INTERNATIONAL JOURNAL OF COMPUTERS COMMUNICATIONS & CONTROL
Online ISSN 1841-9844, ISSN-L 1841-9836, Volume: 20, Issue: 2, Month: April, Year: 2025
Article Number: 7032, https://doi.org/10.15837/ijccc.2025.2.7032

On the Three-Tank Aquaponic Configuration

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Abstract

The objective of this paper is to propose a mathematical model representing the hydraulic behavior of a generic three-tank aquaponic system, capable to support future research on optimized sizing and suited control algorithms. The components of the system are a fish tank, a hydroponic reservoir, and a multi-task buffer water tank. The mathematical model is structural, representing the water-tanks and the water-flows between them, by differential equations, implemented in Matlab-Simulink.

Keywords: aquaponics, hydroponics, three-tank system, nonlinear mathematical model, Matlab-Simulink, fuzzy-interpolative control.

1 Introduction

The Aquaponic technology is a strategic resource for our sustainable future. Aquaponics (AQ) is a farming method that combines aquaculture (raising freshwater fish) with hydroponics (growing plants soilless) [2]. Fish and plants are cultivated in a symbiotic way, which is possible due to the complementary metabolisms of animals and plants. The fish waste is converted by certain bacteria into nutrients that plants can absorb, while the plants filter and purify the water, creating a healthy environment for the fish. Thus, the water's quality is preserved much longer than in the case of aquaculture and hydroponics, significantly decreasing the volume of water consumed. The need to use fertilizers, pesticides and herbicides also decreases. Up to 90% of the globally consumed water in food production could be saved if aquaponic systems were used [13]. Over the last 200 years freshwater fish have contributed more to food security than any other form of aquaculture production [10]. AQ in open seawater is possible, but less obvious because of the heavier operating conditions, the plant species that deserve to be cultivated in this way are very few in number, and it can raise concerns about farmed fish escapes, chemicals use, etc. [13]. Moreover, the mathematical models of the open aquaculture systems are very different of the closed systems' ones. The AQ highly efficiency relies on a closed-loop symbiotic system connecting fish and plants. Symbiosis can be found in most closed agricultural systems [4, 5]. This work aims to address a generic optimal aquaponic configuration, the three tanks one, and to identify an appropriate structural mathematical model of the aquaponic corresponding closed loop, usable for optimal system design and for testing appropriate control algorithms.

2 The Three-Tank Aquaponic System

The simplest AQ solution involves a single tank for fish and plants, but the exploitation of such a system is greatly hampered by the totally different, sometimes even conflicting technological operations that apply to fish and plants, respectively. It is much more efficient for fish breeding and plant cultivation to be carried out in parallel, while maintaining the symbiosis between them. In fact, in most AQ farms, the teams of operators are specialized for each field: aquaculture and hydroponics. Such structures, that are disconnecting aquaculture of hydroponics, involving more than one water tanks, are known as Coupled Tanks Systems [8]. We consider that the most suited configuration fulfilling the above basic needs is the Three-Tank Aquaponic System (3TAS) [1]. 3TAS is an adaptation of the wide-spread Three-Tank Hydraulic System (3THS), in service for decades in many industrial applications, such as food processing, chemical plants, etc. The 3TAS components are the following:

- The fish tank (F).
- Hydroponic tank (P).
- The buffer tank (B). B can be used for different operations such as fresh water admission, waste water evacuation, temperature and chemical conditioning, etc. without perturbing the main FP functioning.
- The interconnecting system that may achieve any possible water transfer between F, H and B, with controlled parameters (flow values, timing). The bidirectional connections are: F $\rightleftarrows$ P, F $\rightleftarrows$ B and P $\rightleftarrows$ B.

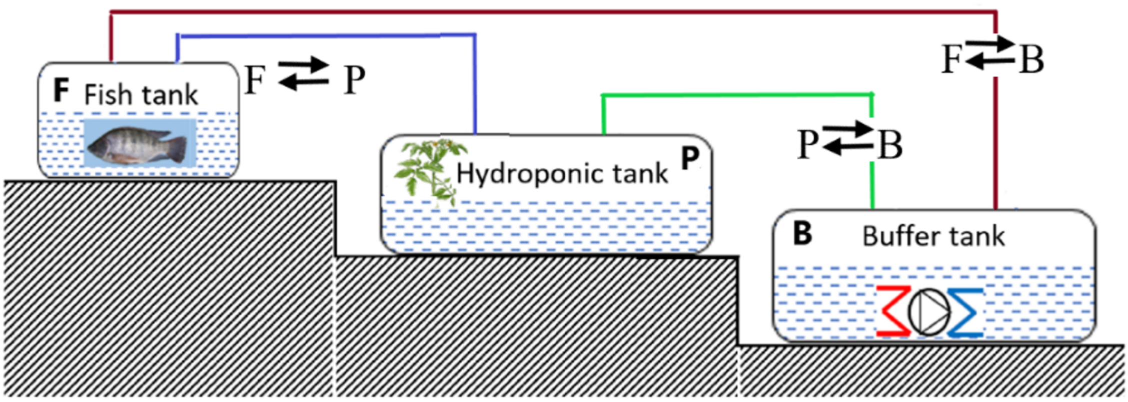


Figure 1: The Three-Tank Aquaponic System

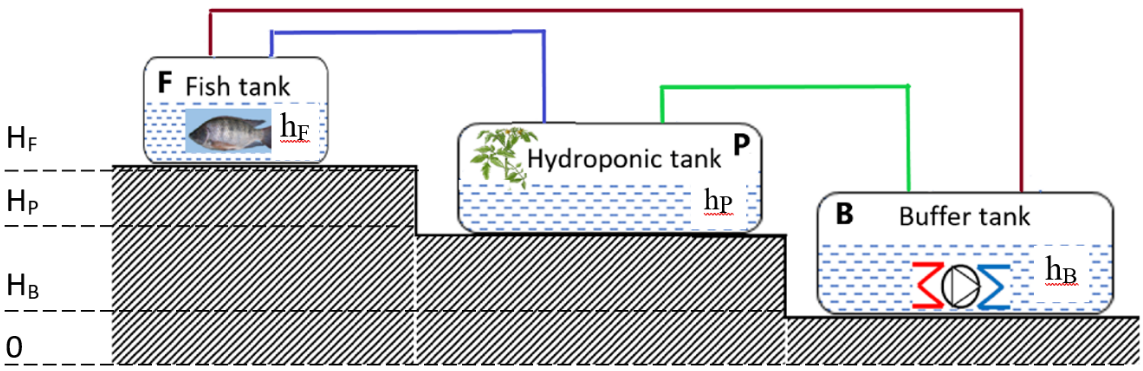


Figure 2: The parameters describing the tanks' location (H) and their water levels (h)

The majority of the 3THS are positioning all three tanks at the same level [1, 6, 12]. In the AQ case we will accept different heights for each of the tanks, allowing the systems designers to adapt to the particular terrain conditions of each project (see Figure 2). Such way one can use gravity for transfers from higher-level tanks to lower-level tanks (see Figure 3).

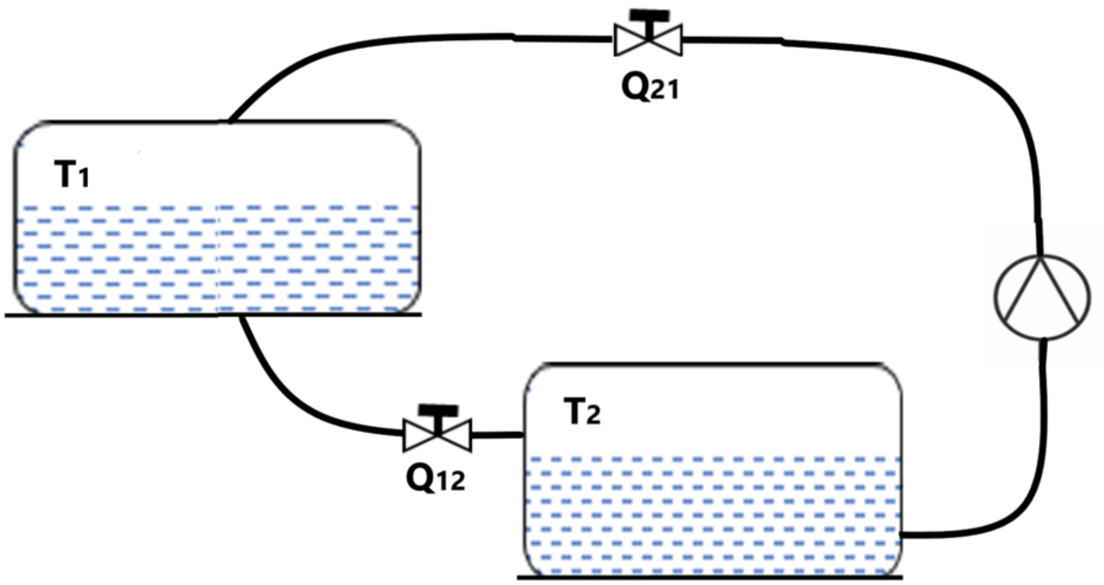


Figure 3: A bidirectional $T_1 \rightleftarrows T_2$ connection

The operation expected for the AQ hydraulic system is the full control of the water transfers between tanks and consequently the full control of water levels in all three tanks.

3 A Mathematical Model for the Three-Tank System

On one hand the 3TAS system has a very simple physical structure, but on the other it is multivariable and nonlinear, which makes it harder to identify and model by synthetic methods (machine learning). Most common models to find in the literature are therefore structural, and we will follow this lead, as well [1, 6, 8, 12].

Let us first consider a single water tank, of area $A[m^2]$, provided at bottom with an evacuation valve. The water height in the tank h [m] depends of the input flow $Q_I[m^3/s]$ and of the leaving flow through the valve $Q_O[m^3/s]$:

$$A\frac{dh}{dt} = Q_I - Q_O \tag{1}$$

If the evacuation is gravitational the equation is:

$$A\frac{dh}{dt} = Q_I - K\sqrt{2 \cdot g \cdot h} \tag{2}$$

where K is a constructive constant characterizing the valve's discharge, depending of the valve's cross section and constructive shape and dimensions, and g is the gravitational acceleration. It is to remark that the gravitational evacuation flow is highly nonlinear and can become very slow in the final stages of the transfers.

The 3TAS model is made up of the following three equations:

$$A_F \frac{dh_F}{dt} = Q_{IF} - K_F \sqrt{2 \cdot g \cdot (H_F + h_F)} - Q_{OF} \tag{3}$$

$$A_P \frac{dh_P}{dt} = Q_{IP} - K_P \sqrt{2 \cdot g \cdot (H_P + h_P)} - Q_{OP} \tag{4}$$

$$A_B \frac{dh_B}{dt} = Q_{IB} - Q_{OB} \tag{5}$$

The B tank which is processing the fresh water admission and the waste water evacuation is not employing the slow gravitational transfer.

This model is an adaptation of a greenhouse Three-tank Watergy configuration [11].

4 The Matlab-Simulink Implementation

The Matlab-Simulink implementation of the fish tank is shown in Figure 4.

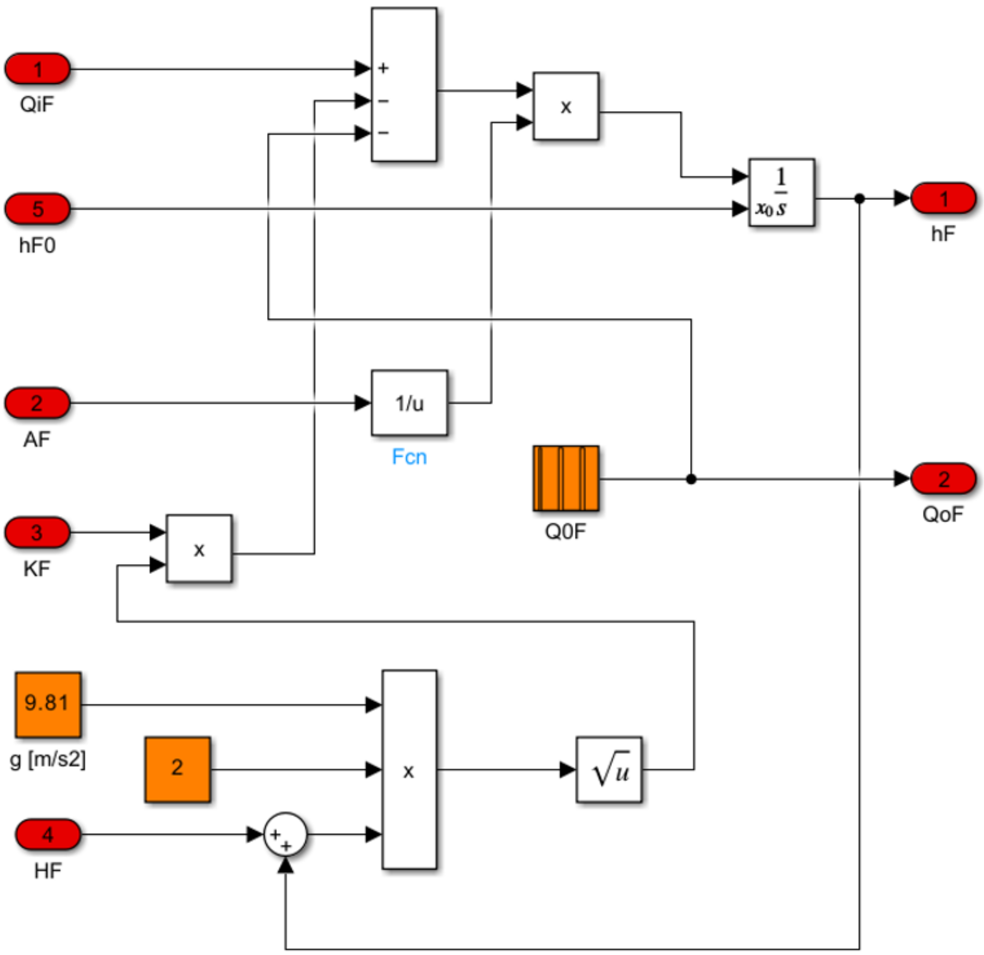


Figure 4: The Simulink model of the fish tank (Eq. 3)

The other tank models, P and B are very similar. The main window of the 3TAS model is shown in Figure 5.

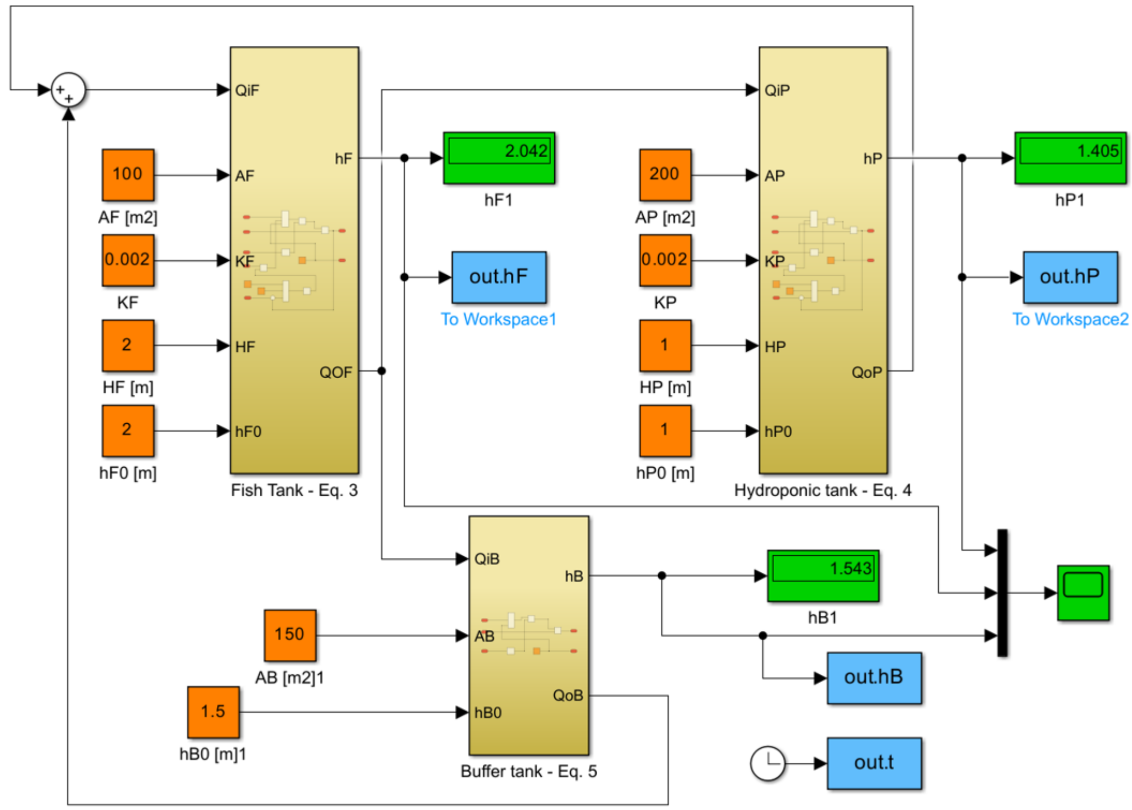


Figure 5: The main window of the Simulink 3TAS model

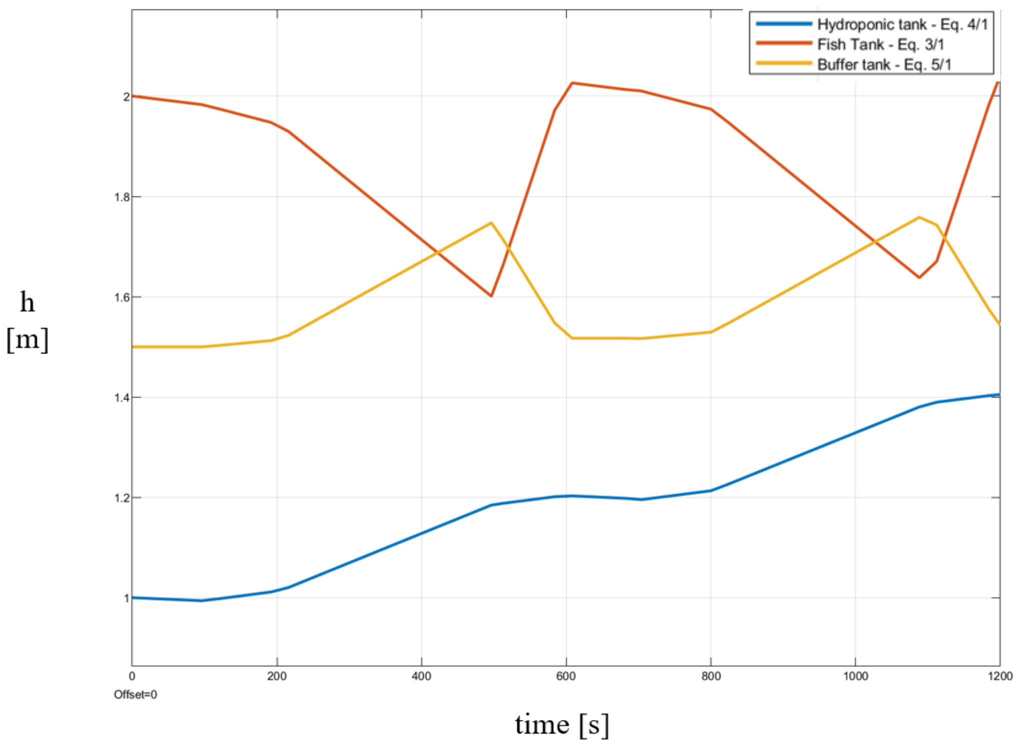


Figure 6: Simulation results

The Figure 6 simulation scenario has only the purpose to test the model in a random continuous-time configuration. The following connections are turned on:
- F→P and P→F which is ensuring the main purpose of AQ: the fish-plants symbiosis; normally the flows are equal, so h_F and h_P remain constant. In the Figure 6 simulation these flows have random

variations just to test the model.
- B→F is providing a small fresh water flow to F-P, to compensate loses.
- Other connections such as B→F, F→B or P→B are also possible.

5 On the Automate Control of the Aquaponic Systems

The AQ control could be mostly sequential, since there is no imperative need to overlap technological operations and precision is not critical in such environment control, unless we don't aim a very smooth operation, convenient for fish and plants. In such case the sequential control can be easily replaced by a fuzzy-interpolative controller implemented with look-up-tables with linear interpolation.

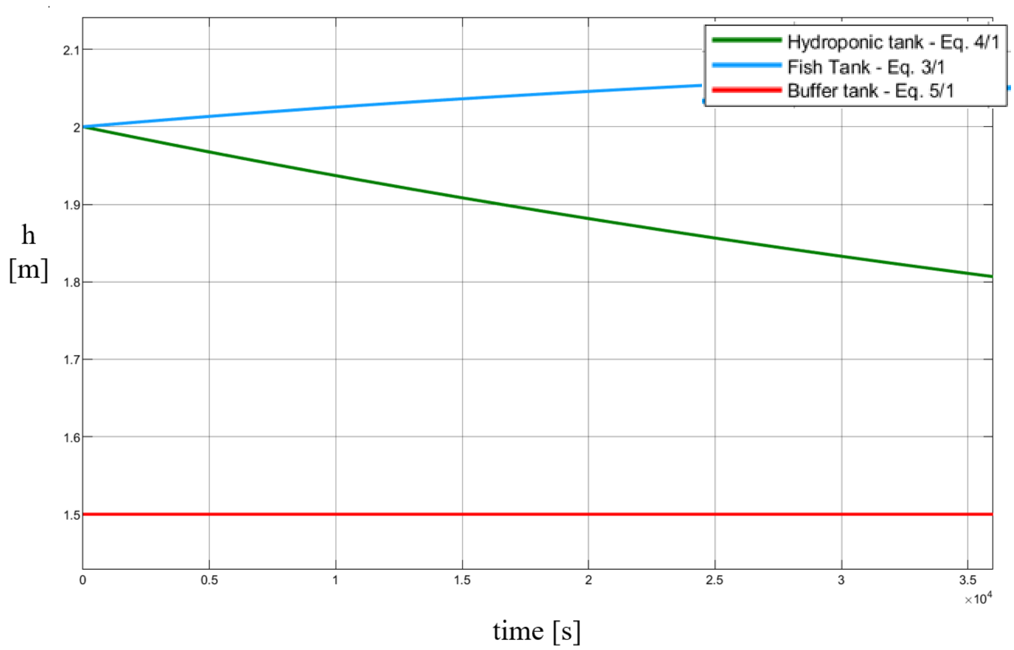
A step further would be the control optimization. Aiming for instance to maximize the carbon offset of the aquaponic farm is realistic, due to the high density of plants, and responds such way to the present days social and political demands [9, 15].

Recent research demonstrates the integration of IoT-type technologies that can facilitate the creation of systems that can monitor the conditions of the greenhouse environment and not only, being able to follow parameters in real time, offering valuable tools to precision agriculture [14].

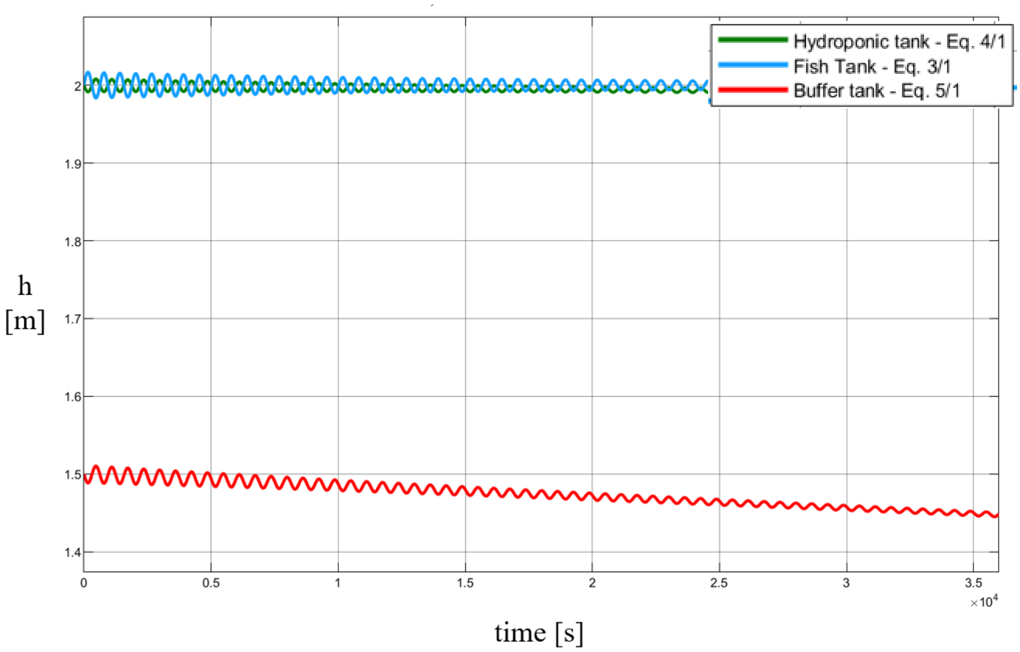
The conventional linear PID control is obviously not able to cope with the nonlinear Three Tank Systems. The authors' recommendation is the following: "Fuzzy regulators for output signals (after error adjustment) or for the state may satisfy these conditions, compared with other regulating solutions" [12].

Our team's experience in this kind of nonlinear systems is positive, thanks to the Fuzzy-Interpolative concept [3, 7] and preliminary tests perform on the 3TAS model are confirming it.

The following (see Figure 7) simulations illustrate only one of the numerous maneuvers necessary during the 3TAS operation: stabilizing the water levels in F and P tanks.



(a) The natural behavior



(b) Stabilized water levels by means of output flows controllers in tanks F and B

Figure 7: Stabilizing the water levels in F and P tanks

6 Conclusions

The paper is discussing a three tank aquaponic system configuration, involving a fish tank, a hydroponic tank for the plants and a buffer tank, positioned at different heights. A mathematical model implemented in Matlab-Simulink is provided and tested.

This model is intended to be used in further research on such system, for sizing and for testing automated control algorithms.

Funding

This work received partial support from the Petroleum–Gas University of Ploiesti, Romania.

Author contributions

The authors contributed equally to this work.

Conflict of interest

The authors declare no conflict of interest.

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Cite this paper as:
Alexuta, D.; Balas, V. E.; Balas, M. M. (2025). On the Three-Tank Aquaponic Configuration, *International Journal of Computers Communications & Control*, 20(2), 7032, 2025.
https://doi.org/10.15837/ijccc.2025.2.7032