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Aquaponic Integration and Automation – A Critical Evaluation

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Abstract

Aquaponics is technology developed from the aquaculture industry that integrates intensive farming of fish and utilizes plants (integrates hydroponics) in a continuous closed loop to clean the water for the fish. The plants clean the water of nitrate (waste form is initially ammonia) which has been converted into a form that is not toxic to fish by bacteria and is accessible to plants. Hydroponics technology is a technique used to grow plants and vegetables that does not incorporate soil, but nutrients that are dissolved in water and plants are either floated or treated with a nutrient film delivered to the roots by a variety of processes. These technologies are becoming more popular with communities and governments as the preservation of water becomes more of an issue in environments where water is becoming restricted in supply and has to be supplemented by mechanical means such as desalination, which comes at additional cost to consumers. The technologies have had a great amount of research interest to find parametres and ranges that the systems require to function successfully yet also remain productive with certain crop varieties. The successful diversification of crop varieties could increase the viability of commercial aquaponics, which could be achieved with the use of optimized advanced process control strategies.

Keywords: process control, automation, distributed automation, aquaponics, hydroponics, aquaculture

1. Introduction

1.1 Aquaponics

In an aquaponics system the nutrients that accumulate in the system is a result of the accumulation of waste from fish and the feed introduced to grow fish. The fish eat food that they require to remain healthy and grow, yet the food used to feed the fish and the waste it produces does not necessarily contain all the needs of various plants. If the technologies are to support the reduction in water and remain competitive in current markets, a greater diversity of products could be required to remain competitive in commercial markets. Existing commercial aquaponics systems are able to grow a range of vegetable greens on a competitive footing yet could come under pressure during seasonal shifts when traditional market growers are able to compete during these seasonal time periods. This could also limit areas in which they are able to compete where established farming techniques could undercut Recirculating Aquaponics System RAS operators with the limited varieties that could be competitively grown. The additional range of products that a system is able to produce could also reduce the financial risk that an investor must carry when entering into a large commercial venture as they would be able to supply a greater number of supply chains limiting market shocks.

Technologies that are able to recover or reduce water use in industry, commercial or farming techniques are becoming practical solutions as water use becomes more of a concern for governments and communities. The development of viable solutions for urban farming techniques (Australia) that are able to produce vegetables and fish products with less water is becoming a favored approach for both private operators and government departments. This is particularly favorable when established water saving techniques can be realized in environments where water is becoming a valuable resource and conservation techniques are becoming more of a priority in the community. The use of these plants and the process`s to remove waste (Amirkolaie) from fish production reduces environmental impacts that could result from intense fish production. These existing technologies, although they use water in their systems, do not use large quantities in comparison to current techniques such as irrigated farming, which can be subject to the environment and associated water evaporation. The use of hydroponics and aquaponics techniques are able to reduce their water usage between 99% (in almost laboratory conditions) (Borras) and 50 % (quantified against plant usage only) (Watch) while still being outside in similar environments to irrigated farming techniques. As these systems can provide large reductions in water usage, a review from an automation perspective should take place and how automation techniques could aid in large-scale commercial production.

Aquaponics systems that are marginal in producing crops profitably (T. Vermeulen, n.d.)or the crops in which they are producing successfully can limit the markets in which they are able to supply and compete in. This is due to established limitations either from biological restrictions or from chemical (including nutrient availability) restrictions in the process, which can limit varieties of plants produced. Most mid to small aquaponics systems will initially begin to operate their systems between pH of 6.8 and 7.2 (Ecolife), although this sets limitations on the amount of fish due to ammonia build up within the system. The higher pH requirements normally above 7 pH to lower ammonia levels, limits the commercially successful aquaponics crop varieties to green leafy varieties such as lettuce (James E. Rakocry), chard, kales, Chinese green vegetables, Bok and Pak Choi or watercress or herbs like Basil. Research (N. Vergotr) into RAS aquaponics systems has determined that there are not enough available nutrients in aquaponics systems to commercially grow fruiting plants such as tomatoes. This has been verified by independent research, which noted that the poor quality of fruit produced in aquaponics could be measured by the dry weight of tomatoes in aquaponics versus hydroponics that resulted in "22 grams/kg dry matter versus 40.8 grams/kg" (Andreas Graber, 2007), which was determined to be from nutrient limitations.

The use of process control and the automation that it incorporates is able to measure and maintain multiple control loops, having multiple control loops that are not dependent on others would remove some of the identified limitations by dividing the process to meet those ranges that have been researched as optimum at particular stages of the process.

2. Method

2.1 Automation Integration

The proposed paper will look at control techniques to make established conditions possible with an engineering approach that treats the system as a process with ranges that need to be met for the system to remain productive. Automation and control can function as both measurement and adjustment to the system on a constant basis, some of the conditions that would normally be difficult to maintain in a system would be contained within the desired range. Process control with automation is able to increase the complexity of the control parameters, which can allow Multiple Inputs and Multiple Outputs (MIMO) to be measured and controlled to achieve desired ranges. The use of ranges that have been established in aquaponics and hydroponics with known viable results can be used to develop a control solution that could overcome some of the limitations that aquaponics operators must tolerate. Currently these parameters can rely on biological process to obtain established system ranges by controlling the system by balancing the nutrients with the amount of fish feed that enters the system in comparison to the amount of plants that are in the system. This approach can restrict other components of the system and compromises are required to keep the system balanced to meet the biological requirements. Automation techniques could also add alternate methods of controlling these nutrient levels with current or existing technologies from other industries. These control techniques could aid in controlling both the inputs and the outputs of the system with the use of instrumentation, measurement and automation control. These control strategies would not just include adding additional nutrients to meet the needs of the plants but recycling those currently present in the system to reduce waste as much as possible, by streaming them into other independent control loops.

2.2 Existing Ranges

As the fish do not need certain nutrients in their diet, they are not added to the feed and have to be added to the water to create conditions that can grow crops successfully. Yet as there are dissolved solids in the water from the fish waste, it can be difficult to add large quantities of additional dissolved nutrients as the water quality would be diminished. As part of the process, ammonia from fish waste is also produced and must be removed, as it is toxic to fish even in very small quantities. The ammonia is converted by bacteria into different forms firstly nitrites then nitrates, which is safe to fish at certain levels. This process also produces carbon dioxide, which also introduces chemical processes, which can change the form of nutrients in the process. The bacteria also has optimum ranges in which it can carry out its biochemical process, which includes temperatures and a range of pHs (Ecolife) which prior research has identified. The fish also have some particular water quality requirements that can also include the amount of suspended solids and preferred levels of dissolved solids within the water for them to remain healthy and productive. Fish can survive in a variety of pH levels depending on their species with most able to survive in ranges of 6.5 to 8.5pH (Andreas Graber, 2007), although there are species that can live in ranges below and above this range such as tilapia, which can survive in as little as 6.0 ph. Some carp and catfish varieties can survive up to ranges of 9.0 ph. However, the nitrifying bacteria prefer to be above the 7 pH range to work efficiently, (Wilson Lennard) with optimum ranges between 7 pH to 8 pH as shown in Figure 1. This factor limits the range otherwise the water will become toxic to fish as ammonia levels will rise no matter what species of fish is used within the system. Alternatively, there would have to be a lowered number of fish density in the system, which would not be optimum for system production rates or an extremely large nitrification tank would need to be constructed to maintain the system.

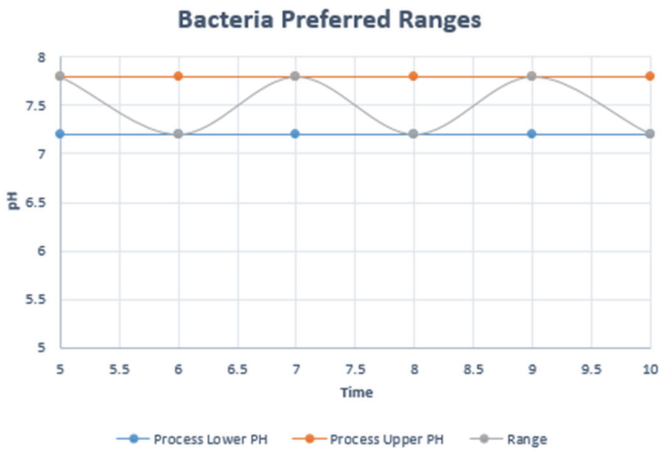

Figure 1. Productive Nitrification Levels

The process ranges of plants however differ from the requirements of certain species of fish and nitrification bacteria and the requirement can be much lower than that required in soils for the plants to have full availability to nutrients. Nutrients such as “Mn, Cu, Zn and especially Fe are reduced at higher pH” (Bugbee), although this nutrient availability is only reduced it can be important in more (Larry Cooper) complex fruiting vegetables to consistently grow fruit that is of uniform size without deformities for the product to remain marketable.

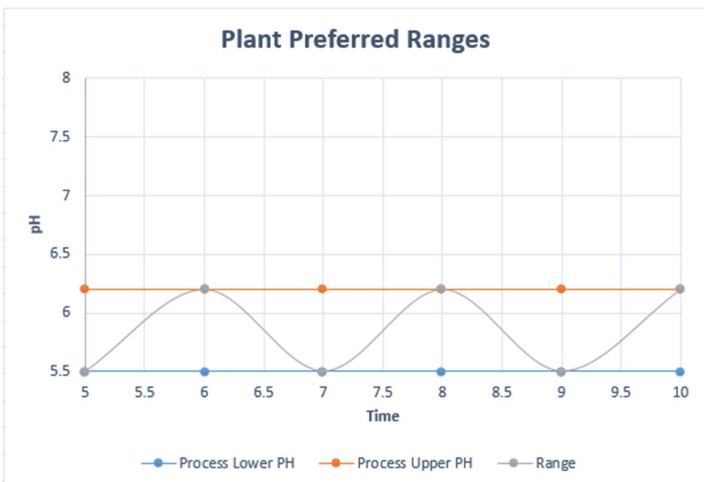

Figure 2. Plant Nutrient Availability

Although there are differences in the ranges between plants and bacteria these system requirements alone do not stop commercial aquaponics operators from producing a variety of crops that are normally green leafy varieties. Although operators will look for a compromise between these ranges, even though they recognize “the pH was disadvantageous to vegetables” (Chito F. Sace). Automation techniques could also be utilized that are able to move nutrients into sub systems of the process that are not subject to the same limitations, such as pH (Konrad Mengel) which can restrict nutrient uptake by plants.

2.3 Control Strategies

Traditionally aquaponics nutrients that are contained in solid waste are removed from the system through a series of settling tanks that can be of a baffle design or clarifier design such as swirl or radial clarifiers. These designs have been trialed in many environments (Jason J. Danaher, 2013) including aquaponics and has proven to successfully remove solids to preferred levels. There are other techniques such as mechanical separators that can remove solids from the aquaponics cycle very efficiently with up to 75 - 90% (James M. Ebeling) of the solids being removed with these designs. As the process would be constantly altering, with fish harvests or crop rotations and natural seasonal changes that could affect growth rates and requirements of both, fish and plants solids in the system would be constantly changing. This would change the amount of solids that would be required to be removed from the process or the amount that could be treated and incorporated back into the system. A combination of these techniques could be used to remove the solids into an offline process for treatment. If the process did not require the addition of solids, mechanical means could then be used to remove these totally from the system. In conjunction with mechanical removal, there are also existing techniques from the wastewater industry that are able to decant water from the solids nutrient stream. When additional dissolved nutrients can be utilized, the decanting process could be put in line with the process making the process able to be both online and offline for effective removal, treatment or reintroduction of nutrient solids. The solids that are totally removed from the process as waste should be treated as a value-adding product, not just as waste and could be on sold as organic fertilizer or to compost manufacturers to enrich their products with nutrients.

Normally a RAS would be treated as a single closed loop, which must allow for all environmental conditions for biological processes to take place. As process control and automation can add additional functionality to the process, it could be broken up into more than one closed loop, with nutrient exchange taking place between the loops to supply cleaning of the fish water but also provide conditions that allows a variety of plants to grow including fruiting vegetables to their full potential.

Recycling of the solids waste from fish that contain nutrients could be in the form of treating waste as a resource in an offline / online process then reintroducing as much as possible back into the process, as the system uses it (mineralization).

Control over the main system nutrients either by removal to the sub system or removal to recycling have some advantages to the main system.

1) The aquaponics system can be regulated with addition of nutrients from more than one source (increase-recycled nutrients reintroduced after a fish harvest to prevent any losses in leafy green plant production).

2) The aquaponics system could also have a much greater survival rate of fish (excess nutrients could be removed when larger quantities of fish/feed are present in the system).

Having control over the nutrients in a sub system that is not reliant on requirements of the main system also has some advantages.

1) The nutrients are being supplemented from the main system (maximise recycled nutrients from excess fish waste)

2) The restrictions of pH levels that can reduce the efficiency of nitrification bacteria are no longer a restriction in the sub system.

3) Plant nutrient uptake can be optimised by allowing for pH levels that are specific to the plants requirements (increase in successful crop varieties)

4) The Total Dissolved Solids (TDS) limitations for fish are not a requirement for the sub system and established nutrient levels for plant varieties can be introduced into the sub system (increase in plant production)

Measured nutrient values that are present in aquaponics systems and some of the nutrients that are deficient can be controlled by the addition of the missing nutrients. The same process of calculation and addition can be replicated on a much more regulated scale by measurement with instruments and control of nutrient dosing systems from control systems such as a Distributed Control Systems (DCS) or Supervisory Control and Data Acquisition (SCADA). These control systems and the technology they are constructed from is considered a mature technology (Stephen J. Sosik) and are produced by many manufacturers, which compete for market share making these systems relatively cost effective. Even minimalistic versions of SCADA have built in Proportional (P), Proportional-Integral (PI), and Proportional Integral Derivative (PID) controller algorithms (Stephen J. Sosik) that can control and maintain ranges such as flow, levels and even control the speed of pumps to keep flow rates at measured limits. This could also include other control techniques such as the monitoring of levels, which could control automatic starting or stopping of pumps, or the measurement of nutrient ranges, which could be increased or decreased by adjusting the speed of dosing pumps.

2.4 Control Strategies - Nutrient Redistribution

Technology from the wastewater industry has been alternate applications in the aquaponics and aquaculture industry in the past, mainly to clean and remove salt from water. The technology has included the use of reverse osmosis units and low operating cost equipment such as electro dialysis or reverse electro dialysis, which is able to automatically clean its membrane by reversing the process. This has predominantly been used to clean water so it can be used in a process or recycled back into the process to lower water usage rates.

However, this automation solution is focusing on controlling nutrient levels by lowering them to established ranges by removal of dissolved nutrients and Total Dissolved Solids (TDS) from the aquaponics solution to be reused in the hydroponic sub system. These would be at pre-determined nutrient levels required for the aquaponics system to remain successful, not to remove nutrients totally from the process. One such technology that could be adapted to this purpose is Selective Electro Dialysis (SED). SED has been developed for many industries, which includes membranes (Vivian B. Jensen) designed specifically to remove nitrates from contaminated water. These membranes transport ions and anions through membranes with the aid of a Direct Current (DC), which attract or repel these nutrients. Along with the membrane design, the DC current allows certain percentages of different nutrients to pass through the membrane such as nitrates in slightly higher densities than the rest of the dissolved solids.

The SED moves nutrients that are dissolved in their ionic form and not those that are bound up in larger forms such as those contained in larger solids that have not been broken down. The dissolved solids continue in the non-concentrate stream, as the SED is designed to operate at specific pressures to prevent build-up on the non-concentrate side of the membranes. It also makes use of a pre-filter to remove suspended solids before entering the membrane. This allows further opportunity to control the level of suspended solids by sending any that are filtered to the online/offline mineralisation tank for further treatment. The concentrate side of the membrane also needs to be kept clean which case studies show is normally from calcium carbonate, which would be present in the aquaponics system. A different process that uses acid dosing to prevent build-up of deposits or any scale that would form on the membrane achieves the cleaning of this side of the membrane. This however has the result of keeping the pH level the same or nearly the same on the non-concentrate side and lowering it on the concentrate side to values similar to plants requirements.

	pH	N	TAN	S	TDS	Ca	Mg	K	P	Fe	Mn	Cu	Zn	B	Mo
Aquaponic / Basil	7.4	42	2.2	N/A	560	11.9	6.5	44.9	8.2	2.5	0.8	0.05	0.44	0.19	0.01
SED removal Rates %	7.8 in - 6.5 out	52.20	33.90		33.90	37.80	36.60	30.60	33.90	33.90	33.90	33.90	33.90	33.90	33.90
57 lt Concentrate		385	13.08		3331	78.92	41.74	241.04	48.77	14.87	4.758	0.297	2.617	1.13	0.0595
350 lt Dilute Concentrate		63	2.13		542	12.85	6.80	39.26	7.94	2.42	0.775	0.048	0.426	0.18	0.0097
Hydroponic Recipe	5.8-6.2	70		50		150	40	120	50	2.8	0.8	0.2	0.3	0.7	0.05
Additional mg/Litre		7		50		138	33	80	42	N/A	N/A	0.15	N/A	0.5	0.04

Figure 3. Estimated Additional Nutrients

Although this selective electro dialysis membrane does advertise that it removes 59% of nitrates and 30% TDS (Vivian B. Jensen J. L.)the results of its percentage of removal rates are taken from an existing water treatment plant. This is due to the system results has more data on the actual percentages on a greater number of specific nutrient types, although it should be noted that the ones identified were all within a few percentage points. The original aquaponics recipe used as an example contains Total Ammonia Nitrogen/Nitrates (TAN) that would be transported to the hydroponics solution, which would breakdown and create additional nitrogen in the hydroponic mixture. TAN is encouraged in some hydroponic mixtures and is not toxic to plants in small amounts as it can be to fish.

The total nitrogen that is present or can be measured in an aquaponics system (Wilson Lennard) does not represent the total nitrogen that is available to plants as bacteria absorb it. There is also no data on bacterial exchange through the SED process, and these bacteria can absorb or contain nutrients, including nitrates. The hydroponics solution which is expected to be ion based (additions to make up complete solution would be in ion form) and measurement may need to be treated similar to aquaponics solutions, with lower hydroponic solution recipes initially being applied until true nutrient availability can be determined. The hydroponic solution used as an example starts at 70 ppm and eventually increases its nitrogen levels up to 150 ppm (George J. Hochmuth) as the plant reaches different clusters or sets of branches. A similar approach could be used until any of the TAN that has entered the system is biochemically changed into nitrates (nitrification bacteria will survive in lower pH levels although are not as efficient), or taken up by plants. Although the hydroponic solutions have predicted levels of nutrients or hydroponic recipe and the nutrients could be in biological forms there are methods available to calibrate hydroponic recipes. The variances in nutrient forms would be mitigated and the recipe adjusted to suit the particular plant variety with a process referred to as plant tissue testing.

3. Conclusion

3.1 Conclusion

Conducting a study on the individual requirements and designing an alternate control solution that meets the identified ranges could highlight that some of the compromises that are currently required to operate a RAS could be overcome and make it possible to grow vegetables with established hydroponics recipes. The systems may not necessarily be restricted to compromising between the different biological requirements of fish, plants or bacteria but could be separated into alternate control loops. Further work to this study will be to research and design a control solution that would allow the nutrients to be distributed to an alternate control loop that is independent to the main system. This research would include newer methods to balance the Total Dissolved Solids entering the aquaponics system to balance those being removed. Automation techniques will be investigated to automate the addition of nutrients and nutrient concentrate to the hydroponic solution, to provide consistent nutrient ranges. The development of this technology would allow operators to take full advantage of sustainable technologies such as aquaponics. The reduction in fertilizers for fruiting crops, taking advantage of water savings, reduced chemical use and eliminated herbicides for growing a greater range of fruiting produce is not only commercially beneficial to operators but communities in areas where water is becoming a valuable resource.

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