing	Real-time remote view needed	History remote access needed	Automatic status change notifications needed
Water temperature	36%	43%	50%	36%	14%	57%
Water level	50%	14%	14%	14%	0%	57%
pH (H+, OH concentration)	64%	21%	43%	21%	7%	43%
Dissolved O2	21%	0%	29%	21%	7%	29%
Dissolved CO2	43%	7%	43%	21%	7%	36%
kH (Carbonate hardness)	50%	0%	36%	14%	0%	14%
gH (Mg2+, Ca2+)	29%	0%	21%	7%	0%	14%
Light intensity	36%	0%	0%	14%	7%	14%
Light spectre	7%	0%	0%	14%	7%	7%
NO2, NO3	36%	0%	21%	21%	0%	43%
Live video feed	7%	7%	0%	29%	0%	7%

Fish-keepers real-time top measured parameters:

- Temperature – 43% fish-keepers measure in real-time
    - 36% fish-keepers find that they need improvement
- pH – measured by 21% respondents in real-time
    - 65% finds that it needs to be automated or improved
- Water level -14% monitoring in real-time
    - 50% respondents find it necessary to improve

It is interesting that when analysing questionnaire results, there is a considerable amount of physical and chemical parameters that are marked as important for automation but none of the aquarists measure them yet in real time. Those parameters have great importance in real-time, but also for historical records and notifications sent in real-time.

Rarely or not at all automated parameters, but interest is very high among fish-keepers:

- Water level
  - 50% respondents would like to own real-time measuring
  - 57% would like to get notifications of level change
- CO_2 (only 7% have automated)
  - 43% respondents were interested in real-time values and historical recordings
- NO_2, NO_3
  - 36% were interested in real-time measuring
  - 43% interested in real-time notifications when status changes

Suggested improvements for measuring parameters:

- Light measuring
  - PAR measure – instead of measuring light intensity and spectre
- Water level keeping
  - Water evaporation speed monitoring
  - Air humidity under tank lid monitoring
  - Air temperature monitoring
  - Ratio between water flow in and out of the tank monitoring
  - Tank leak sensing
  - Emergency alert sending on level change over GSM
- Power grid interruptions
  - Emergency alert sending
  - Keeping critical parameters monitoring on backup battery
- Marine tank mandatory parameters
  - kH, gH, NO_3, PO_4, ORP
- Database of parameter history
  - Recording history of parameters automatically

2.2.3 Remote control and monitor channels

Remote controlling and remote parameters monitoring are as important as choosing channel over which all the activities are made. Questionnaire asked opinion about 3 modern communication channels: GSM, SMS, internet. Internet was divided into three different interfaces: Web browser, PC executable program and mobile application.

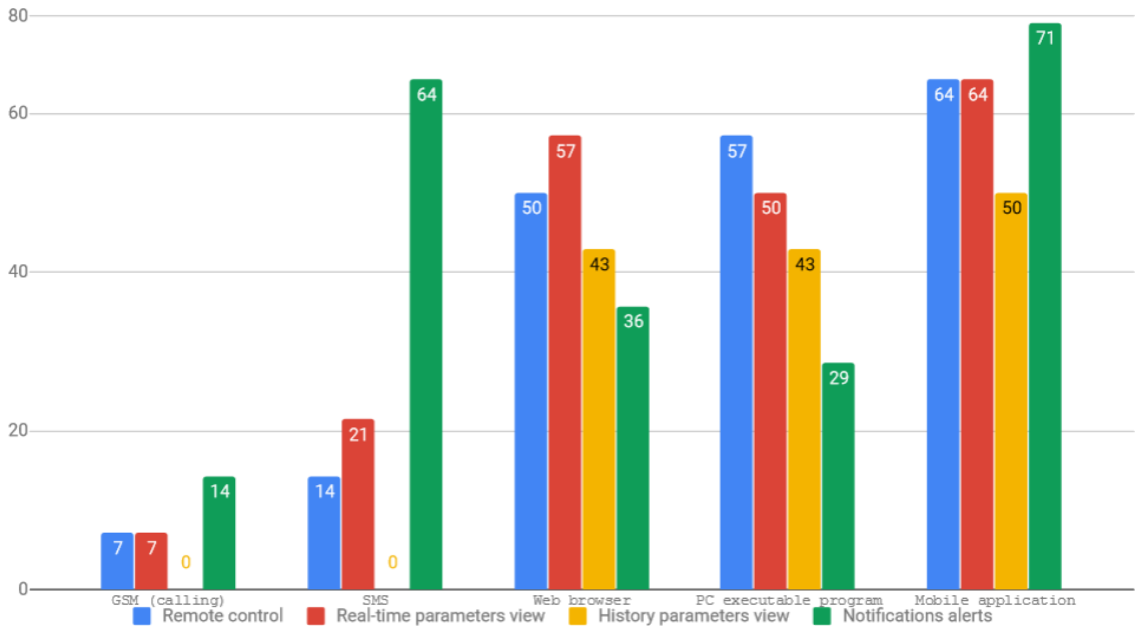

Figure 7: Preferred communication channels

Table 5: Preferred communication channels

	Remote control	Real-time parameters view	History parameters view	Notifications alert
GSM (calling)	7%	7%	0%	14%
SMS	14%	21%	0%	64%
Web browser	50%	57%	43%	36%
PC program	57%	50%	43%	29%
Mobile application	64%	64%	50%	71%

Fish-keepers found that the most convenient way to communicate with aquarium tank is to use mobile application where equally real-time parameter view and remote control should be available. Most important was to get status change notifications like alerts and emergency situations.

Top remote control, parameter monitor and history view channels:

- Mobile application
  - 64% Remote control and parameter monitoring
  - 50% Parameter history view
- PC program
  - 57% Remote control
  - 50% Monitoring parameters
  - 43% History view
- Web browser
  - 50% Remote control
  - 57% Monitoring parameters
  - 43% History view

Alert, Notifications channel Top:

- 71% Mobile application
- 64% SMS applications
- 36% Web browser

However, though SMS as notification sending channel was the second most popular, author of the thesis needs to point out a comment that several fish-keepers mentioned - SMS channel has lower priority than GSM. In case of real emergency, instead of using SMS, it should be used calling service over GSM.

2.2.4 Other topics which are actual

Automatic fish feeder characteristic

There are two types of fish-keepers – the ones who believe that fish should be better hungry than use automatic feeder and others who find that automatic feeder can be handy, especially for those who are long periods away from home.

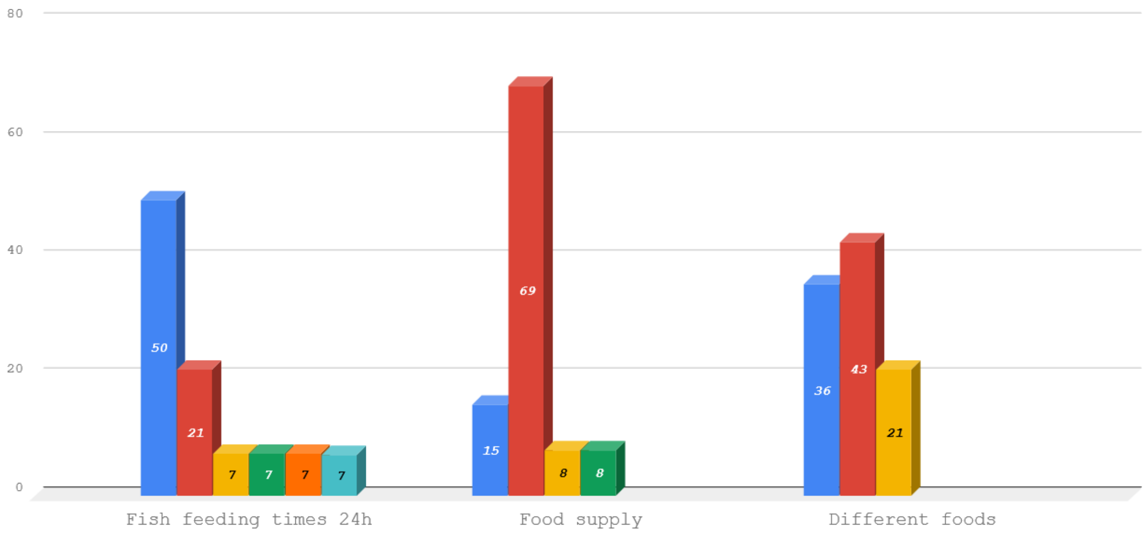

Figure 8: Automatic fish feeder expected characteristic

Fish feeding times per day

- 1 time per day (50%)
- less popular is 2 times per day (21%)

Other opinions divided equally (7% each): 4 times per day, only on vacation, better hungry than automatic and will never change their feeding mechanism.

Food supply continuity in automatic feeder:

- 69% were on the position that 14 days is enough
- 15% thought that 7 days is enough
- 8% had an opinion that 30 days is best
- 8% answered 0 days (I guess that some fish-keeper added that who liked their fishes to be hungry instead)

Assortment of food:

- 2 types of food simultaneously in automatic fish-feeder - preferred 43% respondents
- 1 type of food is enough for 36% respondents
- 3 types of food wanted 21% of respondents

Summarising preferred characteristic of automatic fish-feeder:

- 1 time feeding per day
- 14 days food supply
- 2 types of food

2.2.5 Short- and long-term failures. Features to implement

Below is a summary of feedback from fish-keepers who left notes in the free format comment box.

Thesis author’s questions for free text:

- Short term / long term failures that aquarium system should expect?
- Can features be implemented to solve the problems?
- Additional topics to consider?

Table 6: Short- and long-term failures that aquarium system should expect to handle

Short term failures to be prepared	Long term failures to be prepared
▪ Power-grid interruptions ▪ Filter pump and sump malfunctioning ▪ Temperature short-time drastic change ▪ Tank leak, water level drastic change ▪ pH short-time drastic change ▪ CO_2 overdose ▪ Lack of oxygen	▪ Enlightenment degradation ▪ Water spoilage, water parameters constant deterioration ▪ Long period power-grid interruptions

Aqua-keeper’s expected features to implement:

- Send power grid failure alerts to communication channels
- Video feed for general overview
- In case of water temperature drastic increasing ability to
    - turn of lights, heater etc.

    - open aquarium lid for better cooling
    - send alert to operator (fish-keeper) (and if possible, reason what caused the issue)
- Peripheral devices
    - Considering actuators and sensors degradation
    - Observing unexpected deviations to discover possible failures in future
- Adapting water change interval based on historical parameters to keep water quality as good as possible
- Keep the water level in the tank in case of pump failure
- Measure tank's overall health based on parameters
- Adding every part of the system feedback mechanism to measure system workability
- Use IFTTT protocol for communicating operator interfaces remotely
- Critical sensors and actuators should be connected to UPS
- Log book for tank parameters and system specific parameters

Feedback suggested topics to consider:

- Market research of manufactures (e.g. Profilux, Aquatronica, Neptune Apex, Tunze)
- Validate fish-keeper competence when making such questionnaire and differentiate aquarium keeping disciplines
- If and how aquarium should act when feeling aquarium observer closeness
- Should aquarium react also to outside forces (e.g. regulating lights intensity when outside environment brightens or darken)

2.3 Market product research

Besides the questionnaire results, the Author made additional research to evaluate market situation and find out products that meet expectations. Starting with local dealers and ending with worldwide manufacturers.

Estonian regular and online shops have represented several well-known aquarium and pond equipment manufacturing brands: Aquael, Aqualight, Aquamedic, Aquanova, EHEIM, Hydor, JBL, Juwel, Resun, Schego, Tetra, Trixie, Tunze and other less known. Those brands offer us all everyday simple electromechanical aquarium equipment like shown in Figure 1: Regular hobby fish-keeper (human in loop) setup based on chapter 2.1. For example, they offer simple water filter systems, water pumps, peristaltic pumps, aerators, heaters, UV sterilizers, reverse osmosis, CO2, pH, Cooler, automatic feeder, light and temperature devices, both for controlling or monitoring.

The obtained results were not exactly matching with the expected. Parameter monitors and controllers are quite simple and mostly perform only one task. Usually they are not aware of other parameters even when they are capable of measuring and controlling some parameter status dynamically. One big disadvantage of those devices is that they lack fail-safe operating functionality. Even less - they do not signal to anything when they are malfunctioning. Only visual external observation by an operator can tell if equipment is not functioning properly. Sometimes it may be too late for the fishes in tank.

For example, besides OEM heaters, fish-keepers always use aquarium thermometers to observe the temperature in the tank, because they do not trust heater's thermostat. Aquarists trust their fishes to the “hands” of thermometer and thermostatic heater. In case of a little reading error nothing bad will happen, but if a heater gets stuck into one position and keeps constantly turning on and a keeper is not at home or does not notice then the poor fish get boiled. There are more of those scenarios that can happen: heater won’t turn on anymore and fishes may get frozen (of course it depends on the outside room air temperature), tank glass may crack and fishes dry out or outside filter gets clogged and aquarium will drown and fishes get out of the water and dry out.

Author’s interest was to try to find some system that can monitor and control parameters, simultaneously be aware of itself sensor and actuator condition. In case of discovering anomalies, system will turn into state that is safer to living environment until operator eliminates the problem.

When the Author did a little more research, he finally found CO_2/pH controller on Figure 9[1] which is finally available in Estonia. Controller has relatively high price and without

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1 https://www.jbl.de/images/container/w1940/65649.jpg [Accessed, 3 May 2018]

pH probe which is extra accessory. JBL controller[1] measures two parameters (temperature and pH level) and controls one CO_2 solenoid valve. Product manual instructs that before using equipment manual calibration is required every 30-60 days for correct values which are recorded as constants in controller ROM.

Figure 9: JBL controller for maintaining CO2 and pH

When having more such equipment to the aquarium, the costs will grow, and each controller multiplies amount of same type sensors which is using current parameter (e.g. temperature). For example, if one wants to add heater which has controller that uses another temperature sensor, two temperature sensors are already in the tank. It is not bad but if sensor has different controllers, they won't communicate with each other and none of them will know what the other thinks about the value of the temperature. No feedback means no discovery to faulty parts.

There is no doubt that on the local market there is a lack of advanced aquarium controllers which could completely replace human-operator aquarium keeping activities without worries. In Europe, America and Asia there are together 4 notable whole aquarium controller manufacturers and one community founded open source platform. Table 7 compares three interesting platforms that matched the most with expectations.

[1] https://www.jbl.de/en/products/detail/7395/jbl-proflora-ph-control-touch#details [Accessed, 3 May 2018]

The source and brief description of all platforms is here:

- GHL Profilux – focusing on aquarium, terrarium, pond and caldarium advanced centralised whole in one controller [8]. Origin from Germany.
- Neptune Apex – The Apex Aqua Controller System is the best way to have complete control over your aquarium [9]. Origin from USA.
- Open Aquarium – DIY kit platform is designed to take care of aquarium fish keeping by automating the control and maintenance tasks that take place in the fish tanks and ponds. It has open source C++ based software library for enthusiast [10]. Origin from Spain.
- Aquatronica – focused on the development of systems for water monitoring and management. Developing the application of intelligence to the management of the problems related to the environments where water is the dominant element [11]. Origin from India.
- Tunze – focusing on providing its customers with high-quality products and thus a unique aquarium experience. Mission is to improve water quality in the closed circulation system of an aquarium [12]. Origin from Germany.

Following Table 7 compares expectations from questionnaire results between three very interesting platforms.

Table 7: Market products compared to fish-keeper expectations from questionnaire

Feature	**GHL Profilux 4**	**Neptune Apex**	**Open Aquarium**
Water temp	+	+	+
pH	+	+	+ /
EC[1] Salinity	+	+	+ *
ORP[2]	+	+	-
dissolved O_2	~**	~	-
dissolved CO_2	-	-	-
Air temp	~	~	-
Humidity	~	~	-

* +/+ Both sensors cannot be used at the same time

** ~ Has readiness but not included in default setup

Feature	GHL Profilux 4	Neptune Apex	Open Aquarium
Water leakage Water level NO_2, NO_3 PAR[1] Video feed	+ + - - -	~ ~ - ~ -	+ / + - - -
Water heater Water cooler Feeding fish Water change pump Medicine peristaltic pump	+ + + + +	+ + + + +	+ / + + + / +
Channels Seasonal temp, sunset / sunrise, moon simulation	6-32 Limited + +	4 + + +	4 (R G B W) Programmable
Power bar AC DC DC	6x 240AC 6x 0-10V	110 / 240AC UK 4x 0-10V, 24V	5x 240AC EU Not for general purpose
Power fail Current monitor	+ Must purchase a power supply to utilize the port	+ Requires AUX power port and additional power adapter	- UPS solve power failure
Status Display Auditable alarm LED indicator alarm	3-line unit display + +	+ -	- - -
Web user interface	Very limited not including all features	+ Full control	Open Aquarium Web-server client Full control
Mobile Application	IOS Android	IOS only	Open Aquarium Application client

Feature	GHL Profilux 4	Neptune Apex	Open Aquarium
	(both can be used only over Ethernet support)		
Wi-Fi Ethernet port USB port	+ - +	+ + -	+ + (all here are expandable)
Auxiliary power vs Power bar	+ **Required** Only draws power from the supplied power adapter, does not rely on a power-bar	+ **Not required** to operate the unit, draws power from power bar	+ **Need adapter**
Expansion ports	2x	-	-
Rack / wall mountable	On feet only	bracket	Screws
Starter KIT price[1]	975€	800€	199€ + 99€(Aquaponics)

Figure 10: GHL Profilux4 Ultimate Set for starters [13]

Figure 11: Apex Systems Starter Bundle [14]

Figure 12: Open Aquarium Basic [49] [50]

Most of Estonian fish-keepers have no experience with studied full-aquarium controllers or at least it did not reflect from the questionnaire. Foreign forums helped with user experience. There is little information or nothing about Open Aquarium project which is

[1] Appendix 1 – Starter KITs price and specifications

understandable because it is targeted mainly for IT developers and DIY community groups. Below are main advantages and disadvantages of the studied controllers.

Table 8: Advantages and disadvantages market products

Open Aquarium Advantages:	**Disadvantages:**
▪ Affordable almost for everyone and relatively inexpensive ▪ Open source platform developer shield for Atmega328p MCU (Arduino development board) ▪ Open source software (C++) ▪ Huge developing potential ▪ Full of possibilities and potential ▪ Highly customizable ▪ Web application and server storage ▪ Mobile application ▪ Remote controllable ▪ Potential to setup system as basic disaster prevention system	▪ Is not market ready platform ▪ Does not fit regular fish-keeper pro-file ▪ Need programming and electronic background ▪ Limited hardware possibilities ▪ Raw/Not ready software ▪ Aquarium needs more input/ output ports than possible on current setup ▪ Inaccurate measurement results quality ▪ Inability to build complete complex system due to hardware and software limits ▪ Current software has no smart algorithms and self-decision-making abilities ▪ Needs more powerful microcontroller for developing full aquarium platform solution
GHL Profilux4 Advantages:	**Disadvantages:**
▪ GHL has advanced features ▪ Never have to use programming language ▪ GHL has more features without using extra modules (than Apex)	▪ Advanced features are accessible only through a desktop program ▪ Complex desktop application ▪ Not so flexible than Apex ▪ Does not offer full touch screen controller add-on

GHL Profilux4 Advantages:	Disadvantages:
GHL has out of the box its own Light Bar, Simulation Bar and the LX series, Air/Humidity sensor and cooling fans ▪ GHL is more stable than Apex ▪ Strong hardware implementation	▪ Very expensive to buy and add modules ▪ Software implementation weak ▪ Fixed parameter environment setup ▪ For professional fish-keeper ▪ Not affordable for everyone ▪ Not for a beginner fish-keeper
Neptune Apex System Advantages:	**Disadvantages:**
▪ More features than GHL in Web user-interface ▪ Accessible from any device ▪ Does not require desktop configure program ▪ Apex has some modules that GHL does not have at all: WAV[1] COR[2] and Radion control lightning ▪ Strong software implementation	▪ In case a function is not presented in the drop-down menu, needs an advance programming language ▪ Apex needs more extra modules (than GHL) to use advanced features ▪ Apex is more unstable than GHL ▪ Apex has often suffered from technical issues ▪ Weak hardware implementation ▪ Fixed parameter environment setup ▪ For professional fish-keeper ▪ Not affordable to everyone

[1] WAV - 1Link Controllable wave making pump Neptune Apex system

[2] COR - 1Link Controllable reverse direction flow pump Neptune Apex system

2.4 Summary

This chapter of the thesis researched Estonian fish-keeper user feedback for monitoring and controlling aquarium environments. Additionally, a parallel research was carried out about available market setups worldwide. Research was necessary to point out problematic places and start to develop a modern aquarium control system that is aware of its own environment and can avoid disasters while operator is not around.

Research revealed several interesting solutions. Three controller platforms that are suitable for hobby and professional fish-keepers were chosen for comparison in this thesis as they have a lot of potential to develop great to greater systems.

All the studied systems are usable and have their own good merits and demerits. Firstly, GHL (founded 1998) and Neptune Systems (founded 1995) have been on the market for a long time and they have developed great reliable controllers for keeping eye over aquarium or pond water quality. For serious fish-keepers they are well-known and greatly recognized. Great value comes with great money. Those controllers are quite expensive and suitable only for full-time (serious) professional or hobby fish-keeper. They are not meant for beginner fish-keepers because they need the knowledge about how to keep fishes and are quite expensive. Both controllers should be very simple to use when you know what you are doing.

Open Aquarium controller is a relatively inexpensive open source platform but is not finally manufactured and needs rather programming and electronic education background. Open library consists of basic API commands that are usable for aquarium monitoring and controlling, but system is not ready for avoiding disasters when something goes wrong. Needs huge amount of development to complete tasks independently without human operator presence.

3 Level of Self-Awareness and system integration

This thesis considers different design approaches of the aquarium control system that are expected to be more responsive and adaptive to environmental changes than existent ones. The aquarium is a relatively complex environment with all its physical and chemical parameters where one change takes effect to others which in turn influences the whole balance of microclimate (see Table 9).

Awareness in the broader meaning is defined in the Oxford English Dictionary: “Knowledge or perception of a situation or fact.” [15] The concept of self-awareness has been studied in different aspects and fields under psychology and cognitive sciences, but in computer sciences, there is still plenty of room for development.

Article “Self-Adaptive Software: Landscape and Research Challenges” defines hierarchy of Self-* Properties which is appropriate to highlight on Figure 13. Primitive level property “self-awareness” means that the system is aware of its self-states and behaviour which are based on self-monitoring and reflect what is being monitored. Another property “context-awareness” allows system to be aware of its operational environment [16].

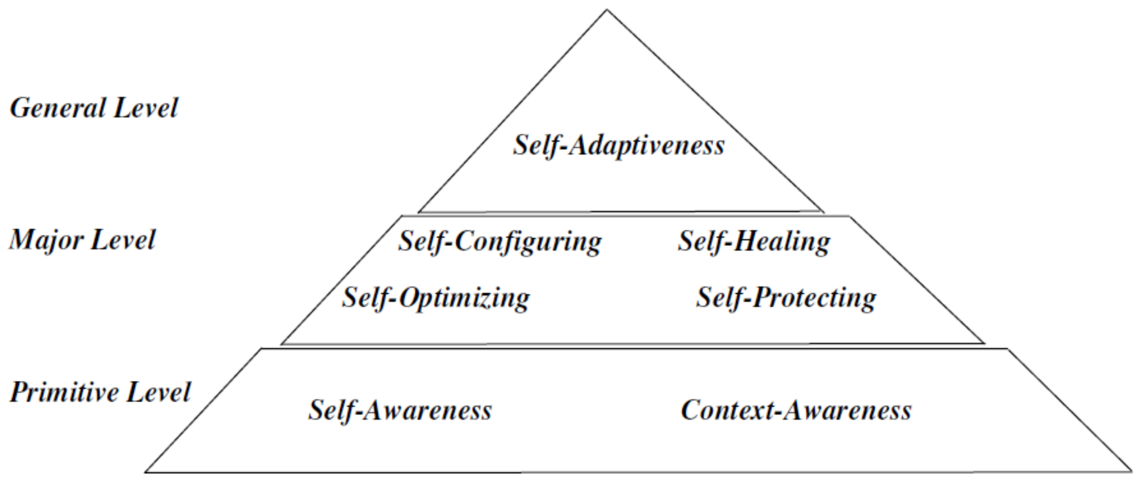

Figure 13: Hierarchy of Self-* Properties [16]

The book “Self-aware Computing Systems” [7] claims to be the first book providing a uniquely holistic view of self-aware computing. This book describes self-expressive relationships and the process of engineering self-aware computing systems based on design patterns and techniques. Citation from the same book: “Self-awareness is a broad concept which describes the property of a system (typically a human) which knows “itself,” based on its senses (perceptual) and internal models (conceptual). This knowledge may take different forms (cf. levels of self-awareness) and be based on perceptions of both internal and external phenomena (cf. public vs. private self-awareness). It can be a property of single systems (e.g., agents) and collective systems.” [7]

According to the article “Architectural Aspects of Self-Aware and Self-Expressive Computing Systems: From Psychology to Engineering”: work on human self-awareness is the basis for a framework to develop computational systems that can adaptively manage complex dynamic trade-offs at runtime. An architectural case study in cloud computing illustrates the framework’s potential benefits [17]. Article defines computational self-awareness three main foundational principles at engineering perspective: 1) public and private self-consciousness, 2) self-awareness based on Ulrich Neisser’s description of five levels [18] and 3) where self-awareness is taken as a property of collective systems.

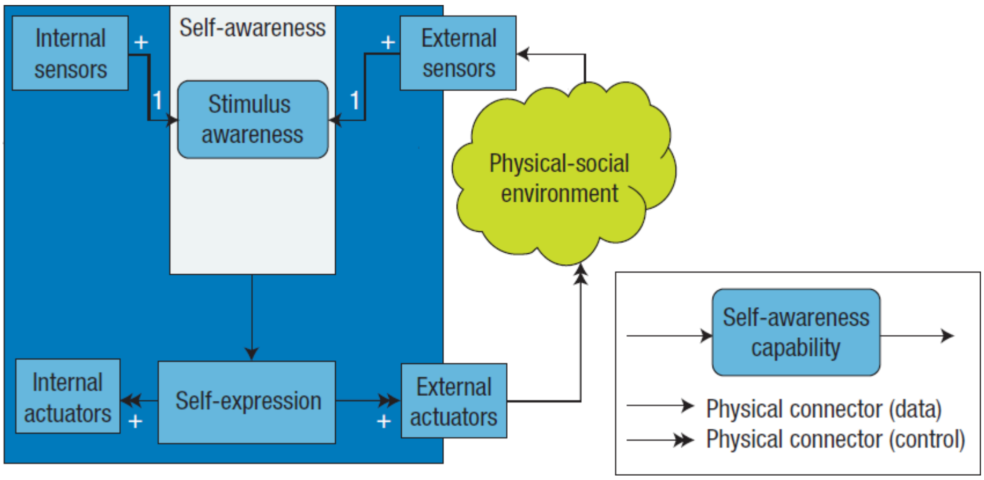

Figure 14: Minimal computational self-awareness approach [19] (pp. 67)

Public and private self-awareness is one of the three foundational principles transferred to an engineering perspective in computational self-awareness by authors of the article. They claim that only the systems that are aware of their internal aspects and external influences can have self-awareness capabilities. A second foundational principle they consider is a psychological description of Ulric Neisser’s self-awareness five levels that capture the broadest range of human self-awareness adapted to engineering aspect. The third principle that transferred to an engineering perspective is that self-awareness is taken as a property of collective systems, even if no component has a global awareness of the entire system [17].

Designing self-consciousness architectural basis for current thesis with limited budget and time, Author considered to select most primitive self-awareness level to prove the concept of the aquarium controller system. One approach to the simplest pattern with minimal computational self-awareness is defined in article “Architectural Aspects of Self-Aware and Self- Expressive Computing Systems: From Psychology to Engineering” [17] (pp. 67 Figure 2). Article proposes basic pattern on given diagram (Figure 14), which contains only the stimulus-awareness capability where detected stimulus types trigger corresponding action.

Current Figure 14 describes a stimulus-aware system which can obtain knowledge of stimuli acting upon it. System has the ability to respond to events but has no knowledge of the past or future stimuli. Stimulus can be private, public and even both because it may originate from internal or external factors. In the same Figure 14 is a term self-expression which is defined in the book “Self-aware Computing Systems: An Engineering Approach“ [7]. Citation from book: “Additionally, we introduced the notion of self-expression, behaviour based on self-awareness. Self-expression typically provides highly dynamic behaviour, able to adapt to a system’s changing self-awareness as it learns. Self-expression may include behaviours considered “normal” functional system behaviour, as well as self-adaptation, self-reconfiguration, self-explanation, or any other forms of individual or collective behaviour informed by a system’s self-awareness [7, p. 21].”

An aquarium controller system may need to trigger some actions in order to cope with emergent events or stimuli. Such possibility could greatly help to manage the aquarium controlling system at runtime. Based on both static and dynamic rules there is an increasing need for aquarium controller to react upon stimuli.

Chosen approach suits perfectly for current thesis because it enables a self-aware node basics. According to the same book previously mentioned [7, p. 16], the (self-aware) node term is used here to refer to various types of systems with self-aware capability e.g. an agent, a robot or a camera. Self-aware collectives (e.g. algorithm) can be viewed as higher level abstraction of self-aware nodes [7].

Such pattern contains enough stimulus awareness because it receives data flow from sensors and actuators. Pattern promotes proper actions of self-expression to trigger based on the type of stimulus detected. For example, aquarium controller is observing actuator power consumption every fifteen minutes and is trying to perceive if consumption stays in expected range or there are deviations:

- Turning on or off peripheral device the overall system power consumption does not change – consequently some device is burned out or there is faulty control chain.
- Actuator is constantly consuming power, but environmental parameter values are moving unexpected direction – consequently sensor might be faulty or actuator is stuck.

However, there are limitations of the pattern that must be taken account when designing real use case. For example, no information is shared amongst the nodes in this pattern. Node is not aware of the environment’s other nodes. Problems are arising when there is a need for intensive interactions or interferences amongst nodes, but this is not in the scope of current thesis research part but will be taken account in future developments.

Chapter 4 introduces internal and external sensors and actuators that monitors and controls environmental parameters but also observing internal states which give feedback of the system health status.

4 Computational self-awareness integration to automatics

The desired goal is to monitor and support environmental microclimate without operator intervention. Such a system can be implemented only with involving monitoring internal status changes and triggering internal actuator activities if needed. Based on the architecture (Figure 14) which is taken as a fundamental designing block for the current thesis, the system can be (stimulus-) aware over itself by linking internal and external sensors together with desired algorithmic behaviour. Self-expressive behaviour is achieved through internal and external actuators which are triggered by stimulus-awareness logic.

4.1 Range of aquarium tank parameters influences

Future version should contain all the parameters listed in Table 9. Table has been complemented with knowledge how parameters are increasing or decreasing their value. Current parameter coverage is combined by analysing questionnaire, thesis author's own knowledge and real products on the market. Current products already have functionality how and what to measure but may lack of self-stimulus and self-expressive behaviour. Some parameters are less important and other probes are too expensive. As in every case, also trade-offs should be made here. Current thesis will just introduce one example from all of the parameters which should give the basis for implementing all parameters with the same standard.

Table 9: Environment parameters and possible variants to influence values

Environment parameter	Ways to increase / raise…	Ways to reduce / lower…
Water temperature	**1)** Heat water **2)** Influence (raise) air temperature **3)** Keep tank lid closed	**1)** Cool water **2)** Influence (decrease) air temperature 3) Open tank lid
Air temperature *(not important when water temperature and evaporation is under control)*	Outside of controllable environment	Outside of controllable environment
Water evaporation	**1)** Rise water temperature more than air	**1)** Decrease water temperature lower than air

Environment parameter	**Ways to increase / raise…**	**Ways to reduce / lower…**
	2) Decrease air temperature lower than water	**2)** Rise air temperature more than water
Water level	**1)** Pumping water in to tank **2)** Prevent evaporation with closed lid	**1)** Pumping water out of tank **2)** Water evaporation
Dissolved O_2	**1)** Aerating water **2)** Living plants producing	**1)** Respiration by fish and other life
Dissolved CO_2	**1)** Via air, gas exchange at the water surface **2)** Respiration by fish and other life **3)** Aerating water	**1)** Aerate water **2)** Nutrient for plants
pH [19] [20]	**1)** Aerate the water, driving off the carbon dioxide (CO_2) **2)** Filter over coral or limestone **3)** Add rocks containing limestone to the tank or use a coral sand substrate **4)** Use alkaline buffer	**1)** Filtering water over peat **2)** Add bogwood to the tank **3)** Inject carbon dioxide (CO_2) **4)** Use acid buffer **5)** Water changes with softened water **6)** Water changes with Reverse Osmosis water
Carbonate Hardness kH [19] [20]	**1)** Injecting carbon dioxide (CO2) **2)** Use reverse osmosis (RO) water. You can mix tap water with reverse osmosis water to achieve the desired kH. **3)** Adding commercially available products to decrease the buffering capacity.	**1)** Adding sodium bicarbonate (baking soda). One teaspoon of baking soda added to 50 litres of water can raise the kH of the water by approx. 4dH without a major effect on pH. **2)** Adding an air stone to increase surface turbulence driving off carbon dioxide (CO2) **3)** Adding commercially available products to increase buffering capacity
General Hardness gH(Mg2+, Ca2+) [19] [20]	**1)** Adding limestone to the aquarium (this will also increase kH which in turn	**1)** Adding peat moss to your filter **2)** Use commercially

Environment parameter	Ways to increase / raise…	Ways to reduce / lower…
	will increase pH) **2)** Adding calcium carbonate will raise gH and kH	available water softening pillows or a water softener (this removes calcium and magnesium ions and replaces them with sodium ions. Many people feel that this is an unacceptable method of softening water as many fish that prefer soft water don't like sodium either. **3)** Mixing tap water with reverse osmosis (RO) water.
Ammonia (NH_3/NH_4+) [21]	**1)** Fish excrements **2)** Dead plant odds **3)** Dead bacterial colonies after water sudden change or medications in water **4)** Filter failure	**1)** Filtering water **2)** Lower temperature **3)** Keep pH below 7.2 **4)** Change water
Nitrite (NO_2-) compounds [22]	**1)** Ammonia level is high	**1)** Keep ammonia low level **2)** Filtering water **3)** Change water
Nitrate (NO_3-) compounds [23]	**1)** Ammonia and nitrite level are high	**1)** Food for Pond plants **2)** Filtering water **2)** Change water
Photosynthetically active radiation (PAR) [24]	**1)** decrease light intensity **2)** change light spectrum **3)** turn off lights	**1)** turn on lights **2)** increase light intensity **3)** change light spectrum

4.2 Environment microclimate model on real life example

Real life environment setup example is established on the Author's personal aquarium. Author owns an aquarium with decorative fishes, whose origin is in wild nature in South-America, except for Siamese Flying Fox (known as Siamese Algae-eater), who is from South-East Asia. Fish shops provide usually three main required parameters when selling fishes: water temperature, general hardness and pH. Below is the table of every fish parameter in detail with their minimum and maximum range. Reading real-life example from Table 10, convenient parameter ranges for the fishes are:

- water temperature between 24-25°C
- pH 6.5
- water salinity 50mg/ml.

Table 10: Water parameter requirements in experimental tank

	Water temperature min	**Water temperature max**	**Water hardness min**	**Water hardness max**	**pH min**	**pH max**
Siamese Flying Fox	22°C	25°C	50mg/ml	50mg/ml	6	6.5
Angelfish	24°C	28°C	50mg/ml	100mg/ml	6.5	6.5
Black Phantom Tetra	23°C	28°C	50mg/ml	100mg/ml	6.5	6.5
Convenient range	**24°C**	**25°C**	**50mg/**	**50mg/ml**	**6.5**	**6.5**

Convenient ranges in Table 10 (which controller must keep) are calculated by taking all the fishes minimum and maximum bearable parameter values that are kept in the same tank. Lower side of the range is calculated by taking maximum value of the minimum and higher side of the range by taking lowest parameter value. NB! If tank includes plants, then plant parameters should also be evaluated to get the whole picture. Although Author grows also plants, they are not pointed out in the current work as they match with the ranges from Table 10.

Many water parameters by the aquarists are manually measured and inserted into a logbook, until today. Many parameters are difficult or expensive to measure with rigid automatics because the cost of the probes or techniques is complex. To get an overview of current thesis and future developments, Author made a brief summary which methods and sensors are possible choices for controller in the future. Table 11 gives short summary with parameter and method or probe which are good candidates. Although all the parameters are measurable with electronics, it may not be reasonable to measure all of them, mainly because of the cost of the probes and their degradation time. Part of future developments will certainly focus on the topic: which parameters are not mandatory to measure, which can be measured indirectly through others etc.

Table 11: Possible variants to measure parameter values with sensors

<table>
<tr><th>Parameter</th><th colspan="2">Sensor / method measured</th></tr>
<tr><td>Water temperature</td><td colspan="2" rowspan="2">✓ Thermistor
✓ Thermocouple
✓ Resistance thermometer
✓ Silicon band-gap temperature sensor</td></tr>
<tr><td>Air temperature</td></tr>
<tr><td>Water evaporation</td><td colspan="2">✓ Measure tank water level</td></tr>
<tr><td>Water level</td><td>Static:
✓ Magnetic and mechanical float
✓ Pneumatic
✓ Conductive
✓ State dependent frequency monitor
✓ Ultrasonic
✓ Capacitance
✓ Microwave</td><td>Continuous:
✓ Magneto strictive
✓ Resistive chain
✓ Hydrostatic pressure
✓ Air bubbler
✓ Gamma ray</td></tr>
<tr><td>Dissolved O_2 [6] [25]</td><td colspan="2">Measuring Dissolved Oxygen by the Sensor Method
✓ Optical Dissolved Oxygen Sensors
✓ Electrochemical Dissolved Oxygen Sensors
✓ Polarographic Dissolved Oxygen Sensors
✓ Pulsed Polarographic Dissolved Oxygen Sensors
✓ Galvanic Dissolved Oxygen Sensors</td></tr>
<tr><td>Dissolved CO_2 [26]</td><td colspan="2">✓ Nomographic determination of free carbon dioxide
✓ Titrimetric method for free carbon dioxide
✓ Carbon dioxide determination by calculation
✓ A portable CO_2 meter (CO_2 Portable Analyser)
✓ An indirect method as described by Watten et al. (2004) [27]</td></tr>
</table>

Parameter	Sensor / method measured
pH	✓ special (trade secrets glass) electrodes with any multi-meter
Carbonate Hardness kH	✓ Electro conductivity probe [28]
General Hardness gH (Mg2+, Ca2+)	
Ammonia (NH3/NH4+) [29]	✓ (NH3/NH4+) Ion-selective electrode
Nitrite (NO2-) compounds	✓ A NO2-/NO3- ion-selective electrode [30]
Nitrate (NO3-) compounds	
Photosynthetically active radiation (PAR) [31]	✓ Light meter

4.3 Proposed system integration to self-awareness

Author chose temperature for the first parameter to implemented on the self-stimulus and expressive pattern for the controller. Temperature is indisputably the most critical parameter for every living organism. This also applies to the aquarium. More reasons why temperature is a good choice: it is unambiguous parameter, relatively fast changing during the day (so experimental time does not stretch too long) and monitoring and controlling devices are rather cheap. In addition, wide variety of sensors and availability of actuators on the market which suit with the controller.

To perceive influence from environmental forces to water temperature, it is reasonable to measure also air temperature. It is self-explanatory that main influencer is air temperature for the water and if water temperature decreases below desired range then action is needed to rise the temperature. In this thesis, water heater is chosen as an external actuator to increase the water temperature to desired range. According to the self-awareness pattern, it is required to add internal sensors for stimulus to perceive self-awareness. As water heater consumes electricity in working state, it is a logical choice to add an internal sensing using the current sensor. Water heater as an external actuator needs mechanism to switch between ON or OFF. In rigid automatics electromechanical relay is suitable candidate for that job acting as a system internal actuator. As the Author’s room temperature is usually slightly below aquarium water temperature, then in the current integration a water cooler (in the form of a water surface fan) is left out. Adding a fan is inevitable for the final system as the room temperature is unknown.

Table 12 maps internal-external, actuators-sensors node elements which will be used in integration pattern. Lines that are solid black will be used in example and algorithm is generated for them in this thesis. Lines highlighted in lilac are possible next developments in the queue using same pattern and algorithm. Notes in the logical brackets point out all the sensors and actuators that will be used for controlling full set of collected parameters from previous work, but equipment is not selected yet.

Table 12: Mapping self-awareness pattern with automatics

	Sensors	**Actuators**
Internal	✓ Total current consumption sensor ✓ Water heater current consumption sensor ✓ Filter current consumption sensor ✓ Light current consumption sensor ✓ {Other internal actuators}	✓ System alert ✓ Water heater on/off relay ✓ Filter pump on/off relay ✓ Light on/off relay ✓ {Other internal actuators}
External	✓ Water temperature sensor ✓ Air temperature sensor ✓ Pump flow sensor ✓ Photosynthetic active radiation sensor ✓ {Other external sensors}	✓ Water heater ✓ Operator feedback to alert ✓ Filter pump ✓ Light ✓ {Other external actuators}

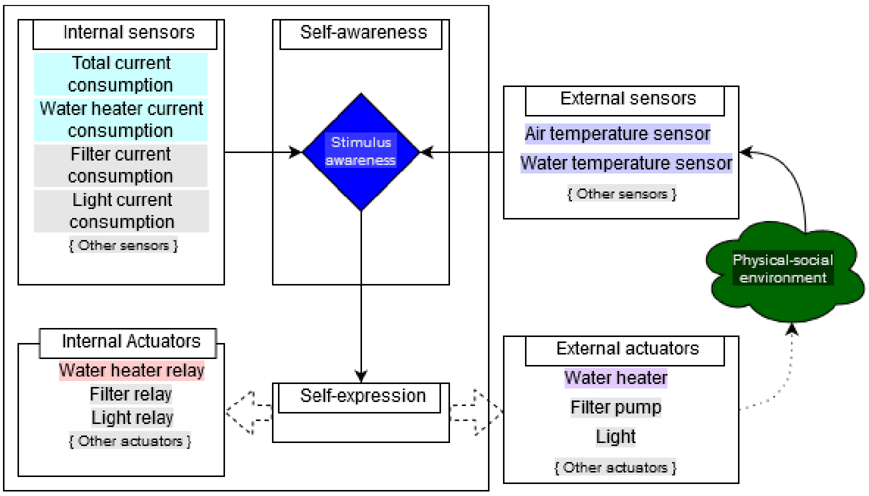

Figure 15: System integration to self-awareness model

Figure 15 is a proposed system integration model for selected self-awareness pattern in current thesis. Model is created by using chapter 3, Figure 14 minimal computational self-awareness pattern and integrated with Table 12 selected sensors and actuators which originate from internal and external of the system.

4.4 Stimulus-awareness and self-expression

Stimulus-awareness is a logic that is a part of the self-awareness. Stimulus-awareness decides self-expressive behaviour based on the internal and external sensors data. Table 13 introduces the selected sensor actuator dependency table to discover the behaviour of a desired algorithm. The table of the whole system (few entries incomplete) is provided in Appendix 2 – Sensors and actuators full dependency table.

Table 13: Optimized dependency table

	Affect actuators	**Affect sensors**
Heater relay on/off	Water heater working status	-
Water heater	-	Increase water temperature Power consumption
System alert	-	Operator feedback alert Unexpected power consumption
Water temperature	Increased by water heater	-
Operator feedback to alert	Solve system alert	-
Heater power consumption	Increased by water heater	-

Flowchart on Figure 16 describes system awareness to perceive water temperature and heater power consumption parameters. Aquarium controller temperature monitoring and controlling algorithm starts with reading environment required parameters as an input: minimum-, maximum-, alert too low- and alert too high-water temperature. Convenient temperature for the fishes was 24-25ºC but on the controller input parameter range is increased by 0.5C. New range is 24.5-25.5ºC. Heater is regulated by bimetal thermostat which is not accurate as shown in Figure 19: Water temperature controlled by heater bi-metal thermostat. Author would like to trigger it whenever controller toggles the heater relay switch. Second reason for increasing temperature range is triggering point’s desired temperature 25ºC and this is exactly in the middle of the new minimum and maximum value.

Controller algorithm lacks self-learning property, which is part of the future developments. At this point, it is reasonable to hardcode desired parameter values for current algorithm which are modifiable by user input. Algorithm is measuring temperature after which parameter value is logged, alert is sent when temperature is in the range of “too low” or “too high” and temperature is controlled. Temperature controlling has three options: temperature is in desired range; temperature is high, or temperature is low. If the temperature is acceptable, then the heater power consumption is measured, and flow is going idle for 15 minutes. For cases where temperature is too low or too high, the alert is sent and when system cannot handle situation then another (system) alert is sent and power is interrupted from the main relay switch after the third failure alert. After cutting power from the actuators, system will start sending temperature alerts to the operator with intervals 1 minute until user input is detected and hopefully failure is eliminated beforehand. User input invokes the system’s normal behaviour and normal flow is continued. This time alerts are reset; main power is restored, and controller will get immediately new temperature reading.

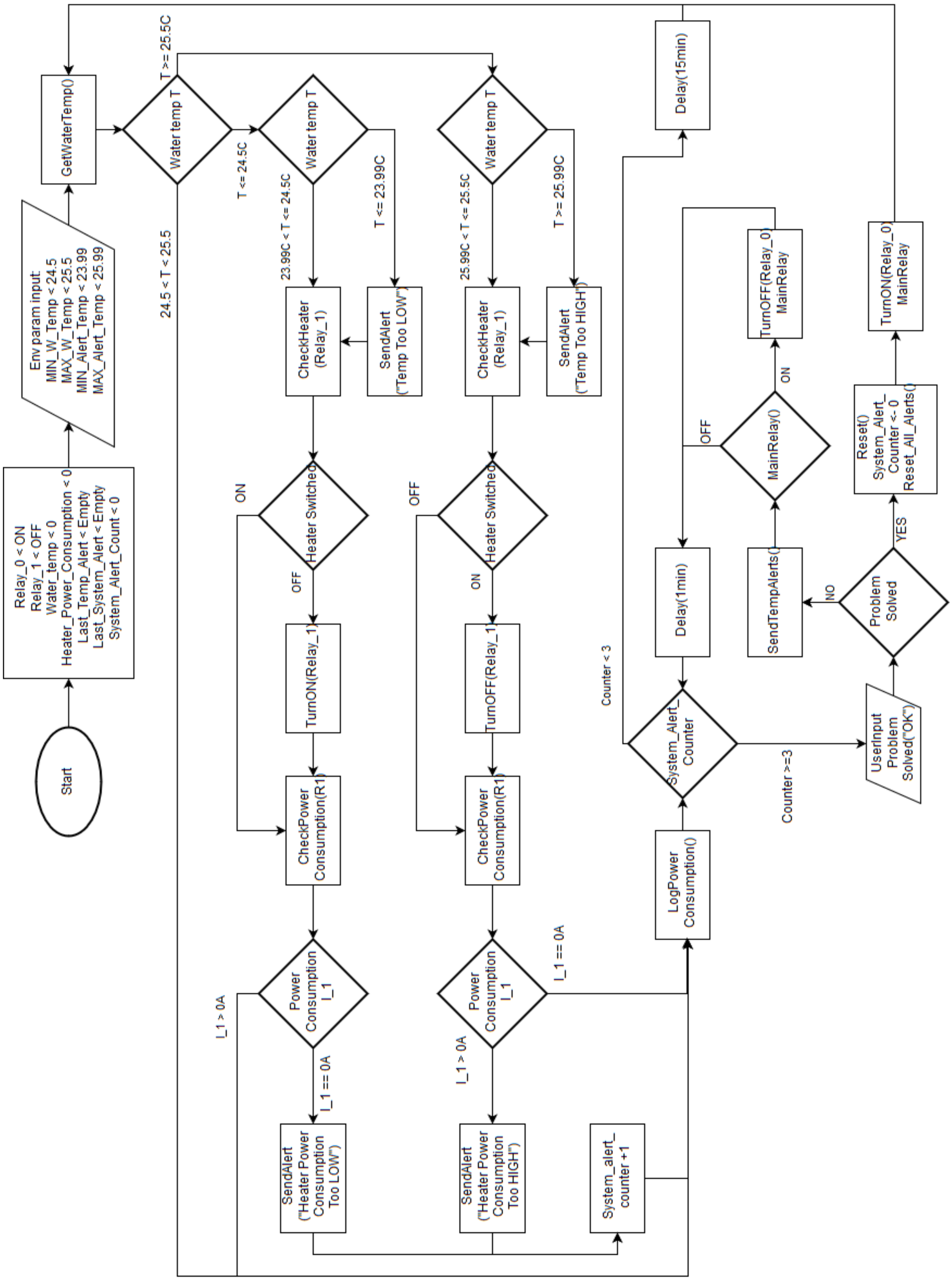

Figure 16: Aquarium controller flow chart

5 Experimental part

Fish keepers use different approaches to reach the same result. From all of the peripheral devices that complete the same tasks, it was necessary to choose one setup for real experimental proof of concept in current thesis. Also, implementing a remote application part largely remains for future work which is briefly topic from chapter 6.

In the analysis of system implementation, most of the possible sensors and actuators are brought out but most of them are not implemented in real experimental part because of limited budget and relatively expensive sensor probes. Some of the probes that are expensive could be implemented by using DIY methods but as this is not part of the thesis topic, they are only lightly described or not mentioned at all.

5.1 System design analysis

Main architecture

Figure 17 is visualizing main architecture of a planned design aquarium controller system. System is divided into four major blocks. Embedded system-on-chip microcontroller unit, environmental and system monitoring sensor block, actuator environment block and remote management application gateway.

Embedded system-on-chip microcontroller unit is collecting sensor unit data, processing and deciding how the system should handle actuators. Each sensor and actuator have a defined behaviour model. The tasks of this block are also to evaluate environment first health level and to communicate it to remote application. Also, primary direct controlling user-interface for the system is provided. Sensors are collecting two kinds of information. First kind is collected environment data and second kind is actuator-based activities feedback. Actuator's block consists primarily of relay driven units which are turning on or off peripheral devices. Some devices need also regulators e.g. to dim lights or to change water pump flow speed. Remote application task is to communicate embedded system and provide real-time monitoring about the environment, sensors, actuators. Second main task would be to analyse already saved historical data and make decisions for the predictive future. Most important task for remote application is to inform user for uncertainty in vivarium microclimate which must be handled as soon as possible. In the meantime, embedded system tries to keep the environment as stable as possible.

SENSOR BASED ENVIRONMENT MONITORING

Sensors block has two main tasks to measure – the changes of the environmental and system variables. Environmental parameters that are measured by the sensors can be both physical (like temperature, water level, water flow) or chemical (e.g. pH, dissolved O_2, CO_2) which all of them are converted to electrical signals and delivered to input of MCU ports. System parameter that is mostly measured is actuators power consumption in amperes. To be sure that system modules are working, basic unit testing is done to toggle them temporarily and measure their current consumption changes. More advanced options to add during system module usage is to expect environmental parameter changing value in one or other way depending if actuator is on or off status.

ACTUATOR BASED ENVIRONMENT CONTROLLING

Actuator’s block consists of physical relays and regulators which are directly related to sensors that bind them into software node, depending on which parameters they can influence. Relays turn peripheral devices directly on/off and are divided into two groups - AC and DC relays. If extra power control is needed, then regulators suited for the device are added into parallel with relay. Actuators most important task is to maintain system status but also used for safety. In case a user intrudes into an aquarium manually for whatever reason and for example the tank lid is opened, then all life-threatening actuators that are powered with alternative current should be turned off into maintenance mode by microcontroller. Last but not least, actuators should be capable to simulate real nature ecosystem conditions like day and night, sunset and sunrise and why not seasonal speciality during year.

REMOTE APPLICATION

Fourth block is meant to support, back-up and get overview of the whole system and environment remotely. Remote application’s block common tasks are to communicate with the embedded system, provide remote monitoring over sensors and actuators, keep additional maintenance and historical data. Application can configure the embedded system remotely and mediate different priority level notifications like information, warning and emergency level.

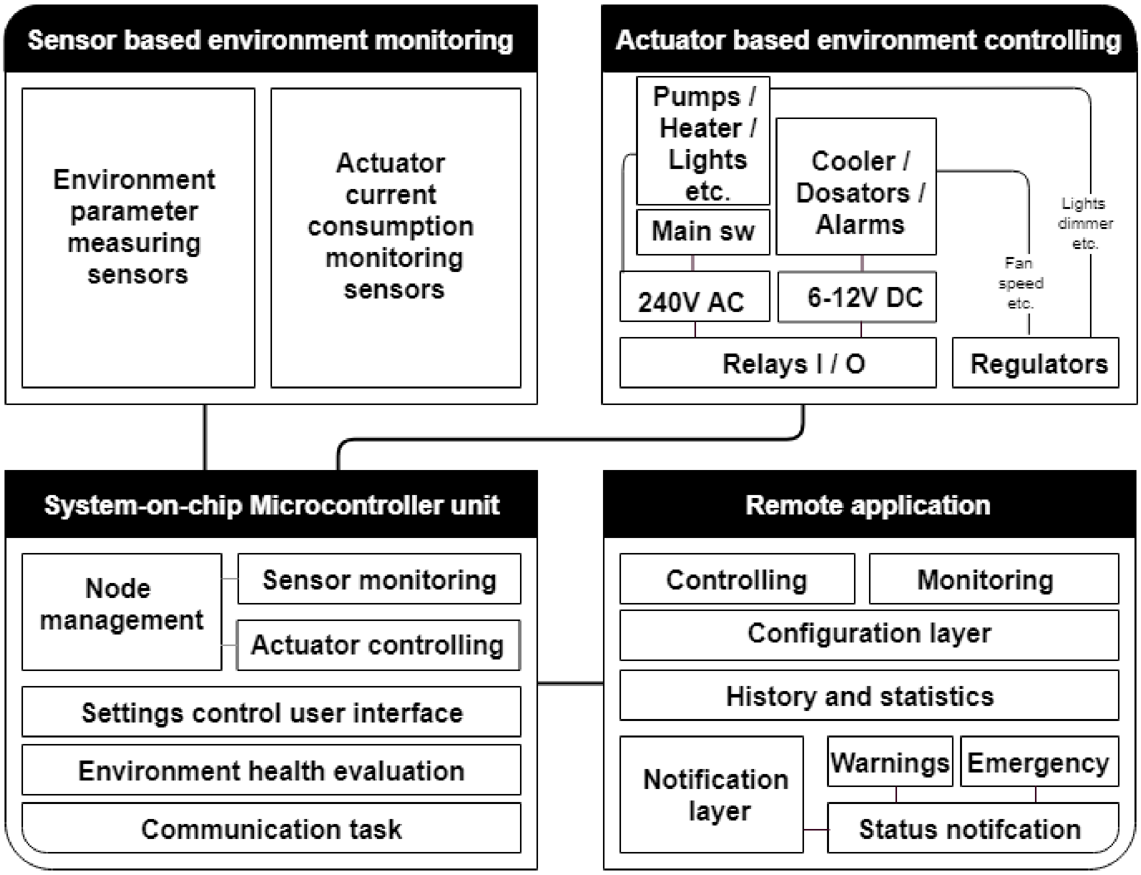

Figure 17: System Architecture Block Diagram.

5.2 Hardware

Aquarium environment microclimate is a complex system, mainly because a lot of parameters need to be monitored and controlled to maintain healthy life in the tank. It sets certain requirements for the system. Each monitoring and controlling device usually need at least one GPIO (general-purpose input/output) port which sets the first requirement for the platform. Next requirement is flash memory for the implemented software. On the other hand, development platform should not be expensive because of the limited budget. Also, very important is the development speed which emerges in development simplicity and availability of the third-party open software libraries. Starting program code from scratch for every peripheral device would take too much time to implement for experimenting and proof of concept.

Considering different microcontroller development platforms – one of the most attractive development choices would have been a starting KIT provided by Open Aquarium project. It includes a microcontroller development board shield which comes with several pre-manufactured sensors and actuators that the aquarium needs. Besides that, it has open software source code and readiness for selected peripherals which is a very reasonable starting point for the current thesis.

It suits well for experimenting, but it has a major disadvantage when implementing full final future version in desired volume. Atmega328p is an 8bit 16MHz microcontroller which lacks the expected amount of GPIO ports and memory for planned desirable software setup when designing into the system all the expected sensors, actuators, direct user interface and communication channels.

Chosen controller for the thesis is Tiva C Series TM4C123GXL Launchpad (Figure 18 [32]) microcontroller development board. It is worth to mention that Tallinn University of Technology use this platform for teaching courses “Basics of Embedded Systems” [33] and “Embedded Systems” [34]. Many lecturers around the world (e.g. Jonathan Valvano Texas University) provide lots of educational material [35] [36] and books [37].

Tiva C Series TM4C123GXL Launchpad has an integrated tm4c123gh6pm 32bit microcontroller. For advanced developing it offers a free IDE (Integrated Development Environment) called Code Composer Studio (CCS), provided by Texas Instrument. For fast scratch programming, Energia.nu IDE is supported, which is forked from Arduino IDE. Many of the Arduino IDE third party open software libraries are supported by the Energia.nu or are easily portable if libraries are developed by keeping in mind hardware abstraction layer (HAL) development conventions.

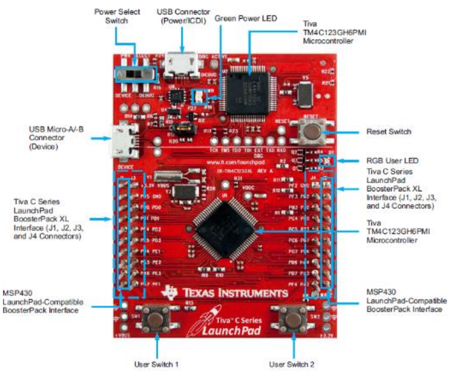

Figure 18: Tiva C Series TM4C123G LaunchPad Evaluation Board

For switching actuators, the optocoupler relay block is chosen. Optocoupler is called also photocoupler. Also known as opto-isolator, which is a small chip that transfers signals between two different circuit using light. Advantage using this type relay block is electrical isolation between microcontroller and higher voltage device that is switched.

Relays in current project:

- Main relay – it turns OFF power from all the devices
- Heater relay– for regulating water temperature
- Light relay – for aquarium day and night cycle simulation
- Filter relay – Heater is not turned OFF; water need to be filtered constantly

For measuring actuators work, it is used in this thesis ACS712 Hall effect-based linear current sensor. Available current ranges for the module are 5A, 20A, 30A. Reason for using current thesis 30A modules is that ordered items were replaced mistakenly against 5A modules. The bigger the power measuring range is the less accurate. For this project accuracy is not very important and author decided to keep them. ACS712 task for current project is to measure every actuator power consumption and discover anomalies when devices are not triggered properly. If device failures, controller must have turn it OFF.

According to the datasheet DS18B20 is digital temperature sensor which provides 9-bit to 12-bit Celsius temperature measurements. Current temperature sensor is selected because of cheap price. Comes with supported libraries to different microcontrollers. Accuracy is ±0.5ºC which is suitable for monitoring aquarium and air temperature. There are also alternatives but as it is packaged into waterproof and pre-wired housing, it was best choice for current project. Mostly comes with pullup resistor 4.7K. Project has two sensors: first is measuring water temperature, second is measuring air temperature.

For user interface classical Nokia5110 LCD display is selected as author had it previously. In the hardware table it is listed with current prices. Given display is easy to use and several open source libraries are available in the internet. Display is currently showing only temperatures and alerts.

Creating timestamps for parameter entries, it is used DS1307 based real time clock. It is also necessary to stick aquarium day and night routines. Current chip is not very accurate but sufficient for this project especially for cheap price.

Hardware setup consist of two main boxes (Appendix 6 – Experimental aquarium controller pictures). With display added is controller and environmental sensor connected to the box and second is power box (hereinafter power bar), which consist mainly of relays for each actuator and their current measuring sensors.

Communication between power bar and microcontroller is hardwired with RJ45 cables, but it is planned to add HC-05 Module for wireless communication. Alternative is to add 433MHz RF link, but it would be only reasonable if switching just relays. HC-05 module Bluetooth technology have more bandwidth to send sensor data from power bar. Microcontroller send relay switching signals to power bar and measures current consumption per relay.

Table 14: Hardware setup and prices[1]

Part	**Pieces**	**Price Estonia / Price (ebay.co.uk)**
TM4C123G Tiva C Launchpad Texas Instruments [32]	1	19€ / 15€
8 Channel Relay Board Module Optocoupler [38]	1	39€ / 5€
Current Sensor Module ACS712 Module [39]	5	7.50€ / 1.5€
Graphical monochrome LCD with backlight [40]	1	9,60€ / 3€
250V AC Wall socket	4	2,39€
Real Time Clock Module [41]	1	3€ / 0.99€
DS18B20 Digital temperature sensor [42]	2	8€ / 2.5€
Tetra HT 300 Heater with bi-metal thermostat [43]	1	29,99€
Aquael Circulator 650 Filter [44]	1	29.90€
LED light (DIY from led stripes and driver)	1	30€
Electrical box	1	10,29
Total	-	**205,84€ / 156,23**

[1] Appendix 5 – Used electronical modules specifications

Additionally, level shifter logic module is used because TM4C123GXL LaunchPad using for signalling 3.3V but for example relays are using for switching on 5V. Level shifter is used currently only for relays.

By ordering parts from ebay.co.uk, additional dispatching cost may be applied. VAT (value added tax) is added by the law. Author saved around 50 Euros by ordering some parts from ebay.co.uk (China) but the abovementioned additional costs are not counted in. Another aspect is the waiting time. Delivery time for ordering parts from local shops is 1-2 days, but when ordering from China, small parts may arrive from 2 weeks to 1 month.

On the **Error! Reference source not found.** is shown development board pinout. As current microcontroller is without development board is impossible to connect with other electronics it is not necessary to draw full schematic (LaunchPad full schematic can be seen reference: [45]). Table 15 show above described hardware modules and their pinout to LaunchPad (Figure 27: LaunchPad with microcontroller TM4C123GH6PM pinout.

Table 15: Hardware connection pinout

Module	Pinout list
LCD Display	Signal (Nokia 5110) LM4F120 pin Reset (RST, pin 1) connected to PA7 SSI0Fss (CE, pin 2) connected to PA3 Data/Command (DC, pin 3) connected to PA6 SSI0Tx (DIN, pin 4) connected to PA5 SSI0Clk (CLK, pin 5) connected to PA2 3.3V (VCC, pin 6) power not connected (BL, pin 7) ground Ground (GND, pin 8)
ACS712 current sensor *Note: It is possible to use the sensor 3.3V or 5V logic but the formula needs to be modified by the used logic*	Power Supply (VDD) connected to 5V power Ground (GND) connected to ground ACS712 Relay1 – Relay4 signals: • ACS712 (1) connected to PD0 • ACS712 (2) connected to PD1 • ACS712 (3) connected to PD2 • ACS712 (4) connected to PD3
RTC DS1307 real time clock	Ground (GND) connected to ground Power supply (VCC) connected to 3.3V

Module	Pinout list
	Clock (SCL, pin) connected to PB2 Data (SDA, pin) connected to PB3
DS18B20 temperature sensor *Note: As it uses 1-Wire then it is possible to add as many sensors to one port as wanted*	Power supply (VDD, pin) 3.3V Data (DQ, pin) connected to PE3 Ground (GND, pin) connected to ground *Note:VDD and DQ is connected to eachother with 4.7K resistor*
Relay switch signals *Note: Relay is triggered only with 5V logic and needs level Shifter from*	Power Supply (VDD) connected to 5V bus Ground (GND) connected to ground Relay 1 –4 switch signals: Relay (1) connected to PE1 Relay (2) connected to PE2 Relay (3) connected to PE3 Relay (4) connected to PE4

5.3 Software

Author decided to use PlatformIO IDE plugin in Microsoft Visual Studio Code for the current thesis because it has support for Arduino IDE, Energia.nu IDE APIs and third-party libraries. It is developed for supporting multiple microcontroller platforms at the same time which make develop soruce code easier for multiple microcontrollers at the same time. Energia.nu IDE is little bit primitive to use because it supports only writing library API's but not maintaining and modifying libraries in C and C++ language itself. When focusing code writing on Tiva C Series microcontroller advanced programming for the current system it may be reasonable to move CSS (Code Composer Studio) IDE provided by Texas Instrument which is forked from Eclipse IDE.

Hardware that needed software implementation for the thesis proof of concept were digital DS18B20 temperature sensor, Nokia PCD8544 LCD display, ACS712 current sensor, DS1307 RTC (Real Time Clock) and Optocoupler isolated relay block for each actuator. Hardware is listed in Microcontroller send relay switching signals to power bar and measures current consumption per relay.

Table 14: Hardware setup and prices and specifications are described in Appendix 5 – Used electronical modules specifications with the reference note.

Currently, only communication channel with the microcontroller is UART (Universal Asynchronous Receiver/Transmitter) hardware which is using asynchronous serial communication protocol.

DS18B20 is digital temperature sensor and using for communication 1-Wire protocol. Library is provided to use free of charge by the Dallas Semiconductor Corporation.

For interfacing Nokia5110 LCD display there were several choices. Now is used Jonathan Valvano source code [35] from his educational materials.

For RTC DS1307 real time clock it is used RTClib open source library from Energia.nu repositories.

Current sensor ACS712 is using voltage divider formula and connected to microcontroller analog port. Voltage is calculated with formula:

$$ValueInAmperes = \frac{OffSetValue - (SamplingAverage * \frac{OperatingVoltage}{Resolution})}{Sensitivity}$$

- OperatingVoltage = 3.3
- OffSetValue = OperatingVoltage / 2
- Resolution = 1024 (10bit)
- SamlingAverage is sum of values taken from the signal pin in short time period e.g. 150 times with 10ms interval which is divided with the multiplier (150)
- Sensitivity = 0.66mV/A (it is ACS712 30A module specific)

Figure 24 shows Aquarium live feed combined with gauges on the web page. Implemented software is additionally capable to communicate over UART and send signal directly to dashboard. In the future it is plan to develop service for monitoring and controlling data remotely.

5.4 Self-aware aquarium controller evaluation

Figure 19: Water temperature controlled by heater bi-metal thermostat and Figure 20 show two experiments of measuring and controlling temperatures. Both experiments are shown on the graphs with 2 days period and 15 min intervals measuring time. Full experimental graph for 5 days period is included in Appendix 3 – Water temperature

measured before setup (Figure 22) and Appendix 4 – Water temperature controlled after setup (Figure 23). Figure 19 (full in Appendix 3 – Water temperature measured before setup) graph is first experiment where only measurements of the water and air temperature were made without controller interference. Temperature is regulated by the bimetal thermostat integrated into heater. The fluctuation of the bimetal thermostat temperature is approximately 1.62ºC, based on the experimental test data results.

Results show that it is impossible to setup such a heater to keep a stable water temperature with accuracy 1ºC. To demonstrate the heater working behaviour controlled by internal thermostat and then compare it with implemented aquarium controller, current sensor module ACS712 was added to monitor heater power consumption. Power consumption is decorated in the Figures with orange dotted line. To show day and night cycle, light power consumption is also added on the graphs with light blue dotted line.

Current implementation does not include water cooler and room air temperature may increase water temperature in the tank a little bit higher than expected. System will still raise “HIGH temperature” alert (see Figure 16, Water temp T decision box) above 25.99ºC.

Table 16 is comparison controlling water temperature and other parameters that is measured before and after temperature regulating is activated by the implemented aquarium controller.

Figure 19: Water temperature controlled by heater bi-metal thermostat

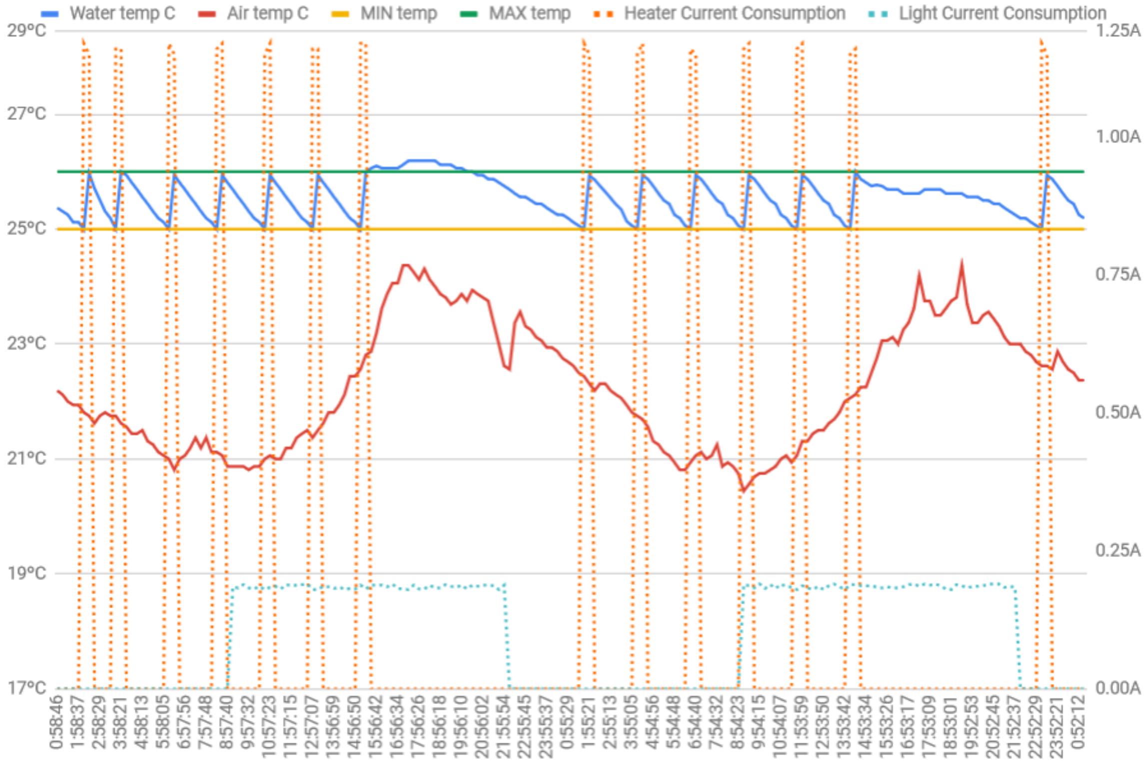

Figure 20: Water temperature controlled by thesis experimental microcontroller

Table 16: Water temperature controlling comparison

	Before setup	**Aquarium controller setup**
Measuring interval	15min	
Heater current consumption (Amperes) ~240VAC	~1.15 – 1.17A (±1.5%)	
Light current consumption (Amperes) ~240VAC	~0.18 - 0.19A (±1.5%)	
Filter pump consumption (Amperes) ~240VAC	~0.2 – 0.3A (±1.5%)	
Total Amperage range measured (lowest and highest peak)	~0.2 – 1.38A (±1.5%)	
Temperature heating range measured by temperature sensor	24.44 – 26.06ºC Gap: 1.62ºC	24.5 – 25.5ºC Gap: 1ºC
Average heating and cooling cycle in low air temperature room	4h 22min 56sec	2h 9min 42sec

Table 16 concludes that when room air temperature is low and does not hold water temperature then water is heated in loop with fixed period. Without controller the heating and cooling cycle is about 4 hours 22 minutes 56 seconds. With controller when heater activating range is regulated on to 1ºC change, the average water heating and cooling cycle is 2 hours 9 minutes and 42 seconds.

Author concludes that experiment results show positive signs to improve system further. Although current implemented design does not include learning from statistical data patterns and does not predict future, it is possible to add to the system with further development. Selected platform has all expected resources to combine more logic and stability into aquarium controller system.

It is significant step to add more precision into regulating water parameters and sending alerts when some of the parameters leave out of the expected range for fish keepers. Now, fish-keepers can start to observe system internal parameters and predict when some peripheral device starts to degrade. In future developments of the system, current implementation would likely to be able to predict system degradation itself and operator's job is only to not ignore the alerts.

6 Conclusions and Future Work

6.1 Conclusion

Obviously, it is fair to admit that the realization of self-awareness is tempting to the extent that such systems have higher reliability and can cope with various changes in the environment and in the parameters of the equipment. However, as no tool is directly supporting the development of this functionality today, development work is very labour-intensive and time-consuming. For this reason, the very limited self-awareness was studied and implemented in this work. However, the experiments showed that even adding a little computational self-awareness increases the reliability of the system and allows for more intelligent control.

6.2 Future work

Current implementation was only proof of concept for realizing if the system is worth to develop. After experimentations and device currently being in everyday use, even if it is only a prototype, it is worth to put effort and time into the system for further development. Especially when competition in the market is currently quite modest.

Current plans are to sort out parameters that need every-day monitoring and controlling, work out proper base algorithm that is expandable for every parameter and optimize the system software and hardware implementation. Design decent direct user interface and remote application which would be usable for every modern device.

Next step would be using some existing or design a new universal sensors and actuators connector solution. E.g. controller can discover and learn selected sensors when they are plugged into a random suitable port. But safety first and foremost, which is to change aquarium controller safe for environment, operator and itself.

Coming back to research of the current thesis, it is attractive to think about adding more layers of self-awareness but currently even the computational self-awareness is quite new paradigm. However, to continue this research and base in Figure 13: Hierarchy of Self-* Properties as a fundamental hierarchy of self-* properties, it is achievable to add self-learning ability to the system, teach the system to adapt to new peripheral devices and learn its deprecation and aging characteristics.

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Appendix 1 – Aquarium controllers starter KIT's includes

Table 17: GHL profilux 4 features and content in the box

GHL profilux4 Starter KIT and prices - Price: ~975€ (may vary different dealers)	
Features: ▪ Multi-channel Lighting Control ▪ Lab Grade Measurement and Controllability ▪ Versatile Pump Control ▪ Unparalleled Security ▪ Connectivity Options ▪ Rock-Solid Hardware ▪ Wide Range of Expansion ▪ Professional Software	Set includes: ▪ ProfiLux 4 controller - White ▪ ProfiLux 4 power supply ▪ Water temperature sensor ▪ pH probe ▪ Redox probe ▪ Conductivity probe ▪ Power-bar 5.1 with PAB-cable 2m ▪ ProfiLux Touch with PAB cable 2m ▪ Calibration fluids (pH 7&9, 50ms, 220mV) ▪ USB cable

Table 18: Neptune Systems Apex features and content in the box

Neptune Systems APEX Starter KIT - Price: 800€ (may vary different dealers)	
Features: ▪ Base Unit Dimensions-4.75" L x 5.25" H x 3.25" W ▪ Energy Bar 832 Dimensions-10" L x 6.5" H x 2.25" W Port Specifications: ▪ Built-in Wi-Fi and Ethernet Port ▪ 12V Power Port ▪ 2 Aqua-bus Ports ▪ Temperature Probe Port	▪ I/O Switch Input ▪ pH Probe Port ▪ pH/ORP Probe Port ▪ Salinity Probe Port ▪ 4 Variable 0-10V channels for LED Dimming or Tunze Pumps

Neptune Systems APEX Starter KIT - Price: 800€ (may vary different dealers)
Set includes: ▪ Apex Control Head Unit (optional display sold separately) ▪ Energy Bar 832 ▪ 6ft. Aquabus Cable ▪ Lab Grade Salinity Probe ▪ Lab Grade Double Junction pH Probe ▪ Lab Grade Double Junction ORP Probe ▪ Temperature Probe

Table 19: Open Aquarium platform features and content in the box

Open Aquarium starter KIT - Price: 199€ basic KIT + 99€ additional Aquaponics set	
Features: ▪ Remotely control your aquarium ▪ Measure temperature ▪ Measure pH ▪ Measure conductivity ▪ Discover water levels ▪ Discover water leakeage ▪ Deploy fish feeder ▪ Deploy water heater / cooler regulating ▪ Deploy change water pumps ▪ Deploy dosing medicines ▪ Deploy simulate day and night cycles ▪ Communication via Wi-Fi, GPRS, 3G ▪ Open source API	Set includes: ▪ 2x Flange ▪ Fish Feeder Cable ▪ Fish Feeder Connector ▪ OpenAquarium box ▪ Big Enclosure for gateway ▪ 3x 20mm Cable Glands ▪ Vent Plug ▪ 4x M3 Metal Nuts ▪ 4x M3 x 10mm Metal Screws Set includes: ▪ ProfiLux 4 controller - White ▪ ProfiLux 4 power supply ▪ Water temperature sensor ▪ pH probe ▪ Redox probe ▪ Conductivity probe
Set includes: ▪ Power-bar 5.1 with PAB-cable 2m	Aquaponics (additional) set includes: ▪ Aquaponics extension ▪ Electro-conductivity sensor

Open Aquarium starter KIT - Price: 199€ basic KIT + 99€ additional Aquaponics set	
▪ ProfiLux Touch with PAB cable 2m ▪ Calibration fluids (pH 7&9, 50ms, 220mV) ▪ USB cable ▪ Gateway Shield for Arduino ▪ Aquarium Automatic Feeder ▪ DS18B20 ▪ Water level ▪ 12V Power Supply	▪ pH sensor ▪ SMA-BNC pigtail ▪ 2x Flange

Appendix 2 – Sensors and actuators full dependency table

		ACTUATORS												SENSORS																		
		Lights on/off	Heater on/off	Filter/Sump pumps on/off	Aerator on/off	CO_2 on/off	Automatic feeder on/off	Water inlet pump on/off	Water outlet pump on/off	*Light intensity dimming*	*Light spectre dimming*	*System alert*	*Water cooler fan*	Temperature	Water level	pH	Dissolved O_2 in water	Dissolved CO_2 in water	kH (Carbonate Hardness)	gH (Mg^{2+} & Ca^{2+})	Light intensity	Light specter	PAR sensor	NO_2 level in water	NO_3 level in water	Video feed	Filter pump flow speed	Operator feedback to alert	Under lid humidity	Air temperature	Lid opening sensor	Power consumption sensor
SENSORS	Power consumption sensor	x	x	x	x			x	x																							
	Lid opening sensor		IO	IO			IO	IO	IO			~	IO																			
	Air temperature											~	x																x			
	Under lid humidity sensor		x									~	*↑↓	x	x															x		
	Operator feedback to alert											x																				
	Filter pump flow speed			x								~																				
	Video feed	x										~																				
	NO_3 level in water							x				~																				
	NO_2 level in water							x				~																				
	PAR sensor	x								x	x	~									x	x										
	Light spectre	x									x	~											x									
	Light intensity	x								x		~											x									
	gH (Mg^{2+} & Ca^{2+})							x				~																				
	kH (Carbonate Hardness)					*↑↓		x				~																				
	Dissolved CO_2 in water			*↑↓	*↑↓	x		x				~																				
	Dissolved O_2 in water				x			x				~																				
	pH			*↑↓				x				~																				
	Water level							x	x			~																	x			
	Temperature		x									~	*↑↓																x	*↑↓		x
ACTUATORS	*Water cooler fan*											~		*↑↓															*↑↓	x	IO	
	System alert	~	~	~	~	~	~	~	~	~	~		~	~	~	~	~	~	~	~	~	~	~	~	~	~	~	x	~	~	~	
	Light spectre dimming	x										~										x	x									
	Light intensity dimming	x										~									x		x									
	Water outlet pump on/off		IO	IO				IO				~			x																IO	x
	Water inlet pump on/off		IO	IO					IO			~			x	x	x	x	x	x				x	x						IO	x
	Automatic feeder on/off											~																			IO	
	CO_2 on/off											~						x	*↑↓													
	Aerator on/off											~					x	*↑↓														x
	Filter/Sump pumps on/off							IO	IO			~				*↑↓		*↑↓									x				IO	x
	Heater on/off							IO	IO			~		x															x		IO	x
	Lights on/off									x	x	~									x	x	x			x						x

Figure 21: Full dependency table of sensors-actuators

x - actuator<->actuator, sensor<->actuator affects each-other
IO - actuator or sensor triggers affected one to reverse position
*↑↓ - actuator affect chemical or physical parameters
~ Anomalies in actuators/sensors triggers system alert

Appendix 3 – Water temperature measured before setup

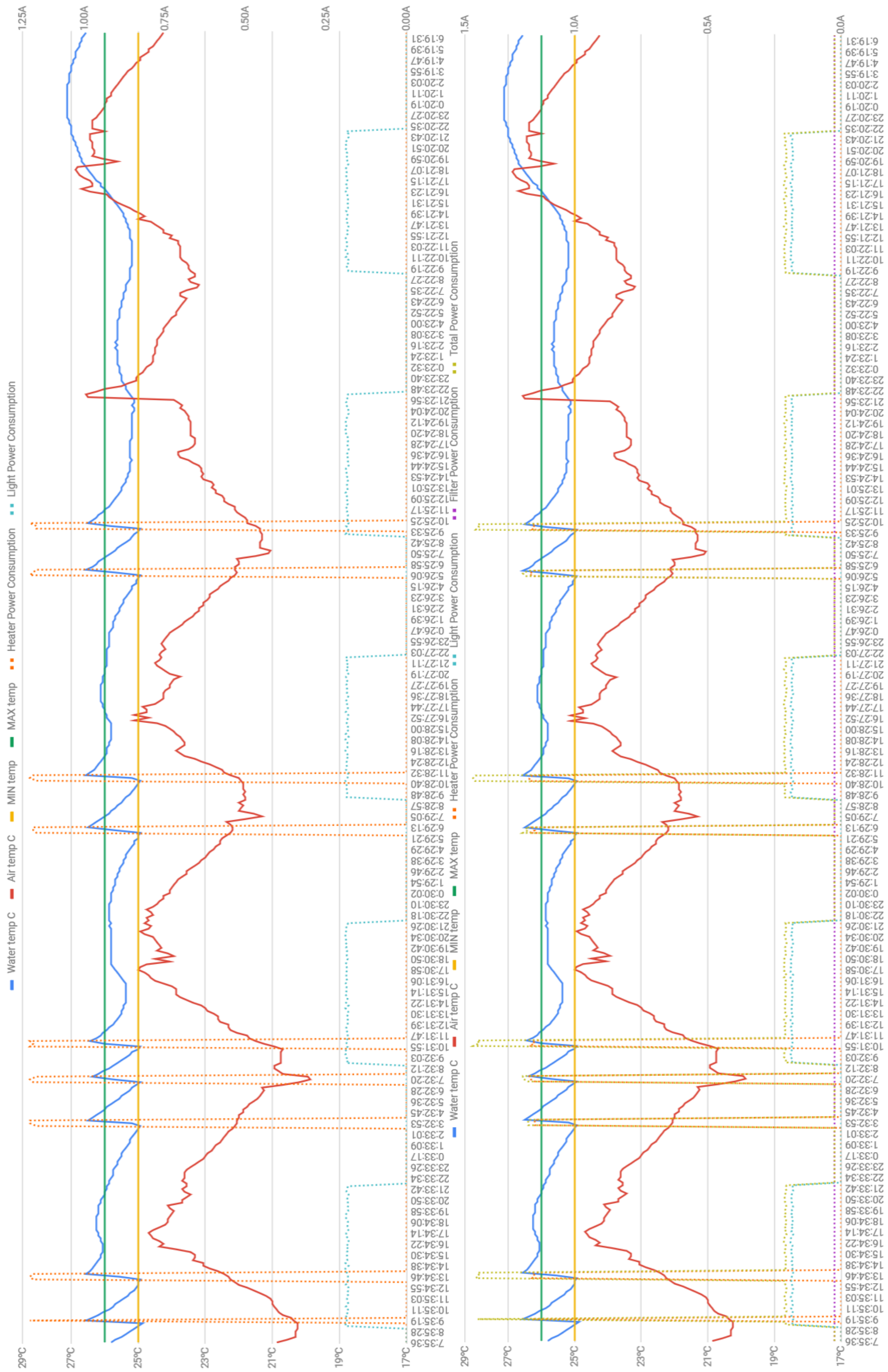

Figure 22: Five days measurements without experimental system

Appendix 4 – Water temperature controlled after setup

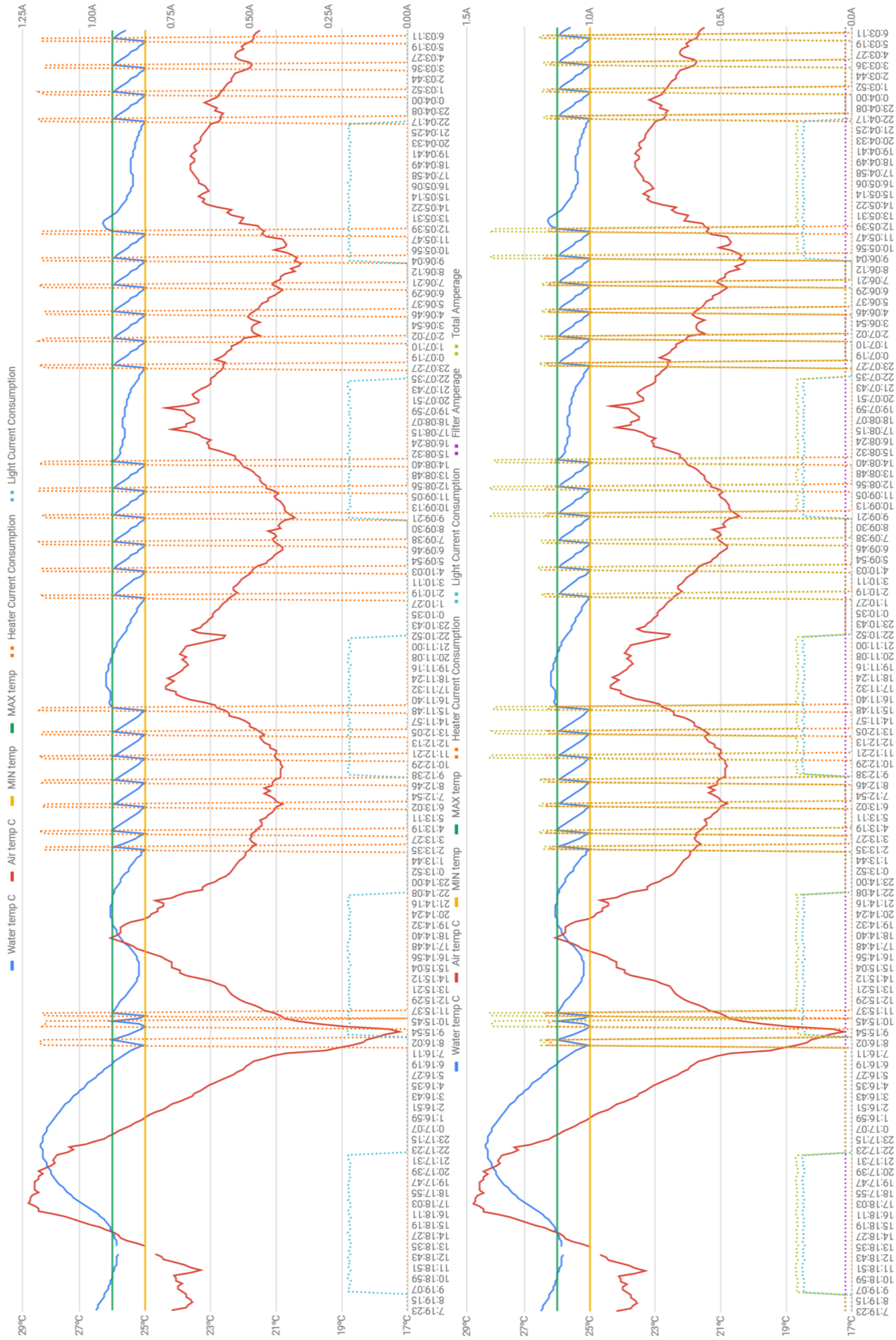

Figure 23: Five days measurements with precise temperature controlling

Appendix 5 – Used electronical modules specifications

Table 20: TM4C123G LaunchPad Evaluation Kit specification

The ARM Cortex-M4F Based MCU TM4C123G LaunchPad Evaluation Kit (EK-TM4C123GXL) offers these features [46]:

- High Performance TM4C123GH6PM MCU:
  - 80MHz 32-bit ARM Cortex-M4-based microcontrollers CPU
  - 256KB Flash, 32KB SRAM, 2KB EEPROM
  - Two Controller Area Network (CAN) modules
  - USB 2.0 Host/Device/OTG + PHY
  - Dual 12-bit 2MSPS ADCs, motion control PWMs
  - UART, 6 I2C, 4 SPI
- On-board In-Circuit Debug Interface (ICDI)
- USB Micro-B plug to USB-A plug cable
- Preloaded RGB quick-start application
- ReadMe First quick-start guide
- EK-TM4C123GXL TivaWare™ for C Series software is available for free downloads.

Table 21: 8 Channel Relay Board Module Optocoupler specification

8 Channel Relay Board Module Optocoupler Specifications [38]:

- Can be used as microcontroller development board module can be used as home appliance control
- 5V TTL control signal
- The control signal DC or AC, 220V AC load can be controlled
- There is a normally open and one normally closed contact
- A power indicator light
- A control indicator, pull off, disconnect does not shine
- Transistor drive to increase the relay coil control pins high impedance
- The control pin has a pull-down circuit to prevent malfunction relay vacant

NB! Current Reference link [38] is 4 relays channel. 8 channel relay url were removed, but relay module remains same.

Table 22: 30A ACS712 Range Electric Current Sensor Module Board specification

30A ACS712 Range Electric Current Sensor Module Board [39]:
• The current sensor chips: ACS712ELC-30A; • Pin 5V power supply, on-board power indicator; • The module can measure the positive and negative 30 amps, corresponding to the analogue output 66mV / A; • No test current through the output voltage is VCC / 2; • PCB board size: 31 (mm) x13 (mm); • Note: ACS712 is based on the principle of the Hall test, please use this field to avoid an impact Package content: • 1 × 5A / 20A / 30A (As your choice) ACS712 Range Angebot Current Stromsensor Sensor Modul Board

Table 23: Blue 84 * 48 Nokia 5110 LCD Display specification

DIY White / Blue 84 * 48 Nokia 5110 LCD Display Screen Module Module for Arduino [40]:
Specification: • "LIGHT" linked with GND, the backlight to be lit. • Need you to compress the screen and PCB tighter, might got loose after the delivery. • Use a 3.3V controller, otherwise the display could be quite vague. LCD5110 Module: • Power supply voltage:2.7V-3.3V,5V is OK, but part of the screen becomes black when tested • Data interface level:2.7-5V • Backlight power supply voltage: highest 3.3V • Installation diameter:2mm • Backlight: Blue

Table 24: SparkFun Logic Level Converter - Bi-Directional specification

SparkFun Logic Level Converter - Bi-Directional [47]:
Description: • Many channels I2C level translator module, IIC UART SPI TTL Bi-Directional level translator module, compatible with 5-3v system • I2C level translator module, 3V to 5V, 5V to 3V for Arduino • VIN connected 5V system power supply • 5A connected 5V system • 5B connected 5V system • GND connected 5V system GND

- 3V3 connected 3V system power supply
- 3A connected 3V system
- 3B connected 3V system
- GND connected 3V system GND
- Size: 16 x 12mm / 0.63 x 0.47 inch

Package includes:

- 2/5/10PCS x 2 Channel IIC Level Converter Module

Table 25: Temperature Sensor - Waterproof (DS18B20) specification

Temperature Sensor - Waterproof (DS18B20) [42]:

- 3.0-5.5V input voltage
- Waterproof
- -55°C to+125°C temperature range
- ±0.5°C accuracy from -10°C to +85°C
- 1 Wire interface
- Probe is 7mm in diameter and roughly 26mm long. Overall length (including wire) is 6 feet.

Table 26: Module Ds1307 24C32 Clock Tiny RTC I2C Battery CR2032

Module Ds1307 24C32 Clock Tiny RTC I2C Battery CR2032 [41]:

- Power supply: 5V
- Memory EEPROM 56 bytes
- Protocol I2C
- Requires two analog ports available
- Size: 2.9 x 2.6 cm
- Hour, Minutes, seconds, AM/PM, day, month, Date, year

Table 27: TetraTec Aquarium Heater 300w HT-300 specification

TetraTec Aquarium Heater 300w HT-300 [43]:

- Model HT300 For Tanks: 300-400L
- Product Dimensions 42.4 x 9.2 x 5.8 cm
- 300 Watts

Table 28: Aquael Powerhead 650 specification

Aquael Powerhead 650 [44]:

- Water circulation 650l/h
- Power consumption 6W

Appendix 6 – Experimental aquarium controller pictures

Figure 24: Aquarium controller dashboard

Figure 25: Aquarium controller and power bar

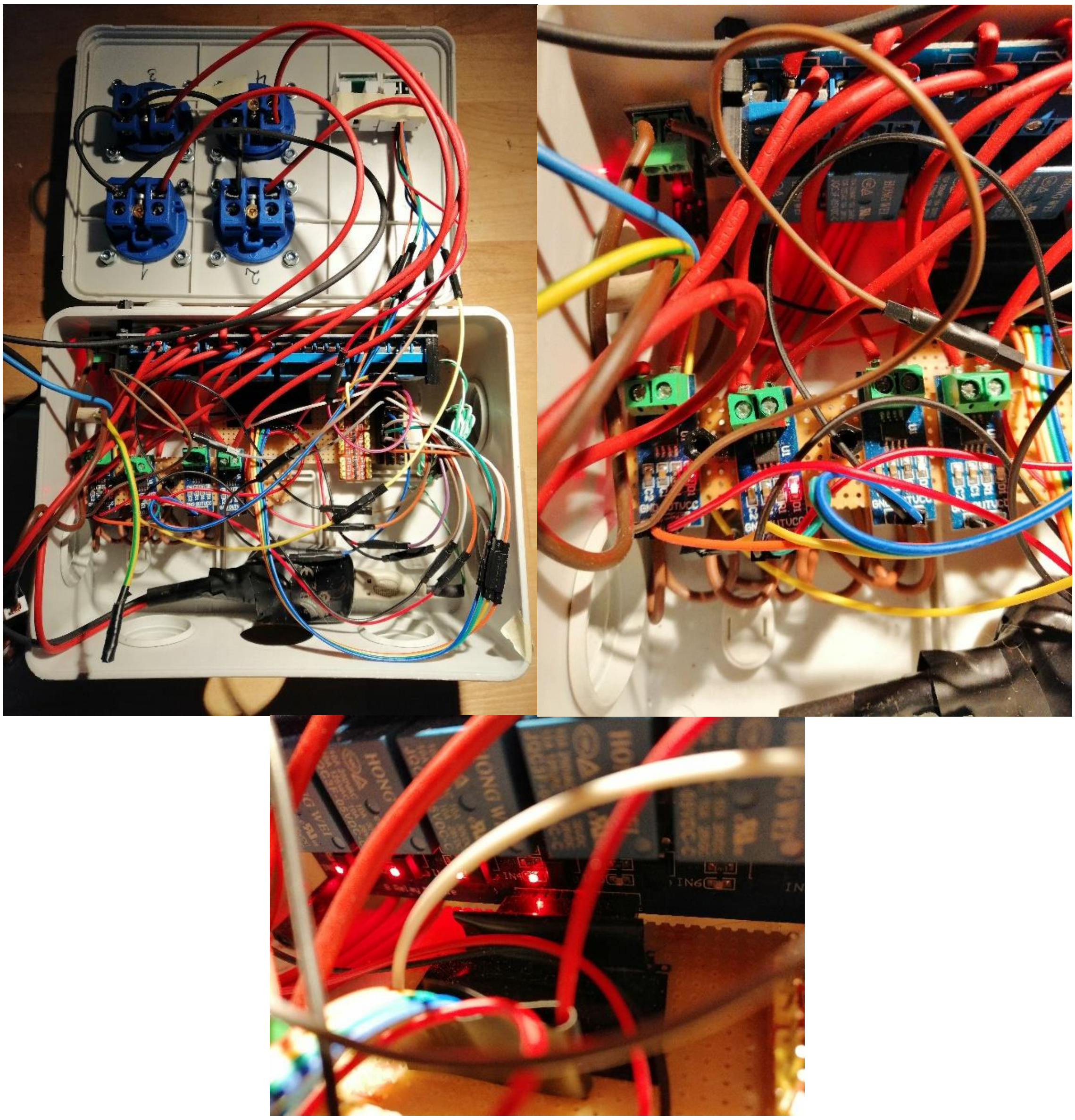

Figure 26: Inside the aquarium power bar

Appendix 7 – TM4C123GH6PM microcontroller pinout on Launchpad

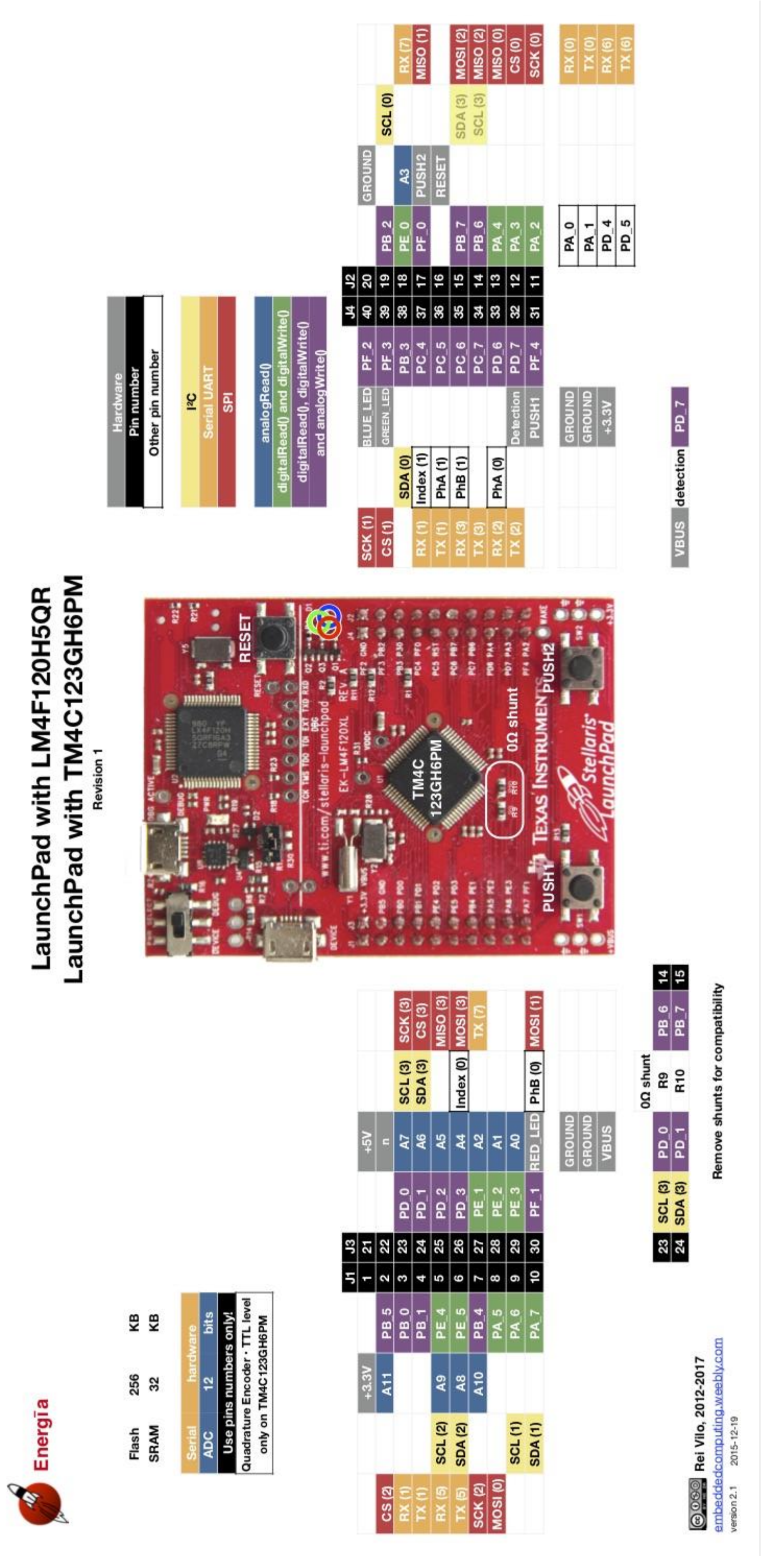

Figure 27: LaunchPad with microcontroller TM4C123GH6PM pinout [48]