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**Design of a Specialist Automatic Control
System**

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Executive Summary

This report analyses the feasibility of a self-regulated control system for an Aquarium. The research undertaken found that there are many variables one must consider before undertaking such a design of an automatic control system for this type of environment.

It is stated that not only does one have to consider water variables such as temperature and oxygen levels, but also for a self-sustaining system one may have to consider lighting and automatic feeding systems.

The report delves into the different subsystems and equipment one may require for any automation machine whilst then tailoring the required equipment needed for an automated aquarium whilst also making many considerations around machine directives and aquarium regulations.

The proposed design implemented basic automation methods found in many industries, utilising common automation techniques, equipment, and communication protocols. The design ensured that a programmable logic controller was utilised to be the central point of the system, intertwining each input and output through many communication protocols.

The design implemented the Industrial Internet of Things which allowed the system to be connected to the outside world, thus, process alarms and monitoring systems were fully visible and thus, the possibility of a smarter system could be achieved.

The proposed design made many considerations around its control, power, and communication methods, but safety and regulation conformity will always be at the highest priority within any automation system. Therefore, no automation system can be fully automated without human interaction, only made smarter with less interaction and automated process improvements.

Therefore, a design of a specialist automatic control system for an aquarium is possible, if one utilises this proposed design whilst altering the equipment specifications based on the requirement for specific wildlife needs.

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1.0. Introduction

This report will determine the feasibility of a self-regulating control system that nurtures endangered aquatic life by utilising control technology to propose an automation system design.

1.1. Problem Statement

A specialist self-regulating aquarium must be designed to nurture endangered aquatic life. One would need to consider the manipulated and controlled variables. Furthermore, one must consider any process alarms and monitoring systems for process improvement.

For the feasibility, one will consider freshwater aquatic life, however, the design must be general-purpose and therefore no equipment-specific operational ranges will be specified, only those that meet general requirements, preventing limitations of the study.

2.0. Considerations and Regulations

One must consider the variables around a self-regulating aquatic environment, whilst conforming to Automation Machine Directives, Health and Safety, Environmental and Aquatic Welfare Regulations.

2.1. Aquarium Regulations

The Federation of British Aquatic Societies (2008, pp. 2-9) states that keeping aquatic life requires conformity to regulations under the Animal Welfare Act 2006. Table 1 shows a summary of the key factors that must be considered for the automation system.

Table 1 Shows Aquarium Welfare Regulations

Aquatic Welfare	Aquarium Specific Needs
A suitable environment must be provided.	This means the environment must have clean water which meets the needs of the fish in terms of oxygen levels, pH levels, cleanliness and so on.
A suitable diet must be provided.	This means the fish must be fed regularly with appropriate food.
Fish must be housed with or apart from others depending on their needs.	This means that fish must be kept together if needed or put into separate tanks if needed.
Fish need to be protected from pain and suffering.	This means that their environment must not harm them in any way.

2.2. Health and Safety Regulations

Machine Directives such as “Machinery Directive 2006/42/EC” must be conformed to for the manufacture and distribution of systems to industry. Even automated machinery requires some human interaction; thus, one can utilise “Provision and Use of Work Equipment Regulations 1998 (PUWER)” for conformity. CE marking can be utilised for equipment conformity for this project, although according to the UK Government website, the UK will utilise UKCA marking in the coming years (Using the UKCA marking, 2021).

Supply of Machinery (Safety) Regulations 2008 must be followed for machine design and manufacture. Following EN/ISO 13849-1 and EN/IEC 62061 can allow conformity at the design, build and implementation stage (Collins, 2019).

2.3. Aquarium Variable Considerations

For a self-regulating system, one must be aware of the environmental variables that need to be manipulated and controlled, whilst conforming to cleanliness, environmental, and health and safety standards.

Meeting environmental and safeguarding of aquatic life regulations, one must ensure automated tank cleaning and fish feeding is achieved to prevent negative effects on the lifespan and behaviour of aquatic life. Water changes must be done at a low rate to prevent high fluctuations in environmental changes causing aquatic stress (Balasubramani, Aakash, Akshay and Bennet, 2020, pp.524-526).

Artificial light interferes with the physiological functions, behaviour, and development of aquatic life; thus, time dependant lighting control must be achieved (Brüning, 2016).

Chiu (2010, pp.1458-1460) states temperature control is very important, especially for aquatic reproduction which would be essential for endangered species.

High temperatures also reduce oxygen levels, which are important for aquatic life survival. Freshwater fish require more parts per million compared to other types like marine wildlife, therefore, this must be considered (Aquarium Oxygen: The Essential Ingredient to a Healthy Aquarium, 2021).

Potential hydrogen (pH) levels also require control for the survival of aquatic life, thus, must be considered (Chiu, 2010, p.1461).

Therefore, for freshwater fish the variables to consider are:

- Lighting
- pH Levels
- Water Flow Rate
- Water Levels
- Water Oxygen Levels
- Water Temperature

Hardyanto, Ciptadi and Asmara (2019, pp. 48-51) expand on these variables stating process improvement can be achieved through the Internet of Things (IoT). The Industrial Internet of Things (IIoT) focuses on interconnecting machines, big data, and machine learning, increasing

reliability and efficiency. It utilises Programmable Logic Controllers (PLCs), Human Machine Interfaces (HMIs) and Distributed Control Systems (DCSs). It essentially combines systems that collect and control data for process improvement which collectively can be known as Industry 4.0. (Banafa, 2015).

3.0. Automation Essentials

This section will describe the general equipment requirements needed for an automation design of the proposed variables.

3.1. Equipment and Instrumentation

Automation processes utilise technologies to produce outcomes with minimal human interaction, increasing efficiency, speed, redundancy, and reliability, reducing mundane or dangerous tasks from human intervention (Groover, 2008, p.85).

Figure 1 shows typical components of an automated system. A program of instructions is required such as ladder logic programming, allowing the control system to execute the instructions, such as an instruction to increase the temperature when it is too low (Groover, 2008, pp.90-93).

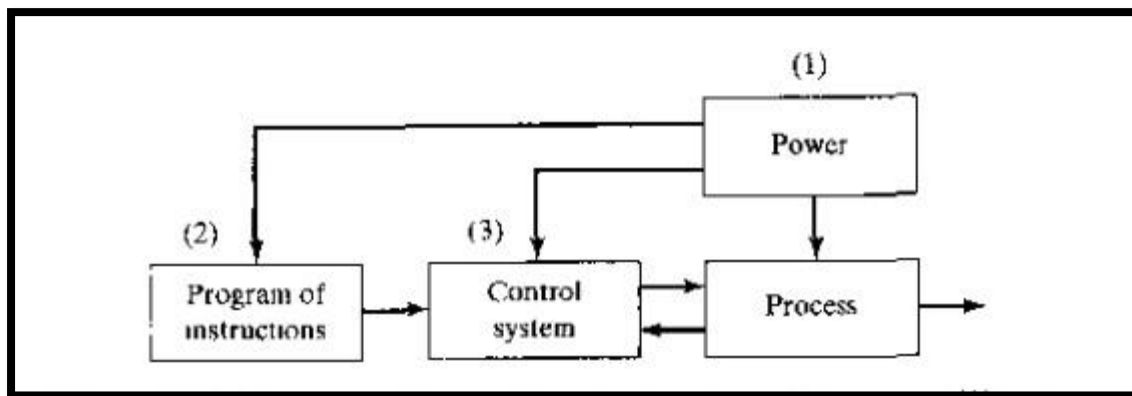


Figure 1 Shows Elements of an Automated System (Groover, 2008, p.88).

In a control system, input parameters (Manipulated Variables) represent the desired output, with an actuator or correction element providing the change onto the process for the desired variable. An open-loop system does not have feedback, whereas a closed-loop has feedback to the input providing accurate adjustments for the output. Figure 2 shows a typical closed-loop process controlling the dryness of clothes.

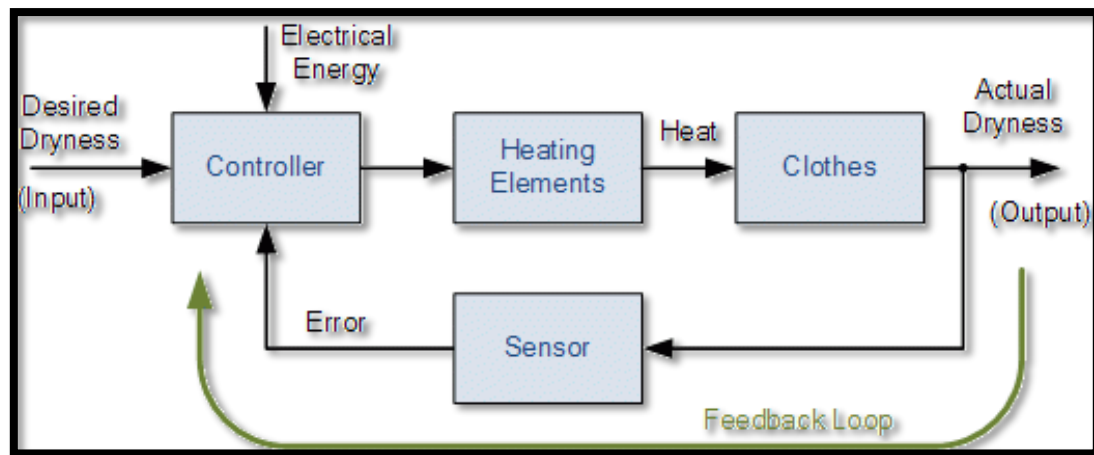


Figure 2 Shows a Closed Loop Clothes Drying Control System (Closed-loop Systems, 2014)

An automated aquarium would require a controller with a Central Processing Unit (CPU) to execute a set of instructions with actuators and correction elements to provide the change in the process, whilst sensors provide manipulated and controlled variable comparison feedback (Tilley, 2017).

Data analysis would increase efficiency, thus, network systems connected to a higher processing unit such as IIoT systems would be required. A hierarchy of this type of system is shown in Figure 3 (Groover, 2008, pp.100-102).

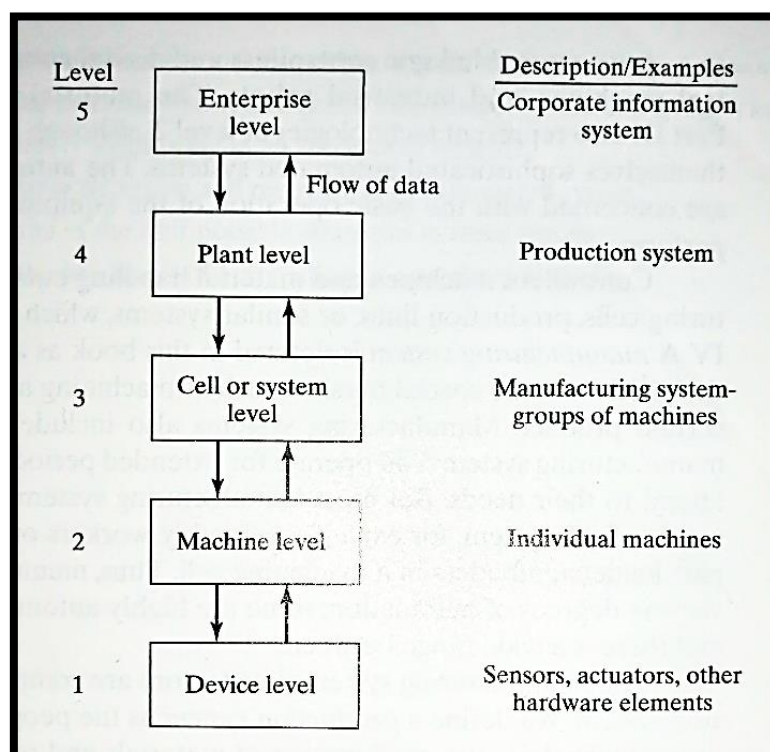


Figure 3 Shows the Five Levels of an Automation Structure (Groover, 2008, p.101)

3.1.1. Controllers

The aquarium will require a controller comparing the parameters from the sensors to the manipulated input, thus, executing the instructions, and controlling the actuators or correction elements.

Continuous controllers have uninterrupted input and outputs with control actions reducing system error. Discrete controllers utilise event or time-based logical order operational sequences (Groover, 2008, pp.108-113).

Proportional Integral Differential (PID) controllers are very accurate and stable continuous controllers utilising control loop feedback. A typical digital temperature PID controller is shown in Figure 4 (Wang, 2020).



Figure 4 Shows a PID Controller (RS Components, 2022)

A PLC is a discrete controller. These are small industrial computers with modular components, consisting of a power supply, processor, inputs, and outputs. They obtain external inputs performing ladder logic sequences, programmed in the processor and thus, alternate the outputs on or off. A simple block diagram can be seen in Figure 5.

They can control entire integrated systems due to the many input and output modules with the processor containing the program of instructions. They can connect to the network through various communication protocols, which can link back to IIoT.

PLCs can have digital (Discrete) or analogue (Continuous) inputs and outputs whereby the inputs read variables like voltage from temperature sensors. Some variables, however, require

signal conditioners before the PLC such as a Wheatstone Bridge converting strain into a linear voltage for the PLC to read (Gonzalez, 2015).

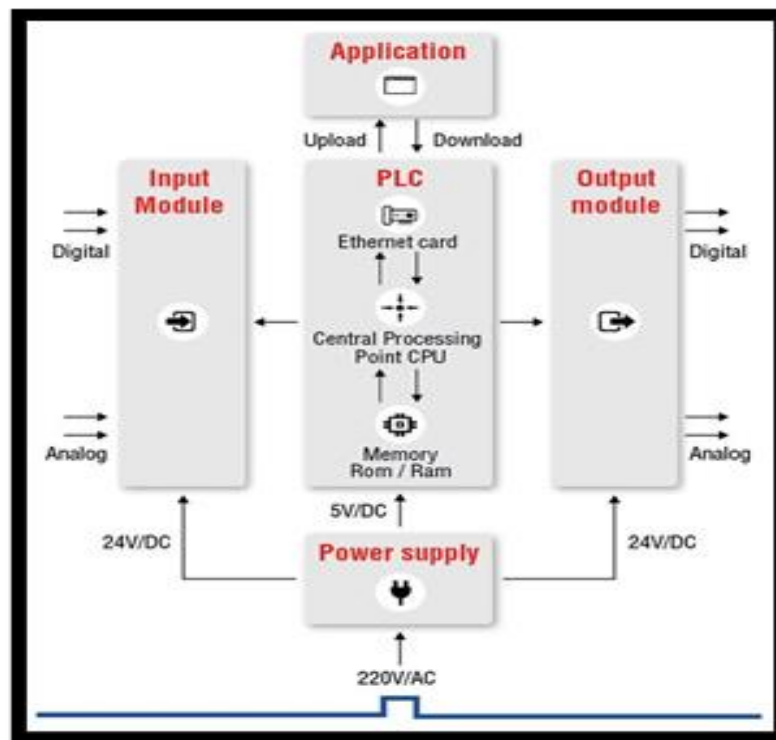


Figure 5 Shows a PLC System (What is the definition of "PLC"?, 2022)

3.1.2. Sensors and Transducers

Sensors would be required for the inputs of the automation machine, which measure surrounding environmental variables and gives a reading in the same signal format. A transducer will be referred to as a sensor in this report for simplicity, however, they measure a physical input and convert it into an electrical output. Examples of physical variables can be seen in Table 2, with Table 3 showing various measurement devices (Groover, 2008, pp.131-134).

The correct sensor must be chosen for its' application such as temperature whereby Thermocouples, Thermistors or Resistance Temperature Detectors (RTD) can be used (Gums,2018).

Sensors must also work within operational ranges of the aquarium requirements and meet CE marking standards. For example, one could not use a temperature sensor with a maximum 10°C range when the water must be 15°C, although these ranges will be dependent on the specific wildlife species. All sensors must also be waterproof to prevent failure which can be achieved

through knowing their Ingress Protection (IP) ratings shown in Figure 6 (Balasubramani, Aakash, Akshay and Bennet, 2020, p.525).

Table 2 Shows Physical Variable Categories (Groover, 2008, p.132)

<i>Stimulus Category</i>	<i>Examples of Physical Variables</i>
Mechanical	Position (displacement, linear and angular), velocity, acceleration, force, torque, pressure, stress, strain, mass, density
Electrical	Voltage, current, charge, resistance, conductivity, capacitance
Thermal	Temperature, heat, heat flow, thermal conductivity, specific heat
Radiation	Type of radiation (e.g., gamma rays, X-rays, visible light), intensity, wavelength
Magnetic	Magnetic field, flux, conductivity, permeability
Chemical	Component identities, concentration, pH levels, presence of toxic ingredients, pollutants

Table 3 Shows Common Measuring Devices within Automation (Groover, 2008, p.134)

<i>Measuring Device</i>	<i>Description</i>
Proximity switch	Binary noncontact sensor is triggered when nearby object induces changes in electromagnetic field. Can be based on any of several physical principles, including inductance, capacitance, ultrasonics, and optics.
Radiation pyrometer	Analog temperature-measuring device that senses electromagnetic radiation in the visible and infrared range of spectrum.
Resistance-temperature detector	Analog temperature-measuring device based on increase in electrical resistance of a metallic material as temperature is increased.
Strain gage	Widely used analog sensor to measure force, torque, or pressure. Based on change in electrical resistance resulting from strain of a conducting material.
Tachometer	Analog device consisting of DC generator that produces an electrical voltage proportional to rotational speed.
Tactile sensor	Measuring device that indicates physical contact between two objects. Can be based on any of several physical devices such as electrical contact (for conducting materials) and piezoelectric effect.
Thermistor	Contraction of <i>thermal</i> and <i>resistor</i> . Analog temperature-measuring device based on change in electrical resistance of a semiconductor material as temperature is increased.
Thermocouple	Analog temperature-measuring device based on thermoelectric effect, in which the junction of two dissimilar metal wires emits a small voltage that is a function of the temperature of the junction. Common standard thermocouples include: chromel-alumel, iron-constantan, and chromel-constantan.
Ultrasonic range sensor	Time lapse between emission and reflection (from object) of high-frequency sound pulses is measured. Can be used to measure distance or simply to indicate presence of object.

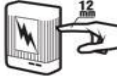
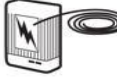
IP (Ingress Protection) Ratings Guide	
SOLIDS	WATER
1  Protected against a solid object greater than 50 mm such as a hand.	1  Protected against vertically falling drops of water. Limited ingress permitted.
2  Protected against a solid object greater than 12.5 mm such as a finger.	2  Protected against vertically falling drops of water with enclosure tilted up to 15 degrees from the vertical. Limited ingress permitted.
3  Protected against a solid object greater than 2.5 mm such as a screwdriver.	3  Protected against sprays of water up to 60 degrees from the vertical. Limited ingress permitted for three minutes.
4  Protected against a solid object greater than 1 mm such as a wire.	4  Protected against water splashed from all directions. Limited ingress permitted.
5  Dust Protected. Limited ingress of dust permitted. Will not interfere with operation of the equipment. Two to eight hours.	5  Protected against jets of water. Limited ingress permitted.
6  Dust tight. No ingress of dust. Two to eight hours.	6  Water from heavy seas or water projected in powerful jets shall not enter the enclosure in harmful quantities.
Rating Example: IP65 INGRESS PROTECTION	
	7  Protection against the effects of immersion in water between 15 cm and 1 m for 30 minutes.
	8  Protection against the effects of immersion in water under pressure for long periods.

Figure 6 Shows an IP Rating Guide (Bohn, 2013)

3.1.3. Signal Conditioners

Environmental sensors produce an analogue signal, thus, must be converted into digital values for the processor which can be done in various ways, with a simple process is shown in Figure 7 (Groover, 2008, p.144).

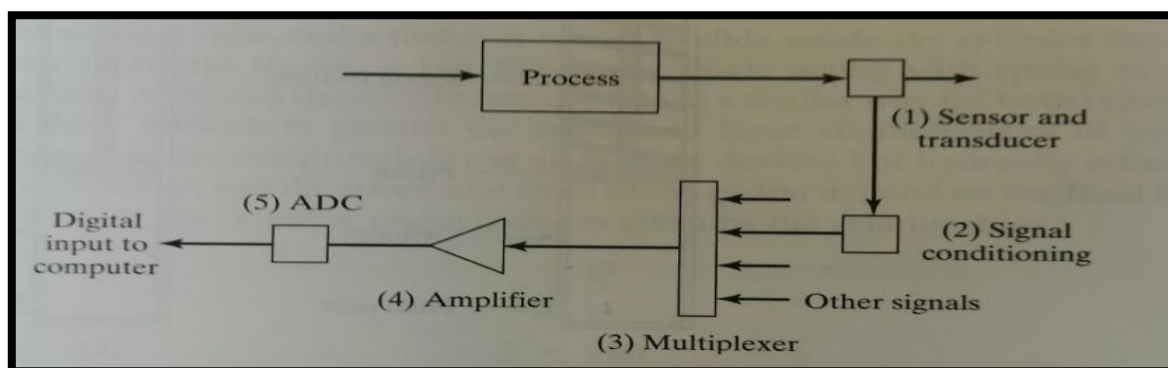


Figure 7 Shows Analog-to-Digital Conversion Steps (Groover, 2018, p.144)

Various devices can condition signals for the use of control. For example, a Wheatstone Bridge shown in Figure 8, measures small changes in electrical resistance for physical quantities like temperature, pressure, and strain (Teja, 2021).

Some devices not only amplify and convert physical quantities into electrical, but they can further condition them into the correct communication protocols like Ethernet IP. For example, Figure 9 shows a Load Cell Amplifier that converts mechanical strain into force or a mass value for a processor to obtain through Ethernet IP.

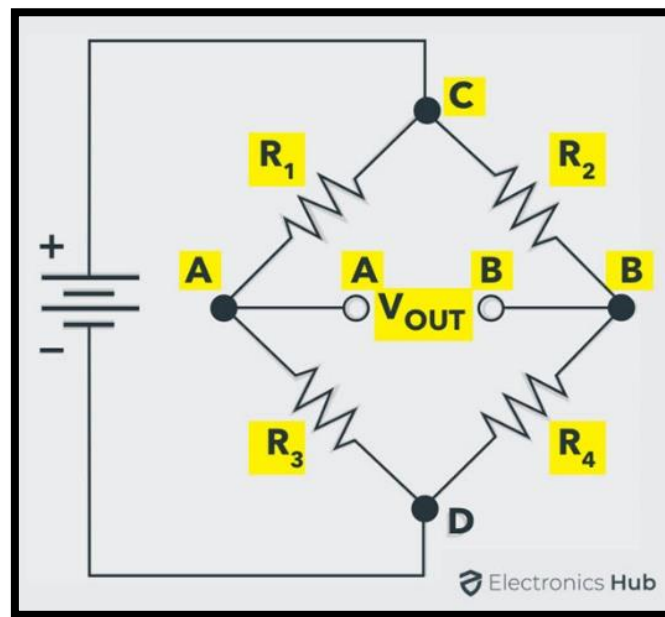


Figure 8 Shows a Wheatstone Bridge Circuit (Teja, 2021)



Figure 9 Shows a Load Cell Amplifier (Target 260S, 2022)

Professionals were emailed for research purposes as shown in Appendix One. It was found that PLCs can have analogue input cards which convert sensor outputs directly for the PLC to recognise as Figure 10 shows.

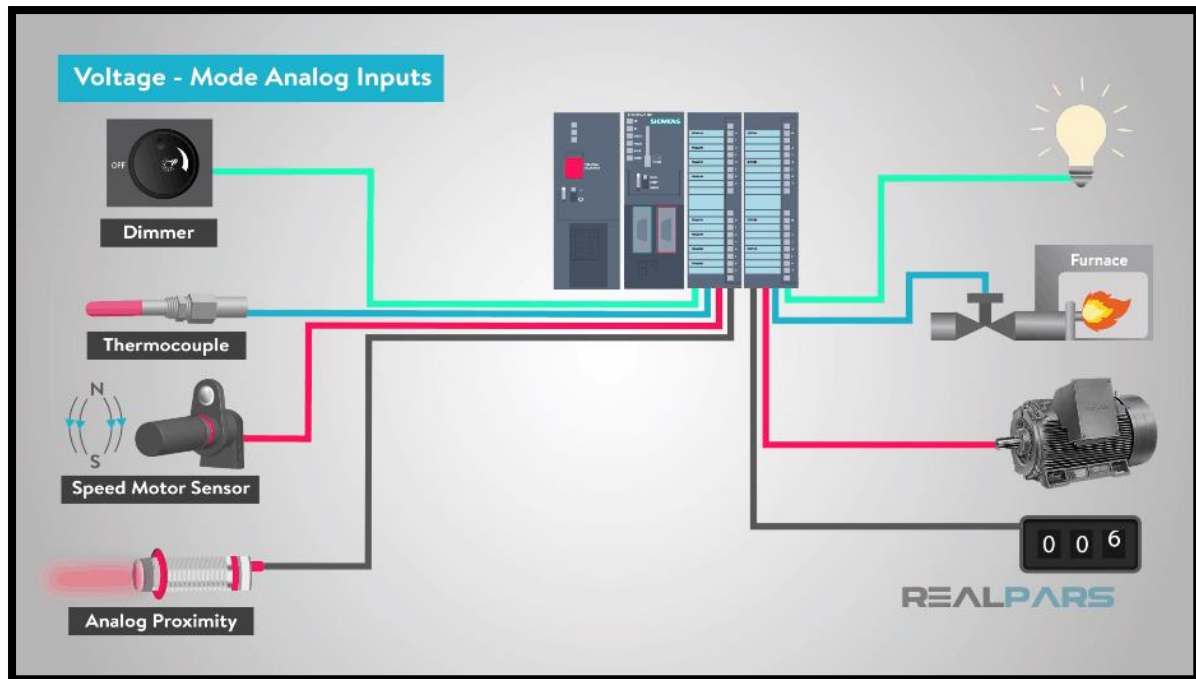


Figure 10 Shows a Typical PLC Control System (PLC Analog Inputs and Signals, 2022)

3.1.4. Actuators and Control Valves

Actuators/Correction Elements receive controller signals, making process changes. If fluid systems are used, control valves are utilised to direct and regulate fluid within the system.

Pneumatics utilise compressed air, whereby the control valve has a mechanical input or an electrical input from a controller to direct the airflow to one side of a piston thus moving it and therefore, airflow is then vented to the atmosphere as shown in Figures 11 and 12.

Hydraulics can transmit higher forces as they utilise incompressible fluid in a closed system. They utilise similar control valves to direct the fluid, but the fluid is directed back to a reservoir as Figure 13 shows.

Control valves come in many configurations such as spring return or double-acting. Double-acting for example can direct fluid to alternate sides to move the piston or both sides to lock the piston. Spring return for another example can only direct air to one side but returns to the origin when the signal is removed as shown in Figure 14 (Woodford, 2021).

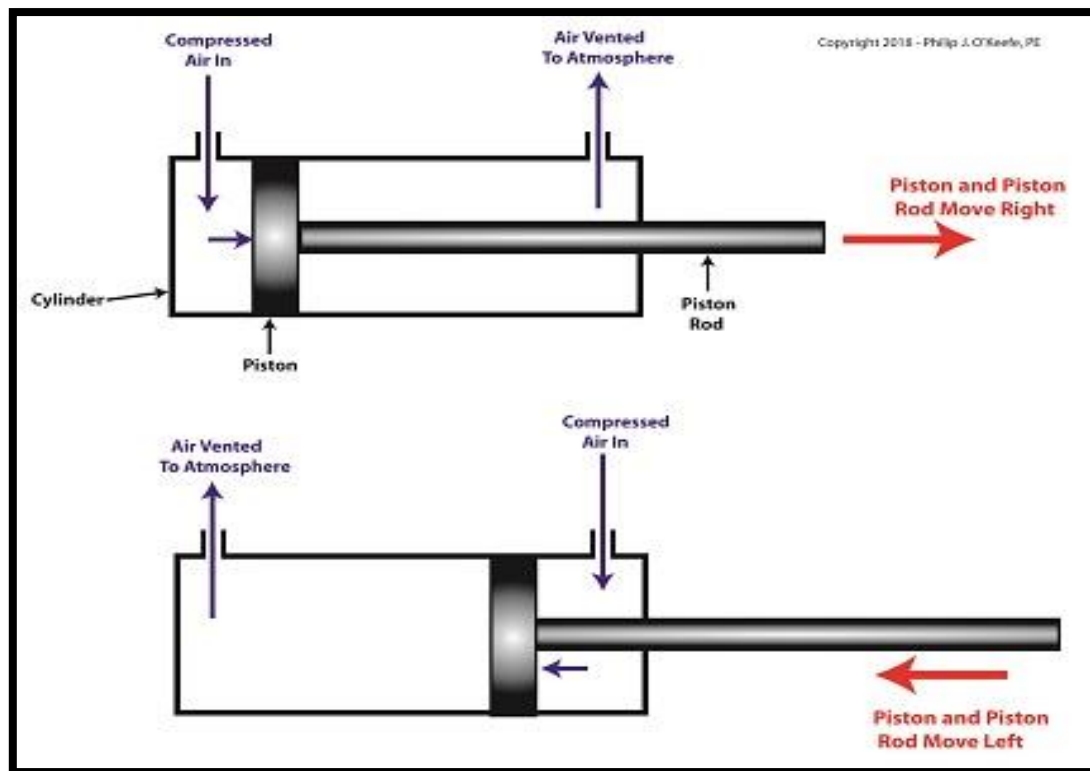


Figure 11 Shows a Pneumatic Piston (O'Keefe, 2018)

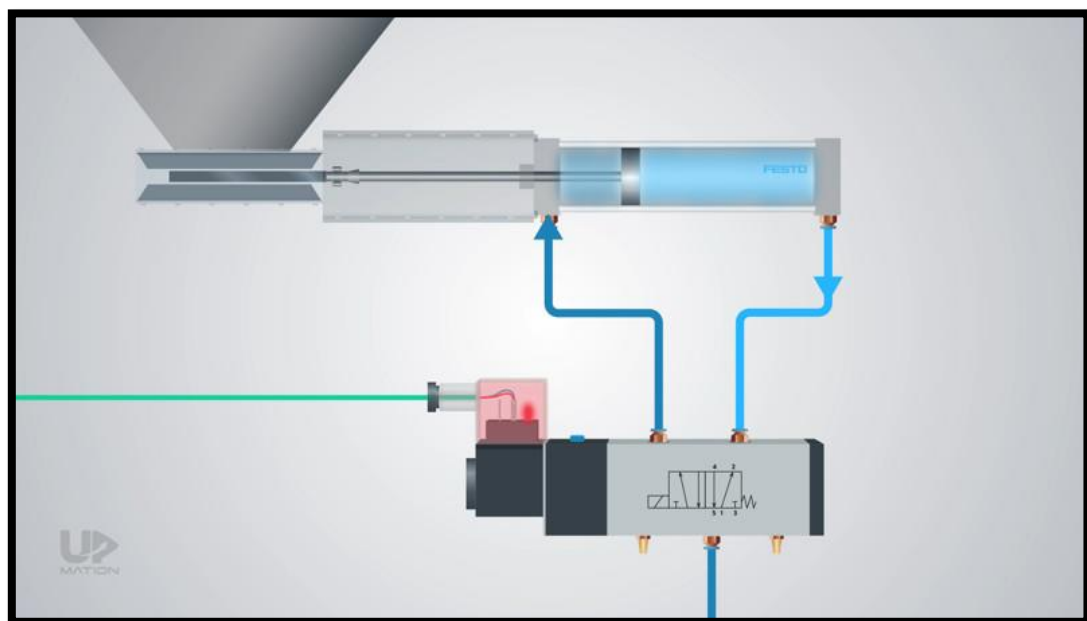


Figure 12 Shows a Solenoid Control Valve (What is a Directional Control Valve?, 2021)

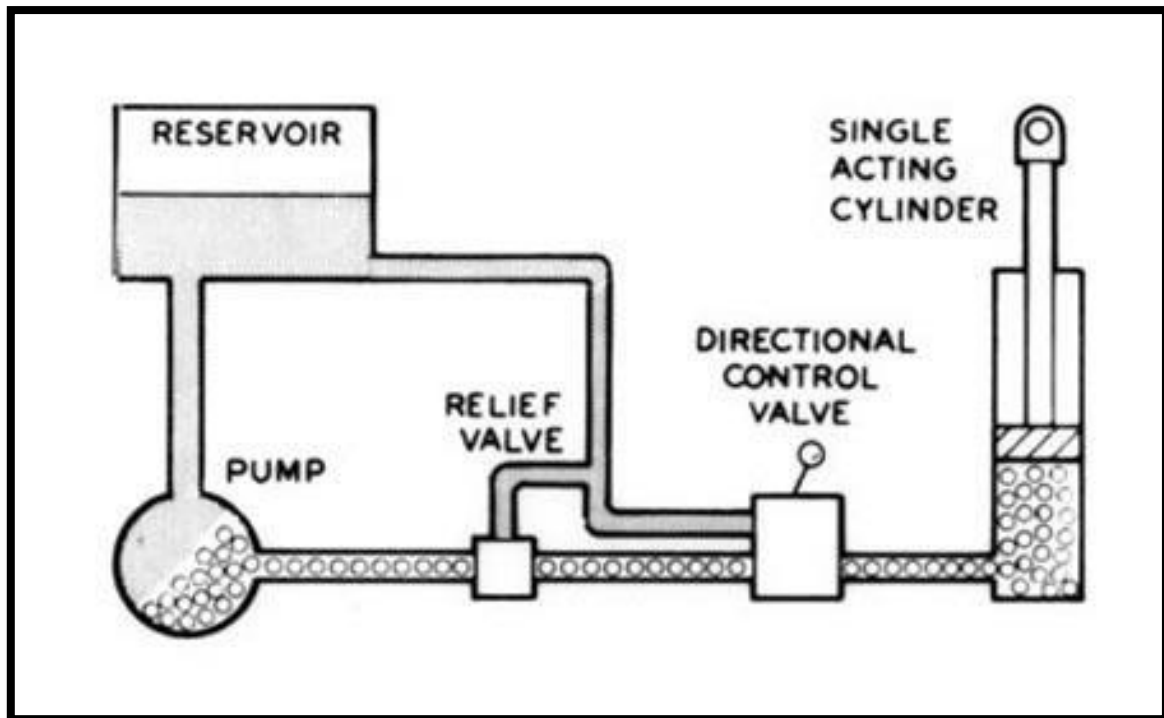


Figure 13 Shows Basic Hydraulic Control (Basic Hydraulic Theory, 2022)

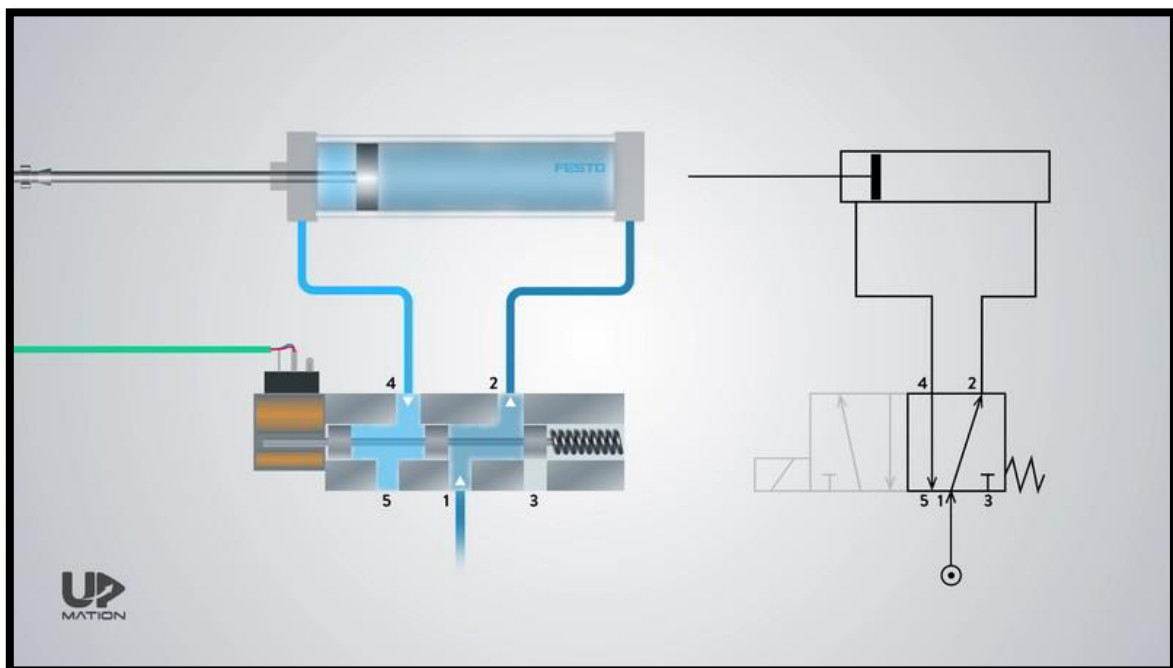


Figure 14 Shows the Airflow through a Control Valve (What is a Directional Control Valve?, 2021)

3.1.5. Power Supply

For Machine Directive conformity, the system will require 230VAC for larger external devices but for automation, a 230VAC to 24VDC switch should be used, as PLCs and instruments are capable of running with only 5VDC input.

For pneumatic power, compressors can be utilised, however, one must ensure measures are made to prevent water ingress into the system, such as non-return valves and filters. One must also ensure regulators are in place to conform to safety regulations as Figure 15 shows. Hydraulics may be utilised and can be in the configuration shown in Figure 16 (Sabhadiya, 2022).

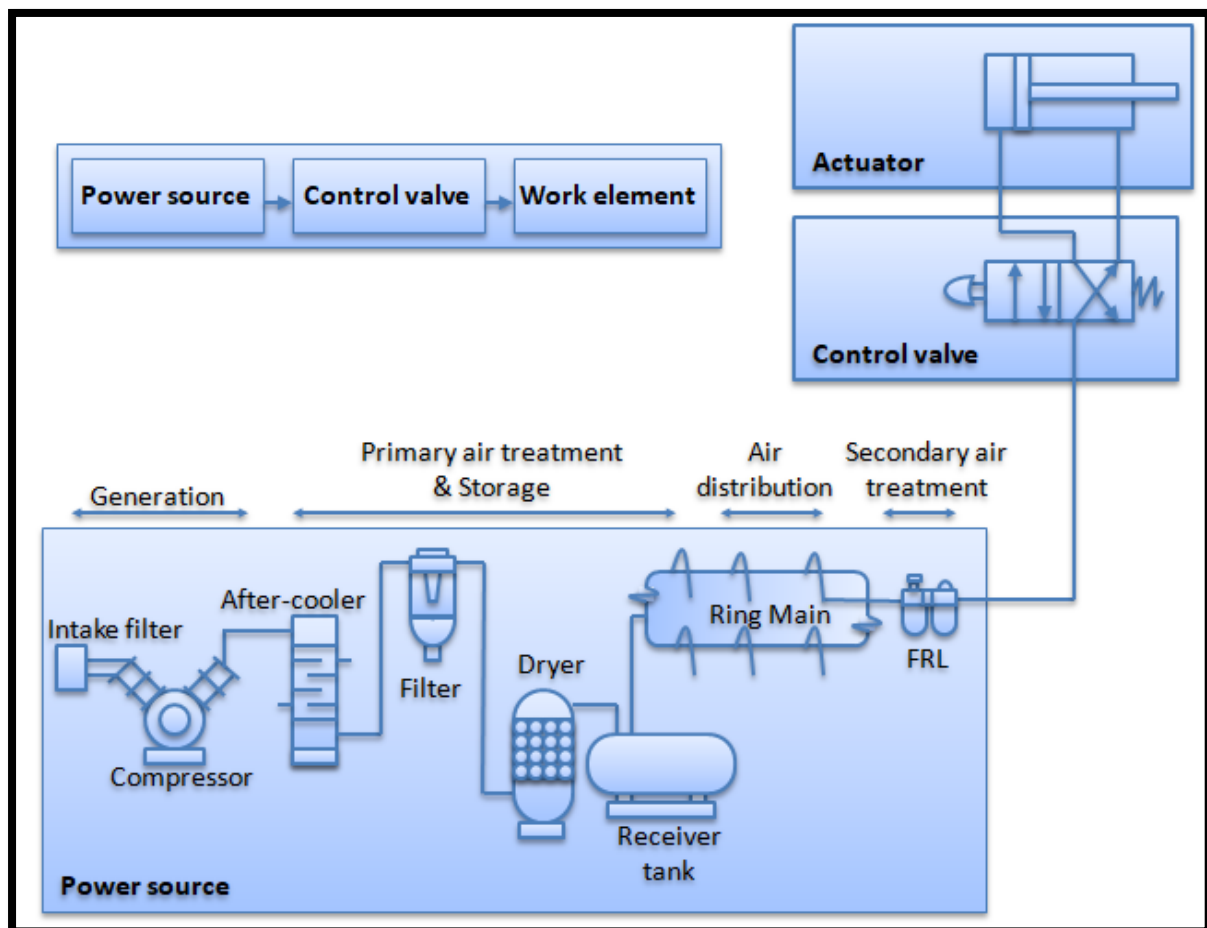


Figure 15 Shows a Pneumatic Power System (Configuring a Typical Pneumatic System, 2022)

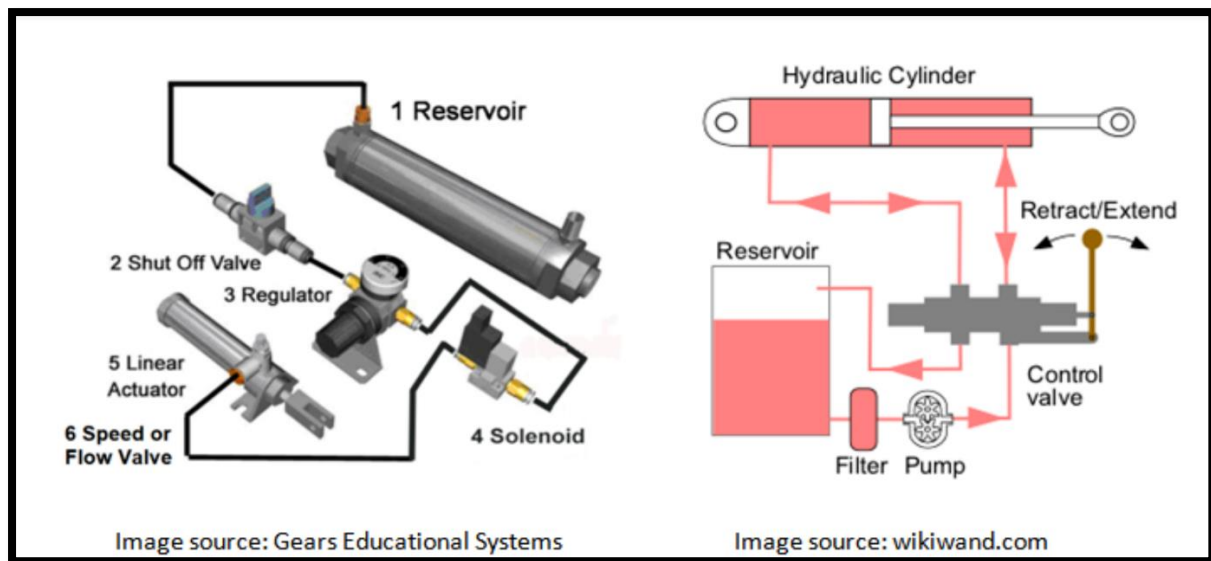


Figure 16 Shows a Hydraulic Power System (Duran-Lamanilao, 2021)

3.1.6. Network

One must ensure the system is connected to a network and that compatibility is achieved, such as device communication protocols are compatible with switches and able to communicate with servers and other IIoT devices, through communication protocols like Ethernet IP. This would allow for, monitoring, process improvements and redundancy control (Immerman, 2017).

4.0. Control Method Design

This section of the report will outline the proposed automation system design, showing the hierarchical structure design, then breaking down each subsystem design, explaining how each subsystem works, thus, enabling one to explain how it all intertwines into a fully working control system. Table 4 states an important design note.

Table 4 Shows a Note to Meet a General-Purpose Design Specification

Important Note:
To meet the design problem for a general-purpose freshwater aquarium
Aquarium parameters such as pH levels, water temperatures and so on, vary depending on the wildlife. Therefore, the suggested equipment will be for a general-purpose freshwater aquarium, and thus, specific equipment ranges can be chosen based on wildlife requirements.

4.1. Control System Design

The control system design will utilise a hierarchical block structure shown in Figure 17. A typical system can be seen in Appendix Two. The system will have a 230VAC to 24VDC power switch supply for the HMI and PLC, which has a 5VDC common. A pneumatic power system will be utilised shown in Figure 18 with a 230VAC power supply.

Each subsystem for the entire system will be described individually with its' own diagram. It can be noted that the block diagrams are for illustrative purposes and the actual system may be assembled differently. For example, some inputs and outputs are shown connected to the PLC on the same line, however, this would not be the case in real system assembly.

It can be further noted that the PLC can be programmed offline utilising a universal serial bus connection from a PC, thus, desired variable values would be programmed at this stage. Therefore, post variable value change will be described in each subsystem explanation.

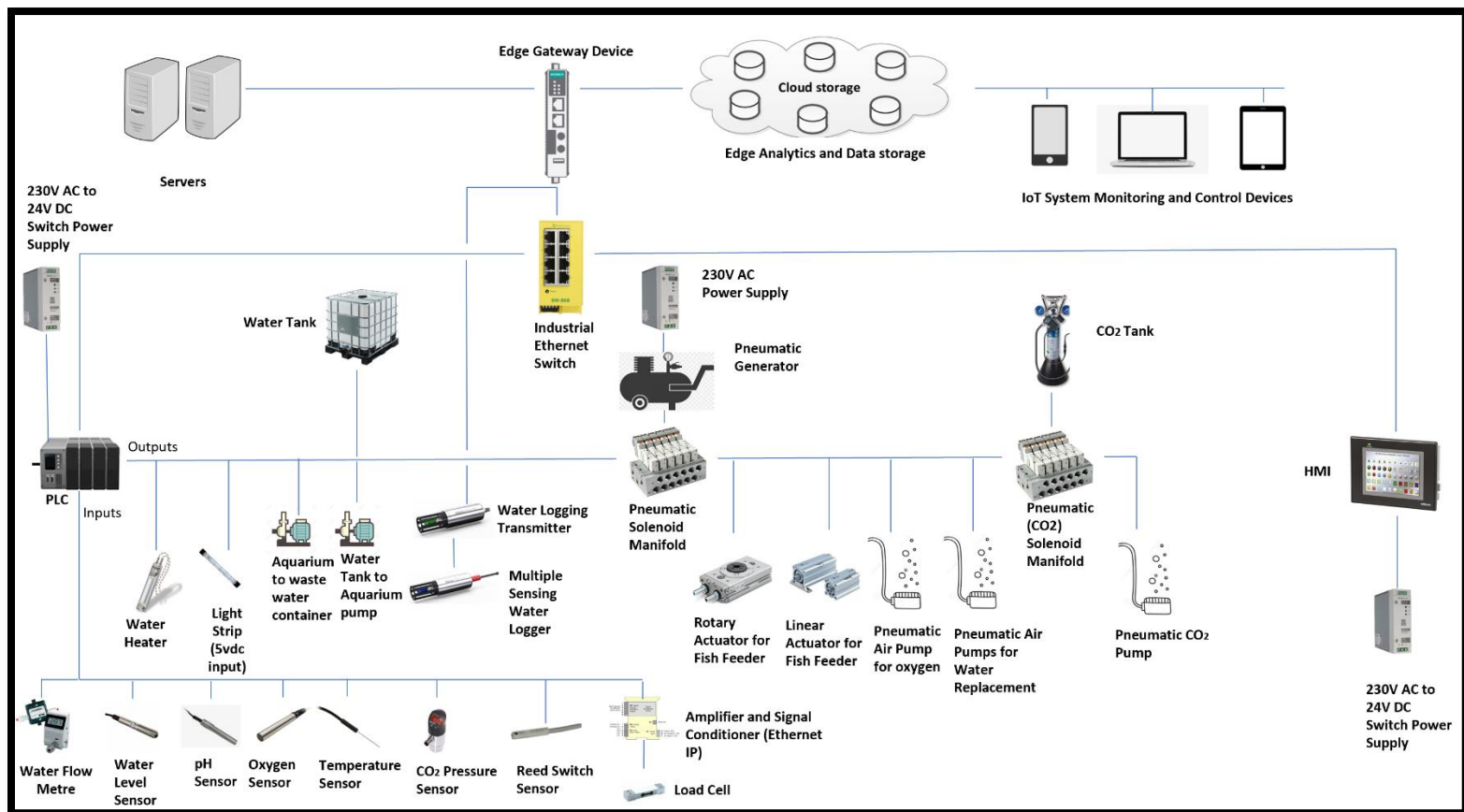


Figure 17 Shows the Entire Control System in Block Diagram Form

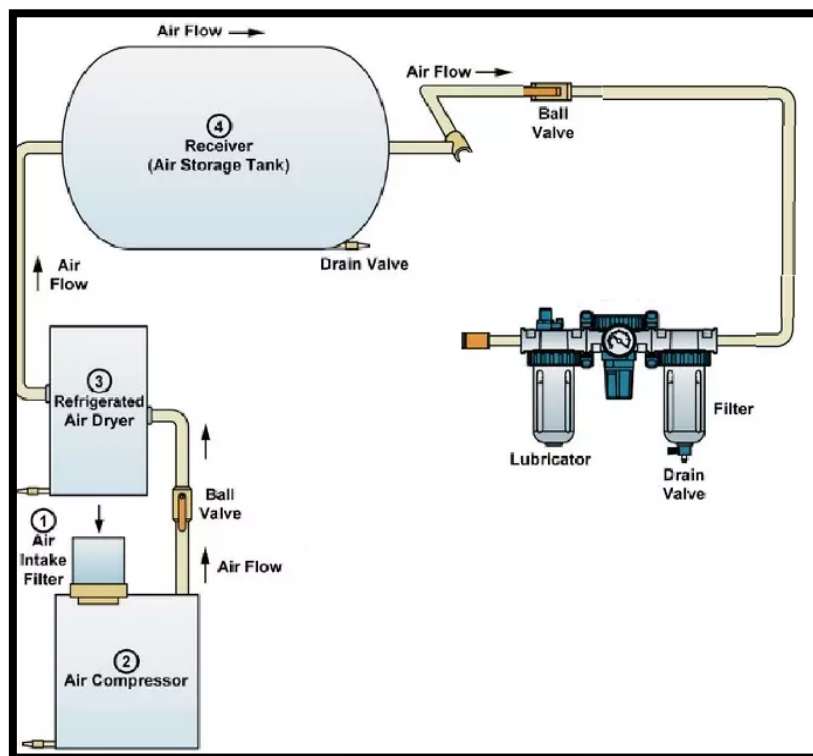


Figure 18 Shows a Pneumatic System (Compressed Air System Components And Network For Using Air Tools, 2022)

4.1.1. Temperature Control

Figure 19 shows the subsystem design for temperature control with Table 5 explaining the operation.

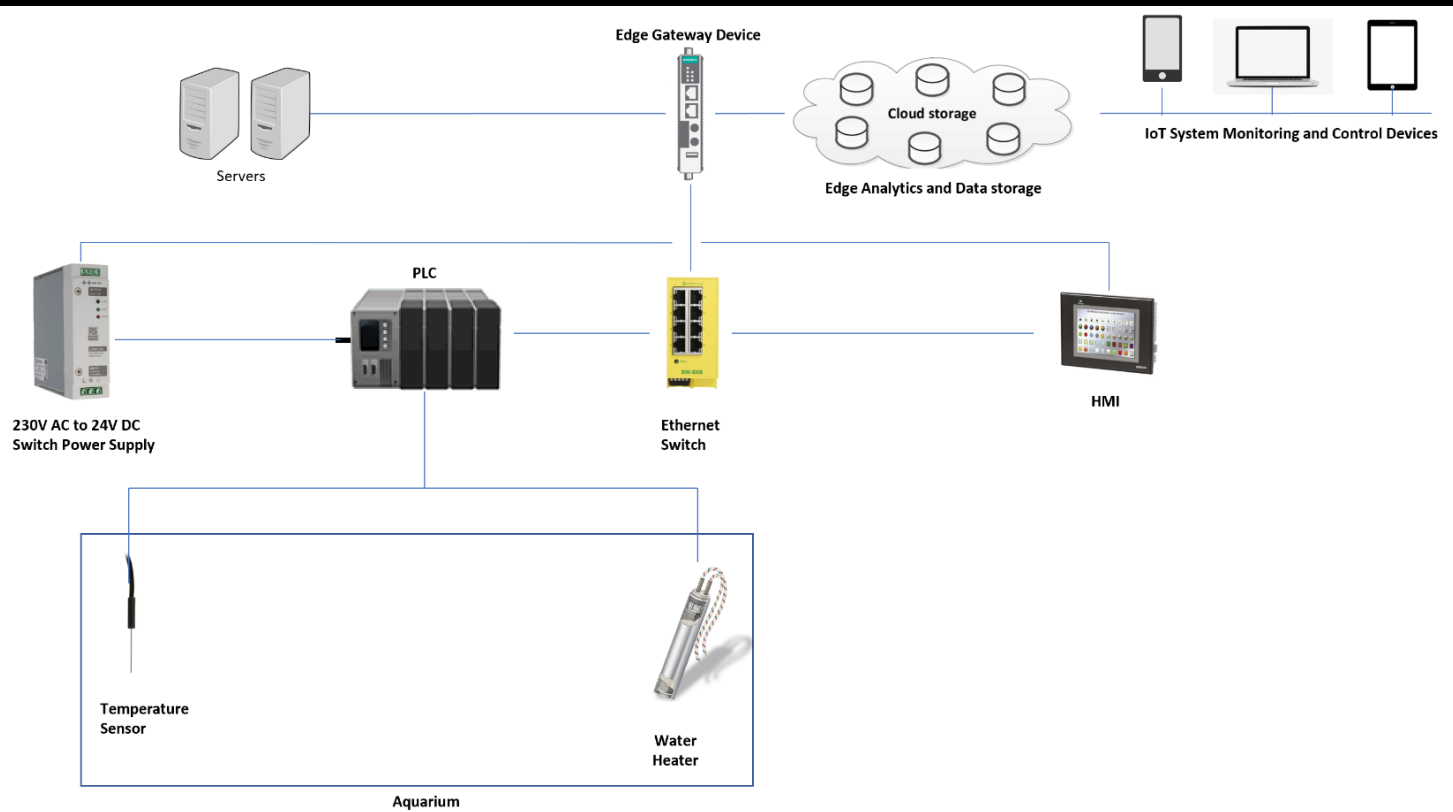


Figure 19 Shows a Temperature Control System

Table 5 Shows the Temperature Control Method

Sensor Input	Controller	Output	Monitoring and Process Alarms
A Water-Proof Temperature Sensor that meets CE marking and IP rating is required for the sensing of water temperature. (Sensor temperature range specification must be chosen based on the water temperature requirements). The sensor must have a continuous analogue output.	A PLC Unit is required which utilises analogue input cards for linear voltage to temperature value conversion. A PID function within the controller will perform pulsing on-off signals for temperature control (Provides temperature output within a set tolerance). For more accurate temperature control, an analogue output card can be utilised, providing a set temperature. Values can be set through the HMI screen with an Ethernet IP connection to the PLC. IIoT systems can control the input and override HMI control through the Edge Gateway to Ethernet IP and then to the PLC.	The water heater receives PID function commands from the PLC, which will remain on until the temperature is within a set tolerance, and then a pulsing signal will occur to maintain the temperature within the desired temperature range. If an analogue output is utilised, the heating element must be compatible with analogue responses and a continuous output from the PLC is executed within a set temperature range.	Inputs and outputs are fed back to the HMI screen and IIoT system through Ethernet IP and Edge Gateway communication protocols. Full monitoring and process alarms are achieved through the system. Smart temperature adjustments can be made through the IIoT system for process improvements.

4.1.2. Oxygen Level Control

Figure 20 shows the control of oxygen subsystem design with Table 6 explaining the operation.

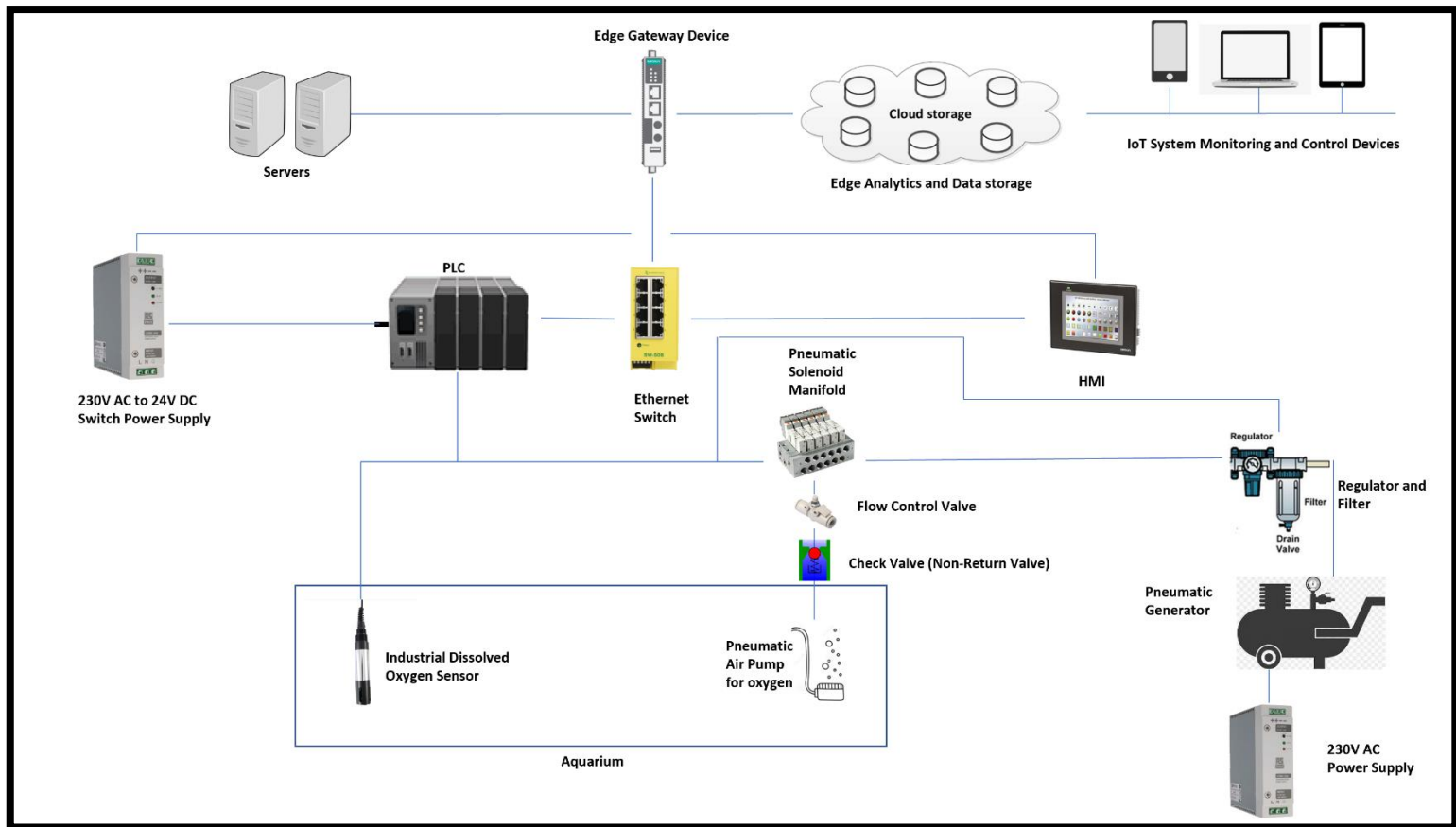


Figure 20 Shows an Oxygen Control System

Table 6 Shows the Oxygen Control Method

Sensor Input	Controller	Output	Monitoring and Process Alarms
A Water-Proof Oxygen Sensor that meets CE Marking and IP rating is required for the reading of oxygen levels within the water. The sensor utilises reference air against dissolved oxygen and outputs a resistance voltage.	A PLC Unit is required which utilises analogue input cards for linear voltage to oxygen value conversion. The PLC uses ladder logic to activate the solenoid valve when the oxygen levels are lower than the manipulated variable input. Output signals are sent from the PLC to the solenoid valve, changing the direction of airflow, and providing airflow through the pump until the output variable matches the desired input variable. Desired oxygen values can be set on the HMI screen and programmed into the PLC through Ethernet IP. IIoT systems can control the input and override HMI control through the Edge Gateway to Ethernet IP and then to the PLC.	To increase oxygen in water such as that in this aquarium, agitation of the water surface is required, thus, providing oxygen into the water (Dissolved Oxygen, 2013). A solenoid control valve receives a signal from the PLC, changing the direction of airflow of the pneumatics. Airflow is forced through a tube and through a Check Valve which prevents water back into the pneumatic system. Air is then excreted through the orifice device in the tank, which in turn provides oxygen into the water whilst increasing oxygen through agitation.	Inputs and outputs are fed back to the HMI screen and IIoT system through Ethernet IP and Edge Gateway communication protocols. Full monitoring and process alarms are achieved through the system. When oxygen remains low for too long, alarms are sent through to monitoring systems to alert that there may be a system error.

4.1.3. pH Level Control

pH levels can have serious negative effects on aquatic life if not monitored and controlled.

Figure 21 shows the pH control subsystem design with Table 7 explaining the operation.

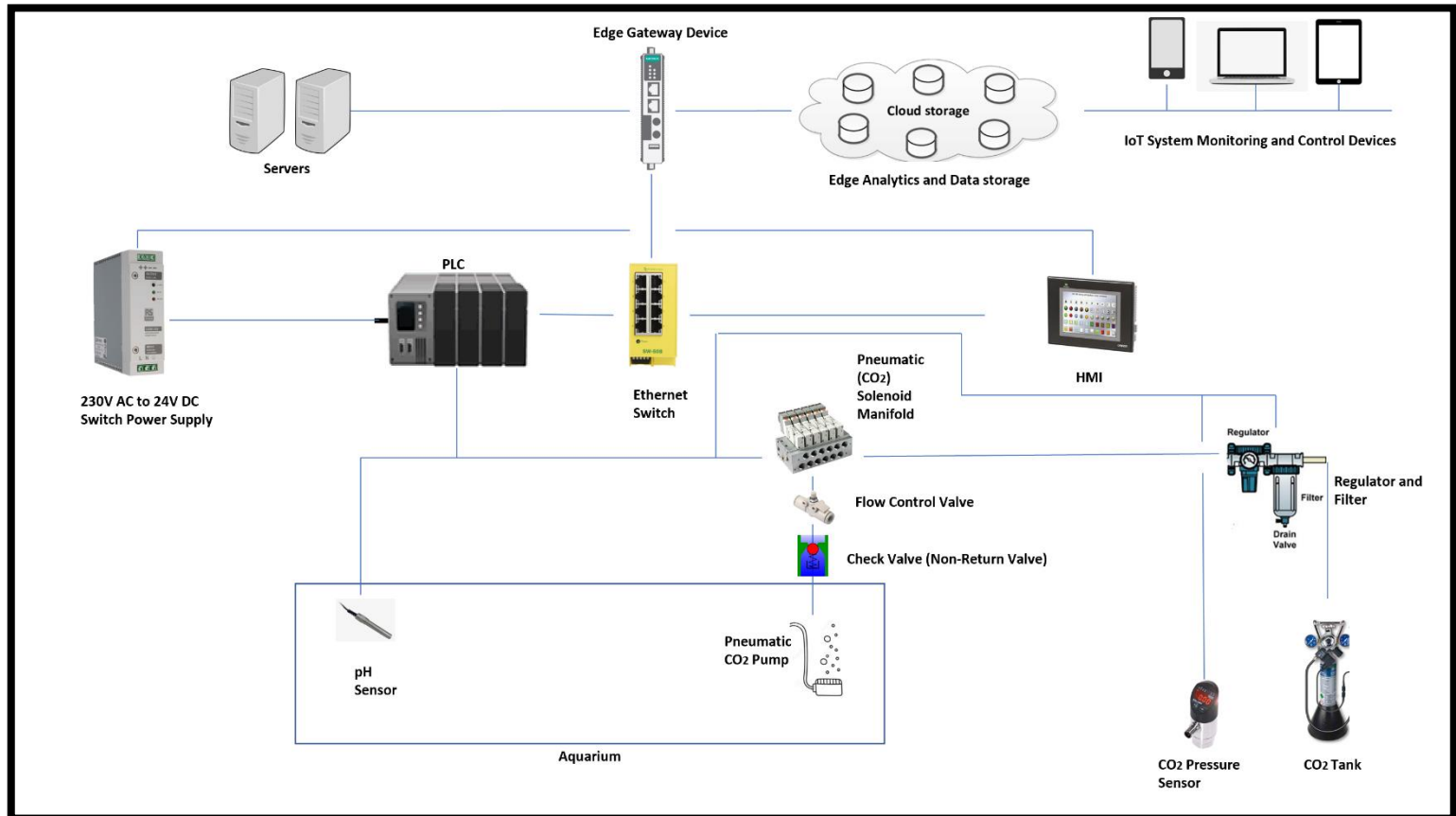


Figure 21 Shows a pH Control System

Table 7 Shows the pH Control Method

Sensor Input	Controller	Output	Monitoring and Process Alarms
A Water-Proof pH Sensor that meets CE Marking and IP rating is required for the reading of pH levels within the water. The sensor detects hydrogen atoms present in the water and directs a voltage to the PLC.	PLC Unit uses an analogue input to detect a voltage from the sensor which is converted to a pH value. The PLC utilises ladder logic to read the input value set in the program for the pH level requirement. If this level is too high, the PLC will turn on the output to control the solenoid valve until the value coming back from the sensor matches the desired input. Desired pH values can be set on the HMI screen and programmed into the PLC through Ethernet IP. IIoT systems can control the input and override HMI control through the Edge Gateway to Ethernet IP and then to the PLC.	pH levels can be controlled by the release of CO₂. If the pH levels in the tank are getting too high, an increase in CO₂ in the aquarium will dissolve and cause pH levels to drop. The solenoid control valve receives a signal from PLC, changing the direction of CO₂ of the pneumatics. CO₂ is forced through a tube and through a Check valve which prevents water back into the pneumatic system. CO₂ is then excreted through the orifice device in the tank. If pH is too low, water changes are required (Explained later on).	Inputs and outputs are fed back to the HMI screen and IIoT system through Ethernet IP and Edge Gateway communication protocols. Full monitoring and process alarms are achieved through the system. When pH remains high for too long, alarms are sent through to monitoring systems to alert that there may be a system error.

4.1.4. Lighting Control

The lighting control subsystem design can be seen in Figure 22 with an operational explanation in Table 8.

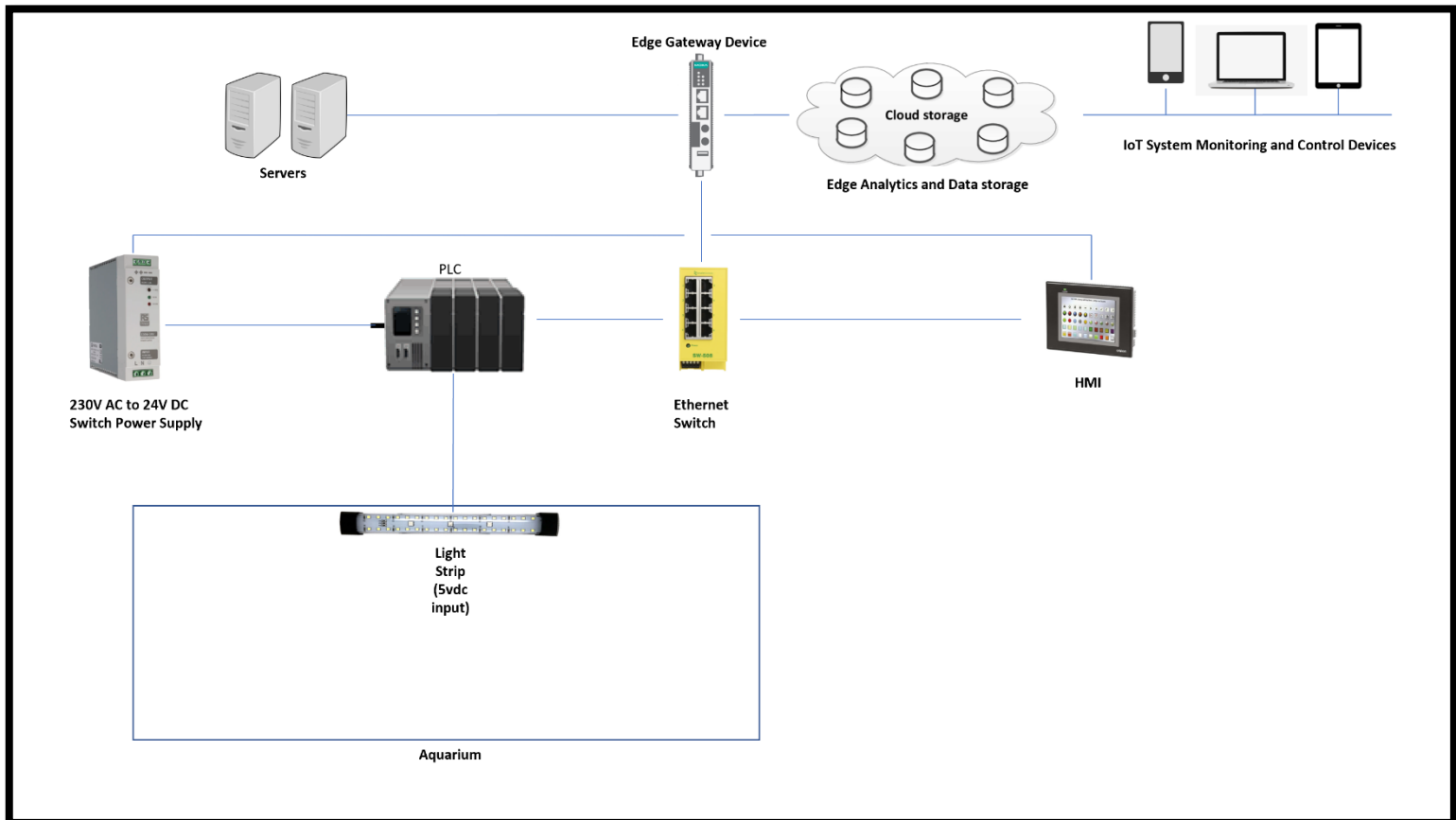


Figure 22 Shows Lighting Control

Table 8 Shows the Lighting Control Method

Sensor Input	Controller	Output	Monitoring and Process Alarms
Lighting systems do not require a lighting sensor and feedback can be achieved through electrical continuity.	The PLC unit has functions within the program that can be set on a timing system. The timing values representing time, are achieved through functions or counters within the PLC program. The program will then send an output signal when the time value is achieved at set points. Time values are programmed into the PLC and can be set and shown on the HMI screen through the Ethernet IP or set from IIoT devices through the Edge Gateway.	The output signal from the PLC will send a 5VDC signal to the LED lighting strip which will be enough to turn on the strip until the signal is turned off by the PLC again.	Inputs and outputs are fed back to the HMI screen and IIoT system through Ethernet IP and Edge Gateway communication protocols. Full monitoring and process alarms are achieved through the system. When no signal is sent back to the PLC alarms are sent through to monitoring systems to alert there may be a system error. Smart lighting can be achieved by the IIoT system, changing the timings automatically based on the time of year.

4.1.5. Tank Cleanliness Control

To ensure tank cleanliness, thus, complying with regulations, a water change system has been designed as shown in Figure 23 with Table 9 explaining its' operation.

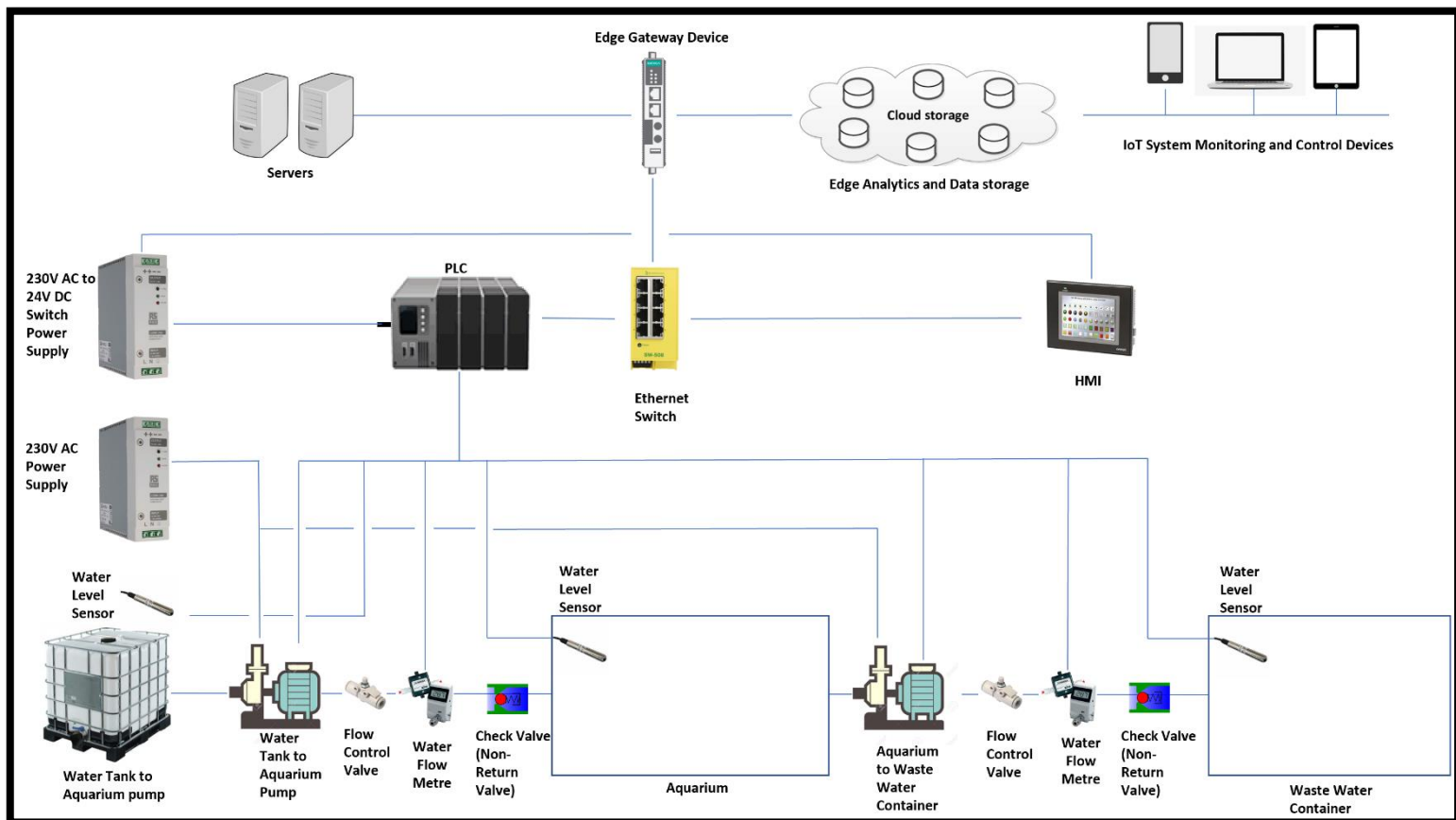


Figure 23 Shows a Water Change Control System

Table 9 Shows the Water Cleaning Method

Sensor Input	Controller	Output	Monitoring and Process Alarms
A water change will affect the pH, oxygen, and temperature variables; therefore, these sensors are already implemented.	The PLC unit has functions within the program that can be set on a timing system. The timing values representing time, are achieved through functions or counters within the PLC program.	The output from the PLC will send a signal to turn on a pump which will extract water from the aquarium at a set flow rate into a waste tank.	Inputs and outputs are fed back to the HMI screen and IIoT system through Ethernet IP and Edge Gateway communication protocols.
A water flow sensor would be required to control the water flow rate in and out of the aquarium, preventing sudden changes in the critical variables which may cause the wildlife stress due to the time it takes the other systems to respond.	The program will then send an output signal when the time value is achieved at set points. Time values are programmed into the PLC and can be set and shown on the HMI screen through the Ethernet IP or set from IIoT devices through the Edge Gateway.	In doing so, it will trigger another output within the PLC program to activate the pump that controls water from a water tank into the aquarium. After a set time based on the flow rate through the flow sensors, the waste pump will stop, and a water level sensor will ensure the water is at the correct level. Once achieved, the water tank pump will stop.	Full monitoring and process alarms are achieved through the system. When the mass flow rate is sent to the PLC, if it is too high, the output will turn off to the allow aquarium to settle and oxygen, pH, and temperature to adjust. Water level sensors can also be placed in the water tank and waste tank to alert the HMI through Ethernet IP and IIoT devices through the Edge Gateway when the water tank needs replacing, and the waste tank needs emptying.
Water level sensors will determine if the water is at the correct level.			

4.1.6. Water Level Control

Water levels are achieved from the water changing process, however, for built-in redundancy, this mechanical mechanism shown in Figure 24 provides automatic overflow in case of sensor failure.

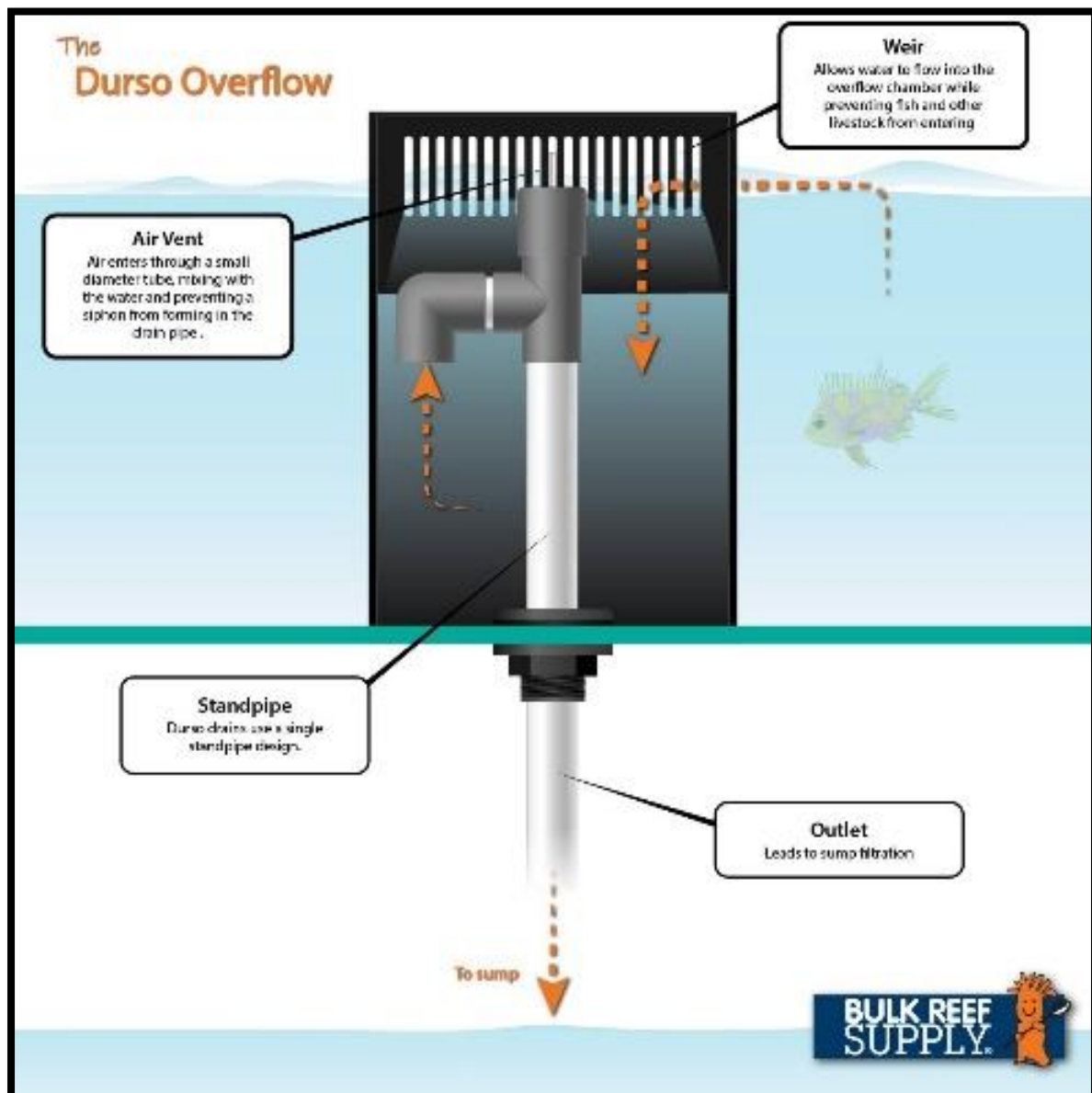


Figure 24 Shows a Mechanical Water Overflow System (Farnsworth, 2022)

4.1.7. Feeding Control System

Figure 25 shows the feeding control system design with Table 10 explaining the operation. Appendix Three shows and explains the feeding mechanism design.

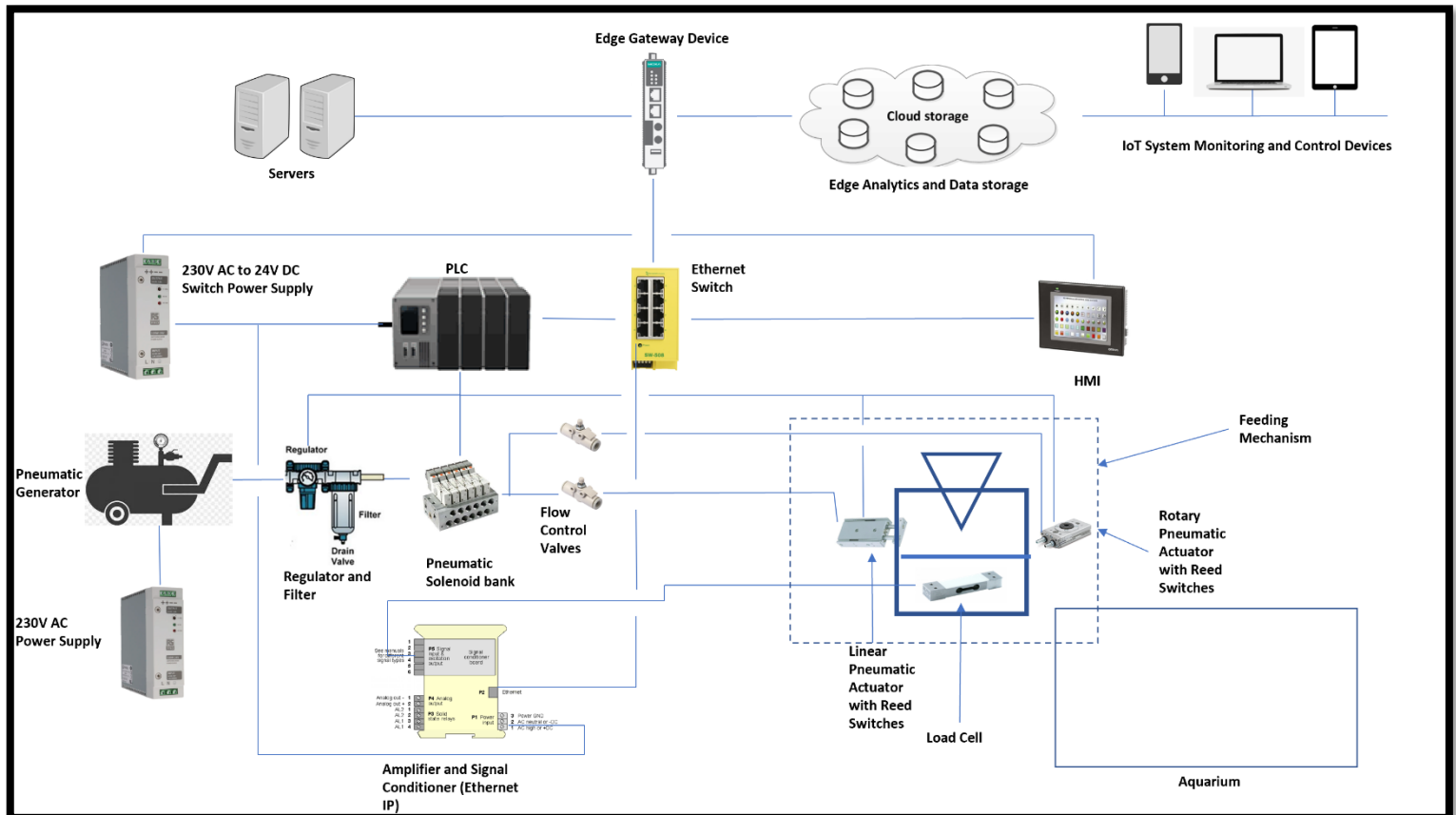


Figure 25 Shows an Automated Feeding System

Table 10 Shows the Feeding System Control Method

Sensor Input	Controller	Output	Monitoring and Process Alarms
A load cell strain gauge connected to a signal conditioner and amplifier (Wheatstone Bridge) will convert strain into an electrical voltage and send a converted signal through Ethernet IP to the PLC. Reed switches on the actuators will activate when a magnet inside the actuator comes into proximity from rotation or extension.	A PLC will be utilised, retrieving a value from the loadcell, thus, determining the weight of the food within the feeding system. The PLC unit has functions within the program that can be set on a timing system. The timing values representing time, are achieved through functions or counters within the PLC program. These timers will send an output signal to control valve solenoids during a time of day when feeding is required. Time values are programmed into the PLC and can be set and shown on the HMI screen through the Ethernet IP or set from IIoT devices through the Edge Gateway.	When the time value is achieved within the PLC an output signal is sent to the control valves, changing the direction of airflow to one side of the linear piston, extending the piston. A reed switch sensor will indicate when the actuator is extended, thus, sending another output from the PLC to rotate the rotary actuator, thus, providing a set food amount for the wildlife. This will also have a reed switch to ensure food has been dispensed.	Inputs and outputs are fed back to the HMI screen and IIoT system through Ethernet IP and Edge Gateway communication protocols. Full monitoring and process alarms are achieved through the system. The food will be stored in a large funnel directed onto a plate, thus, when the plate is full will hold up the food. This weight will be felt by the load cell and the strain will be converted into a voltage through the amplifier which will send a signal through Ethernet IP to the PLC. When the value gets too low, the PLC will send a signal through Ethernet IP to a HMI, stating food needs to be replenished. This signal will further be sent through the Edge Gateway to IIoT systems, automatically ordering more food.

4.2. Control System Integration and Redundancy

Utilising a PLC allows for each subsystem to operate individually as well as collectively. Therefore, if one variable changes, one response would occur, but if multiple variables change, then multiple responses occur.

This ensures self-regulation and reliability, thus, if the temperature changes also effecting oxygen levels, not only does a temperature response occur but also an oxygen response.

Therefore, with the integration of all subsystems into one system, self-regulation can be achieved. Furthermore, this integration allows for multiple monitoring through the PLC and to IIoT systems, connected through Ethernet IP, Switches and Edge Gates.

Redundancy is built into the design as this monitoring allows the system to not only be controlled through a HMI but also through IIoT systems which can be monitored anywhere. The system will produce smart monitoring when errors occur or processes such as low food levels occur, which can automatically order new food stock.

As shown in Figure 26, Data Loggers and Transmitters can be utilised which bypass the PLC and directly connect to the Edge Gateway to provide instant data which allows for redundancy if the system sensors were to fail as well as provide accurate environmental sensor comparisons for process improvements.

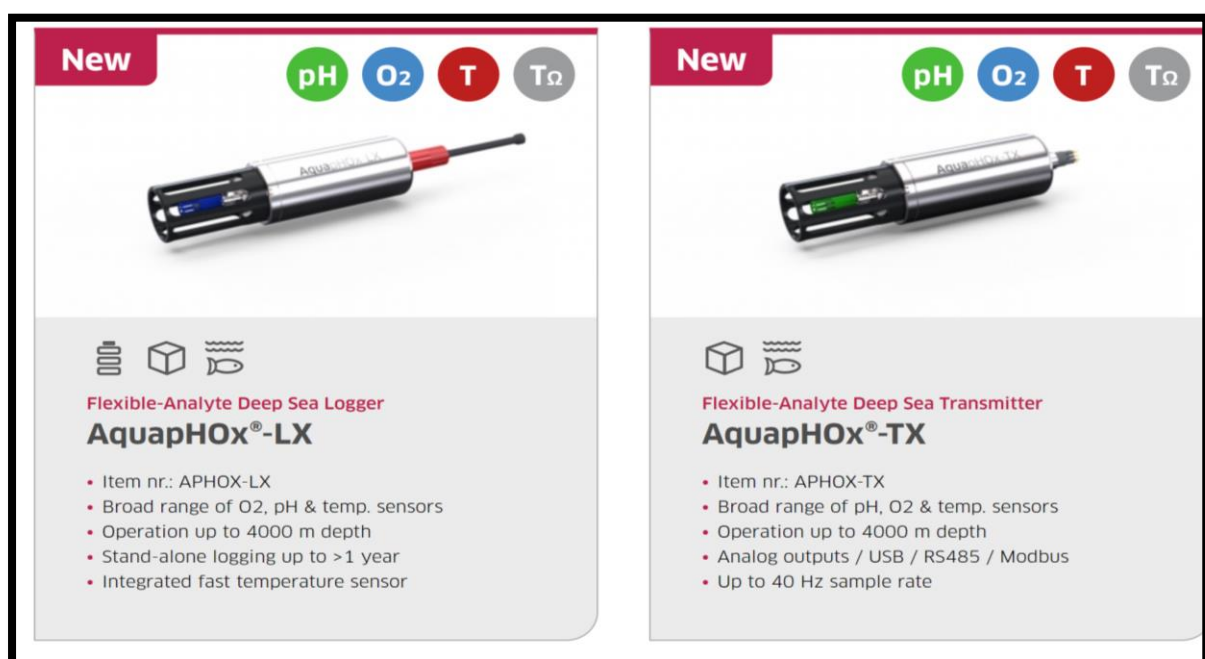


Figure 26 Shows Environmental Data Loggers and Transmitters (PyroScience meters, 2022)

5.0. Review and Further Considerations

The system design will be utilised for generic freshwater aquarium automation; thus, equipment ranges will be determined by wildlife species.

Meeting Machine Directives meant low force pneumatic systems, low voltages and advanced monitoring was utilised to reduce health and safety risks. Table 11 was utilised to compare pneumatics and hydraulics, with pneumatic being the safer more diverse environmental option. Although check valves, filters, dryers and seals need to be utilised within any submerged system to prevent water into the pneumatics.

IIoT systems improve integration and processes, whilst monitoring energy outputs, thus, reducing carbon footprints. Process improvement through process alarms and error logging occurs with further redundancy due to data loggers and transmitters.

Dummy tanks shown in Figure 27 can be utilised for environmental change before the main aquarium, allowing for maintenance and reduced sudden aquarium changes which may stress or harm the wildlife.

Closed-Loop subsystems integrated through a PLC and other communication protocols allow for a smart, redundant hierarchical control system that conforms to regulations and meets the system specification whilst allowing for future improvements through IIoT systems.

No system can be fully automated, due to machine maintenance and replenishment. However, further automation can be achieved indirectly with hydraulic systems such as lifting aquarium lids, doors and equipment through automated actuators due to the high force capabilities. To meet regulations, proximity sensors, interlocks and emergency stops should be implemented in case of an emergency during human interaction. Hydraulic fluid can be toxic, thus, water is recommended for the medium to prevent harm to wildlife or persons during a leak.

Table 11 Shows the Advantages and Disadvantages of Hydraulic and Pneumatic Systems (Duran-Lamanilao, 2021)

	Advantages	Disadvantages
Pneumatic Systems	- Flexible temperature - Safe, explosion proof - Clean - Easy to store, utilize and maintain - Available in very small sizes - Works in wide temperature range	- Requires installation of expensive air-producing equipment - Easy to leak - Potential noise - Easily produces condensation or moisture - Does not work underwater or in extreme temperatures - More costly in terms of energy usage
Hydraulic Systems	- Ease and accuracy of control - High force potential - Simple, safe and economical - Can be operated manually - Operates very well in a very hot working environment	- Risk of hydraulic oil leaks - Risk of lines bursting that can result in serious human injuries - Susceptible to contamination and foreign object damage

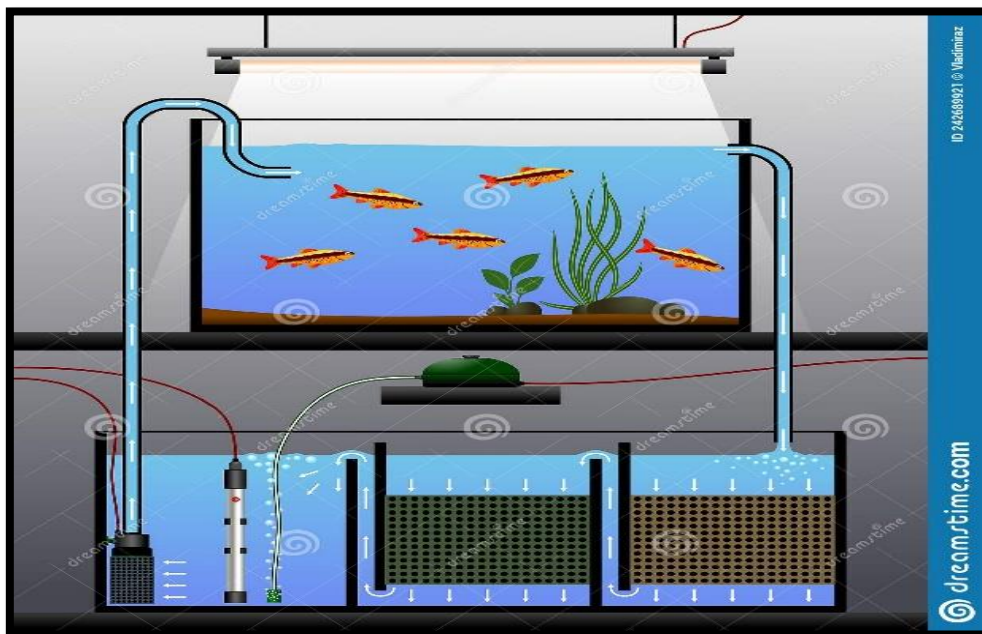


Figure 27 Shows an Aquarium Water Alteration Process (Zadvinskii, 2022)

6.0. Conclusion

Control technology is advancing with repetitive or dangerous tasks being automated, whilst industry 4.0., particularly IIoT, is allowing for process improvements.

Automation has its benefits but can be complicated and regulations must be adhered to, thus, feasibility is required.

This system requires consideration of many variables to be self-regulating, from water temperature to oxygen levels. The proposal suggested modern environmental sensors and correction elements intertwined with a PLC, providing a self-regulating environment for aquatic life. Combined with advanced monitoring through IIoT systems, the design would lead to a smart system that would require little human interaction whilst conforming to regulations.

Further system redundancy within the design proposal reduces machine failure risk, thus, must be considered during system implementation. Furthermore, safe methods, utilising small force and voltage devices were suggested, conforming to environmental and health and safety regulations.

Therefore, although some human interaction will always be required, an automated control system for an aquarium is feasible if one utilises the proposed design, whilst altering specific equipment for the specification ranges required for particular wildlife needs.

References

Balasubramani, S., Aakash Ram, S., Akshay Bharadwaj, S. and Bennet Niffin, N., 2020. Smart Aquarium Management System. *Advances in Parallel Computing*, [online]pp.523-527. Available at: <https://www.researchgate.net/publication/345690191_Smart_Aquarium_Management_System> [Accessed 12 March 2022].

Banafa, A., 2015. *The Industrial Internet of Things (IIoT): Challenges, Requirements and Benefits*. [online] pp.1-5. Available at: <https://www.researchgate.net/publication/274512563_The_Industrial_Internet_of_Things_IIoT_Challenges_Requirements_and_Benefits> [Accessed 29 March 2022].

Brüning, A., 2016. *Disruptive light: when night becomes day for fish*. [online] Igb-berlin.de. Available at: <[https://www.igb-berlin.de/en/news/disruptive-light-when-night-becomes-day-fish#:~:text=Artificial%20light%20blurs%20the%20boundary,of%20diadromous%20\(migratory\)%20fish.](https://www.igb-berlin.de/en/news/disruptive-light-when-night-becomes-day-fish#:~:text=Artificial%20light%20blurs%20the%20boundary,of%20diadromous%20(migratory)%20fish.)> [Accessed 12 March 2022].

Chiu, M., 2010. A Multi-functional Aquarium Equipped with Automatic Thermal Control/Fodder-Feeding/water Treatment using a Network Remote Control System. *Information Technology Journal*, [online] 9(7), pp.1458-1466. Available at: <https://www.researchgate.net/publication/49942071_A_Multi-functional_Aquarium_Equipped_with_Automatic_Thermal_ControlFodder-Feedingwater_Treatment_using_a_Network_Remote_Control_System> [Accessed 29 March 2022].

Collins, D., 2019. *What's the difference between PL and SIL machine safety standards?*. [online] Motioncontroltips.com. Available at: <<https://www.motioncontroltips.com/whats-the-difference-between-pl-sil-machine-safety-standards/>> [Accessed 12 March 2022].

Federation of British Aquatic Societies, 2008. *YOUR LEGAL DUTY OF CARE FOR KEEPING FISH UNDER THE ANIMAL WELFARE ACT*. 1st ed. Federation of British Aquatic Societies, pp.2-9.

FishLab. 2021. *Aquarium Oxygen: The Essential Ingredient to a Healthy Aquarium*. [online] Available at: <<https://fishlab.com/aquarium-oxygen/>> [Accessed 12 March 2022].

Fondriest Environmental, Inc. 2013. *Dissolved Oxygen*. [online] Available at: <<https://www.fondriest.com/environmental-measurements/parameters/water-quality/dissolved-oxygen/>> [Accessed 23 March 2022].

Gonzalez, C., 2015. *Engineering Essentials: What Is a Programmable Logic Controller?*. [online] Machinedesign.com. Available at: <<https://www.machinedesign.com/learning-resources/engineering-essentials/article/21834250/engineering-essentials-what-is-a-programmable-logic-controller>> [Accessed 3 April 2022].

GOV.UK. 2021. *Using the UKCA marking*. [online] Available at: <<https://www.gov.uk/guidance/using-the-ukca-marking>> [Accessed 3 April 2022].

Groover, M., 2008. *Automation, production systems, and computer-integrated manufacturing*. 3rd ed. Upper Saddle River, N.J.: Prentice Hall, pp.85-285.

Gums, J., 2018. *Types of Temperature Sensors*. [online] Digi-Key Electronics. Available at: <<https://www.digikey.co.uk/en/blog/types-of-temperature-sensors>> [Accessed 13 March 2022].

Hardyanto, R., Ciptadi, P. and Asmara, A., 2019. Smart Aquarium Based On Internet of Things. *Journal of Business and Information Systems (e-ISSN: 2685-2543)*, [online] 1(1), pp.48-53. Available at: <<https://thejbis.org/index.php/jbis/article/view/12>>.

Immerman, G., 2017. *Why Industry 4.0 is Important and Why Manufacturers Should Care*. [online] Machinemetrics.com. Available at: <<https://www.machinemetrics.com/blog/why-industry-4-0-is-important>> [Accessed 3 April 2022].

Sabhadiya, J., 2022. *What Is Air Compressor?- Definition, Types And Working - Engineering Choice*. [online] Engineering Choice. Available at: <<https://www.engineeringchoice.com/air-compressor/#:~:text=An%20air%20compressor%20is%20a,storage%20tank%2C%20increasing%20the%20pressure.>> [Accessed 3 April 2022].

Teja, R., 2021. *Wheatstone Bridge | Working, Examples, Applications*. [online] Electronics Hub. Available at: <<https://www.electronicshub.org/wheatstone-bridge/>> [Accessed 20 March 2022].

Tilley, J., 2017. Automation, robotics, and the factory of the future. [online] Available at: <<https://www.mckinsey.com/business-functions/operations/our-insights/automation-robotics-and-the-factory-of-the-future>> [Accessed 25 March 2022].

Wang, L., 2020. Basics of PID Control. *PID Control System Design and Automatic Tuning using MATLAB/Simulink*, [online] pp.17-20. Available at: <https://www.researchgate.net/publication/346653954_Basics_of_PID_Control> [Accessed 25 March 2022].

Woodford, C., 2021. *Pneumatics: a simple introduction*. [online] Explain that Stuff. Available at: <<https://www.explainthatstuff.com/pneumatics.html>> [Accessed 20 March 2022].

Figure References

Figure 1 - Groover, M., 2008. *Automation, production systems, and computer-integrated manufacturing*. 3rd ed. Upper Saddle River, N.J.: Prentice Hall, p.88

Figure 2 - Electronics Tutorials. 2014. *Closed-loop Systems*. [online] Available at: <<https://www.electronics-tutorials.ws/systems/closed-loop-system.html>> [Accessed 2 April 2022].

Figure 3 - Groover, M., 2008. *Automation, production systems, and computer-integrated manufacturing*. 3rd ed. Upper Saddle River, N.J.: Prentice Hall, p.101

Figure 4 - RS Components., 2022. *Temperature Controllers* [online] Available at: <<https://uk.rs-online.com/web/c/automation-control-gear/process-control/temperature-controllers/>> [Accessed 2 April 2022].

Figure 5 - Unitronics. 2022. *What is the definition of "PLC"?*. [online] Available at: <<https://www.unitronicsplc.com/what-is-plc-programmable-logic-controller/>> [Accessed 2 April 2022].

Figure 6 - Bohn, R., 2013. *IP Ratings Explained - What Are IP Ratings? | NEMA Enclosures*. [online] Stainless Steel Enclosures | NEMA Enclosures. Available at: <<https://www.nemaenclosures.com/blog/ingress-protection-ratings/>> [Accessed 2 April 2022].

Figure 7 - Groover, M., 2008. *Automation, production systems, and computer-integrated manufacturing*. 3rd ed. Upper Saddle River, N.J.: Prentice Hall, p.144

Figure 8 - Teja, R., 2021. *Wheatstone Bridge | Working, Examples, Applications*. [online] Electronics Hub. Available at: <<https://www.electronicshub.org/wheatstone-bridge/>> [Accessed 2 April 2022].

Figure 9 - Applied Weighing International. 2022. *Target 260S*. [online] Available at: <<https://appliedweighing.co.uk/products/target-260s-load-cell-amplifier/>> [Accessed 2 April 2022].

Figure 10 - PLC Programming Courses for Beginners | RealPars. 2022. *PLC Analog Inputs and Signals*. [online] Available at: <<https://realpars.com/plc-analog-inputs/>> [Accessed 2 April 2022].

Figure 11 - O’Keefe, P., 2018. *The Depositor’s Pneumatic Actuator*. [online] Engineeringexpert.net. Available at: <<http://www.engineeringexpert.net/Engineering-Expert-Witness-Blog/the-depositors-pneumatic-actuator-2>> [Accessed 2 April 2022].

Figure 12 - Upmation. 2021. *What is a Directional Control Valve?*. [online] Available at: <<https://upmation.com/directional-control-valve/>> [Accessed 2 April 2022].

Figure 13 - Cross MFG. 2022. *Basic Hydraulic Theory*. [online] Available at: <<https://crossmfg.com/resources/technical-and-terminology/basic-hydraulic-theory>> [Accessed 2 April 2022].

Figure 14 - Upmation. 2021. *What is a Directional Control Valve?*. [online] Available at: <<https://upmation.com/directional-control-valve/>> [Accessed 2 April 2022].

Figure 15 - Fluidsys Training Centre. 2022. *Configuring a Typical Pneumatic System*. [online] Available at: <<https://fluidsys.org/2018/05/17/a-typical-pneumatic-system/>> [Accessed 2 April 2022].

Figure 16 - Duran-Lamanilao, D., 2021. *Assessing the Pros and Cons of Pneumatic and Hydraulic Systems - Gulf Coast Air & Hydraulics*. [online] Gulf Coast Air & Hydraulics. Available at: <<http://wegetstuffdone.com/assessing-pros-cons-pneumatic-hydraulic-systems/>> [Accessed 2 April 2022].

Figure 18 - GISON MACHINERY CO., LTD. 2022. *Compressed Air System Components And Network For Using Air Tools*. [online] Available at: <<https://www.gison.com.tw/en/page/Compressed-Air-System-Network-and-Components/air-tool-application.html>> [Accessed 2 April 2022].

Figure 24 - Farnsworth, R., 2022. *Overflow Boxes and Drain Styles - Durso, Herbie, and Bean Animal*. [online] Bulk Reef Supply. Available at: <<https://www.bulkreefsupply.com/content/post/md-2017-08-durso-herbie-bean-animal-overflow>> [Accessed 2 April 2022].

Figure 26 - Pyroscience.com. 2022. *PyroScience meters*. [online] Available at: <<https://www.pyroscience.com/en/products/all-meters/aquaphox-tx>> [Accessed 2 April 2022].

Figure 27 - Zadvinskii, V., 2022. *Aquarium with external sump filtration..* [online] Dream Time. Available at: <<https://www.dreamstime.com/aquarium-external-sump-filtration-schematic-diagram-vector-illustration-filter-image242689921>> [Accessed 2 April 2022].

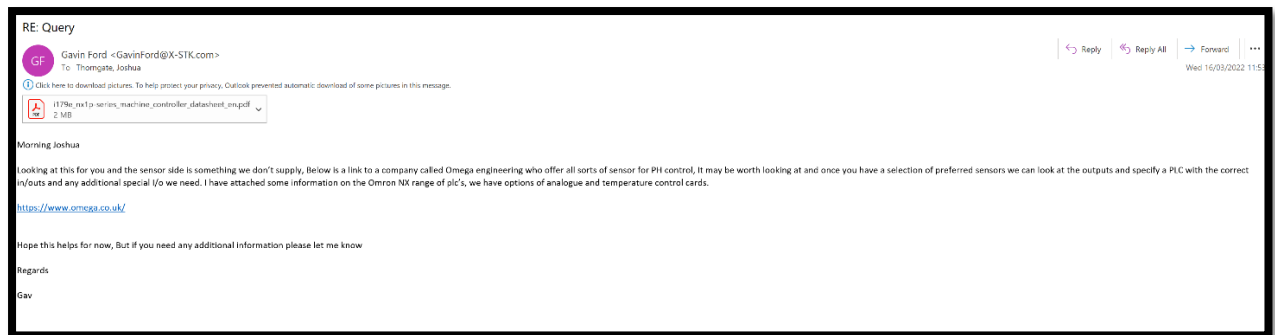
Table References

Table 2 - Groover, M., 2008. *Automation, production systems, and computer-integrated manufacturing*. 3rd ed. Upper Saddle River, N.J.: Prentice Hall, p.132

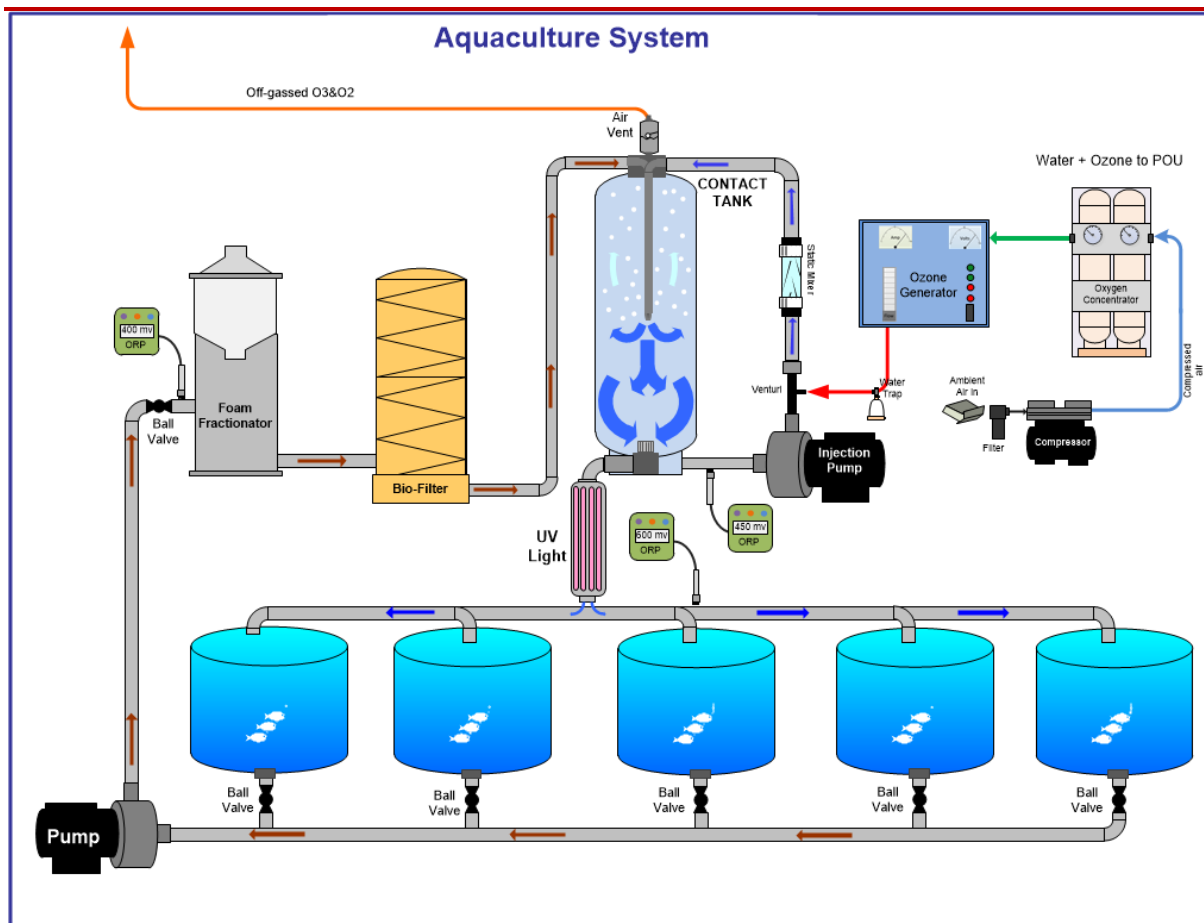
Table 3 - Groover, M., 2008. *Automation, production systems, and computer-integrated manufacturing*. 3rd ed. Upper Saddle River, N.J.: Prentice Hall, p.134

Table 11 - Duran-Lamanilao, D., 2021. *Assessing the Pros and Cons of Pneumatic and Hydraulic Systems - Gulf Coast Air & Hydraulics*. [online] Gulf Coast Air & Hydraulics. Available at: <<http://wegetstuffdone.com/assessing-pros-cons-pneumatic-hydraulic-systems/>> [Accessed 2 April 2022].

Appendix One

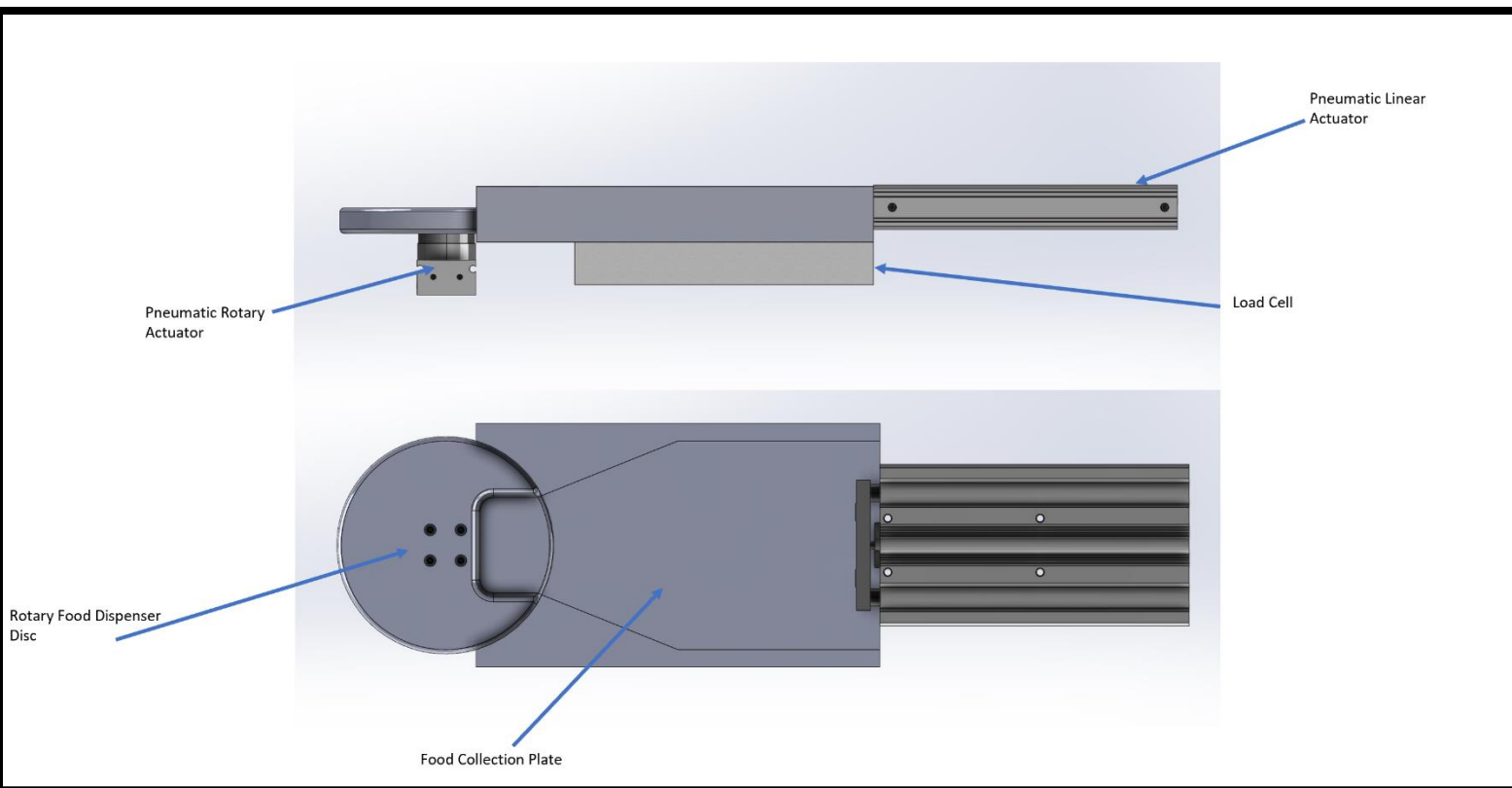


Appendix Two



Holmes-Farley, R., 2019. *Optimal Parameters for a Coral Reef Aquarium*. [online] REEF2REEF Saltwater and Reef Aquarium Forum. Available at: <<https://www.reef2reef.com/threads/optimal-parameters-for-a-coral-reef-aquarium-by-randy-holmes-farley.173563/>> [Accessed 2 April 2022].

Appendix Three



The figure above shows a concept for the feeding system. It must be noted that this would not be the entire design and more mechanical and electrical components would be required, however, the design represents the concept.

As one can see, the fish food mechanism has a rotary actuator and a linear actuator. Food would come fully loaded into a funnel and the food would utilise gravity to drop onto the food collection plate. The load cell would utilise strain converted into a voltage and sent through the Wheatstone Bridge Amplifier through Ethernet IP to the PLC to detect how much weight was on the collection plate, thus, sending the data through to the IIoT systems to automatically order more food supply when required.

During set times programmed into the PLC from the HMI or IIoT system, the PLC will send an output signal to send out the linear actuator pushing the food into a pocket on the rotary food dispenser disc. Once the reed switch for the linear actuator was turned on from full extension, the rotary actuator turns 180 degrees, dispensing the set amount of food into the aquarium. The activated actuators can be seen in the figure below.

