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Development of an economic smart aquaponic system based on IoT

M.M.M. Mahmoud [a,*], Rania Darwish [a], A.M. Bassiuny [b]

[a] *Department of Mechanical Engineering, Helwan University Cairo, Egypt*
[b] *Dean Faculty of Engineering, Heliopolis University, (On leave from Faculty of Engineering, Helwan University), Cairo, Egypt*

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ABSTRACT

Aquaponics is a sustainable farming practice that combines aquaculture and hydroponics in a recirculating system. The nutrients from the fish waste are used by the plants to grow, and the plants filter the water for the fish. This process is self-sustaining and requires little human intervention. The monitoring and control of aquaponic systems is a complex task. In this research, the Internet of Things (IoT) is utilized to monitor and control the proposed system. In addition, a digital twin (DT) is deployed to digitize the physical system. The results explore that IoT and DT can improve aquaponic systems by collecting data about environmental conditions that is used to regulate plant growth, monitor fish health, optimize crop production, and optimize nutrient recycling. This decreased the need for and cost of human monitoring and improved the system's economics.

Introduction

Aquaponics is a method of cultivating plants and aquatic organisms in a symbiotic environment. This approach combines aquaculture and hydroponics and enables individuals to grow fresh and organic products without using harmful pesticides or fertilizers. In a typical aquaculture, fish waste builds up and makes the water more hazardous; however, in an aquaponic system, the fish waste is converted into nitrates, which are then used as plant nourishment. All living things require the element nitrogen to survive. An important source of nitrogen for the growth of plants is the ammonia nitrogen excreted by fish. The fish waste-carrying water is then pumped into the aquaculture system, where biological nitrification, denitrification, and plant absorption convert the nutrients into nitrate as shown in Fig. 1.

With the production of high-quality fish and vegetables coordinated with the recovery of waste that is very nitrogen- rich, aquaponics has a great deal of promise to become a sustainable technology [1]. Water, oxygen, light, food for aquatic animals, and electricity to pump, filter, and oxygenate the water are the system's five primary inputs. To maintain a steady system, spawn or fry may be added to replace grown fish that are removed. An aquaponics system can continuously produce edible aquatic species raised in aquaculture as well as plants like hydroponically grown vegetables. The issue with the aquaponics system is that it necessitates constant, daily monitoring, including fish feeding, making sure the water circulates from the aquarium to the growing aquarium and back, and controlling the temperature, pH, and pH level. System failure may result from the owner's carelessness and lack of supervision. Therefore, the absence of the Internet of Things (IoT) makes maintenance difficult because it is challenging to leave the system unattended for a long time. Any human would find it challenging to manage this vast task around the clock, seven days a week [2,3].

Literature review

Over the years, considerable research has been conducted on incorporating the Internet of Things into aquaponic systems. In a prior investigation [4], a monitoring system was outlined to observe water temperature, pH level, dissolved oxygen (DO), and various other parameters relevant to aquaponics. The system included sensors to gather data, which was subsequently transmitted to a cloud server and made accessible in real time through the internet network. Consequently, the system effectively maintained the quality and flow of the water, ensuring their preservation. A system was created by Abhay Dutta et al. Dutta et al., [5] to store databases, along with the establishment of a monitoring division. This division was responsible for monitoring the pH level, temperature, humidity, and water level of aquaponics systems. The collected information was then transmitted to a web server, where users could access the data in both JavaScript object notation format and graphical format. In their study, Daniela et al. (D. [6]) presented an aquaponics system that operates automatically and includes features such as continuous water withdrawal adjustment, monitoring of water temperature, pH level, and air temperature. To mitigate environmental

* Corresponding author.
E-mail addresses: Mohamed.Mahmoud.93@h-eng.helwan.edu.eg (M.M.M. Mahmoud), abdelhalim.bassiuny@hu.edu.eg (A.M. Bassiuny).

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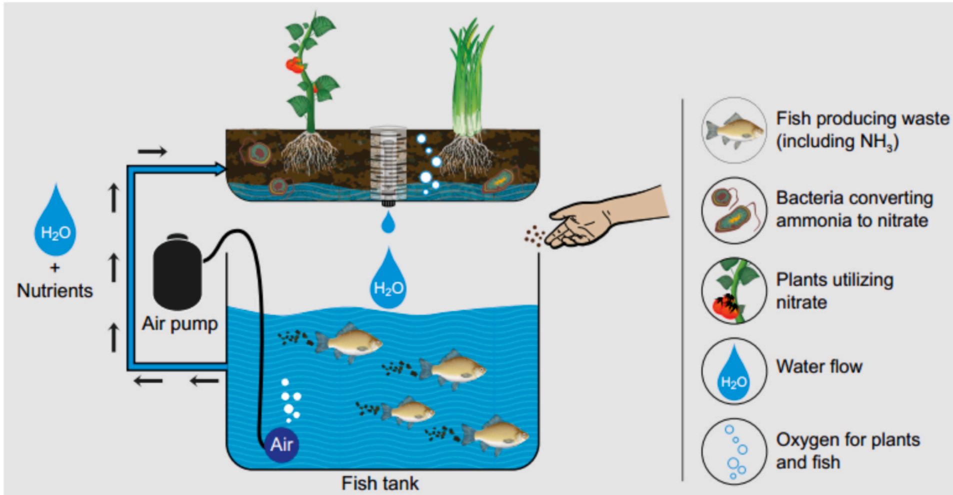

Fig. 1. Aquaponics life cycle.

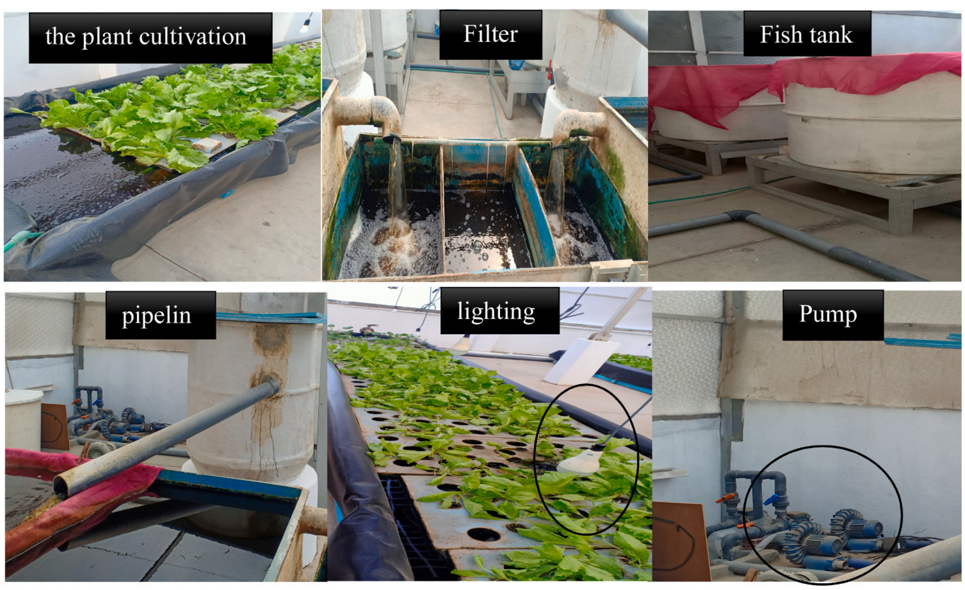

Fig. 2. The overall Aquaponic system.

pollution, the aquaponics greenhouse is also powered by a solar system. A system has been created by Adrian K. Pasha et al. Adrian, Pasha. [7] which enables the visualization of various parameters in a hydroponic system, including water temperature, pH level, and water level. Additionally, information regarding the water pump, lamp, fan, and bell is also displayed. The system presents this information in a tabular format on a web page, which can be accessed from different web browsers and various types of devices. The system has been designed to be user-friendly for monitoring and control purposes. However, there is potential for further development to expand the monitoring of additional parameters and control of more devices.

Have presented diverse approaches to monitor aquaponics systems through the utilization of the Internet of Things. However, an experienced operator is still required to observe the system readings and promptly respond to any malfunctions. Furthermore, the existing methods do not facilitate system control by the operator through the Internet of Things.

This paper aims to design an automated aquaponic system that uses IoT to turn on and off the lighting, water pump, air pump, and heater, as well as regulate the water pH level, plant temperature, and dissolved oxygen levels. Digital twin is deployed where real time data acquisition from physical entities are connected to simulate the representations. The developed system can help save time since the system can be supervised and controlled at home or in any location with the use of internet hydroponics and edible aquatic species raised in aquaculture. System implementation does not require the presence of an experienced worker, which leads to ease of operation and follow-up of the system.

Methodology

The major objective of the proposed system is to create an IoT-based aquaponics monitoring system that can monitor pH level, oxygen level, temperature, and other parameters using a variety of sensors and then display and upload the results to the operator. Furthermore, the proposed system processes data and autonomously changes fundamental variables like temperature, the amount of dissolved oxygen in the water, and pH levels using a few actuators. The system is controlled remotely by the operator via the IoT using a phone or computer. For the best growth and survival of the fish and plants in the aquarium, the water quality is continuously monitored. The proposed approach is

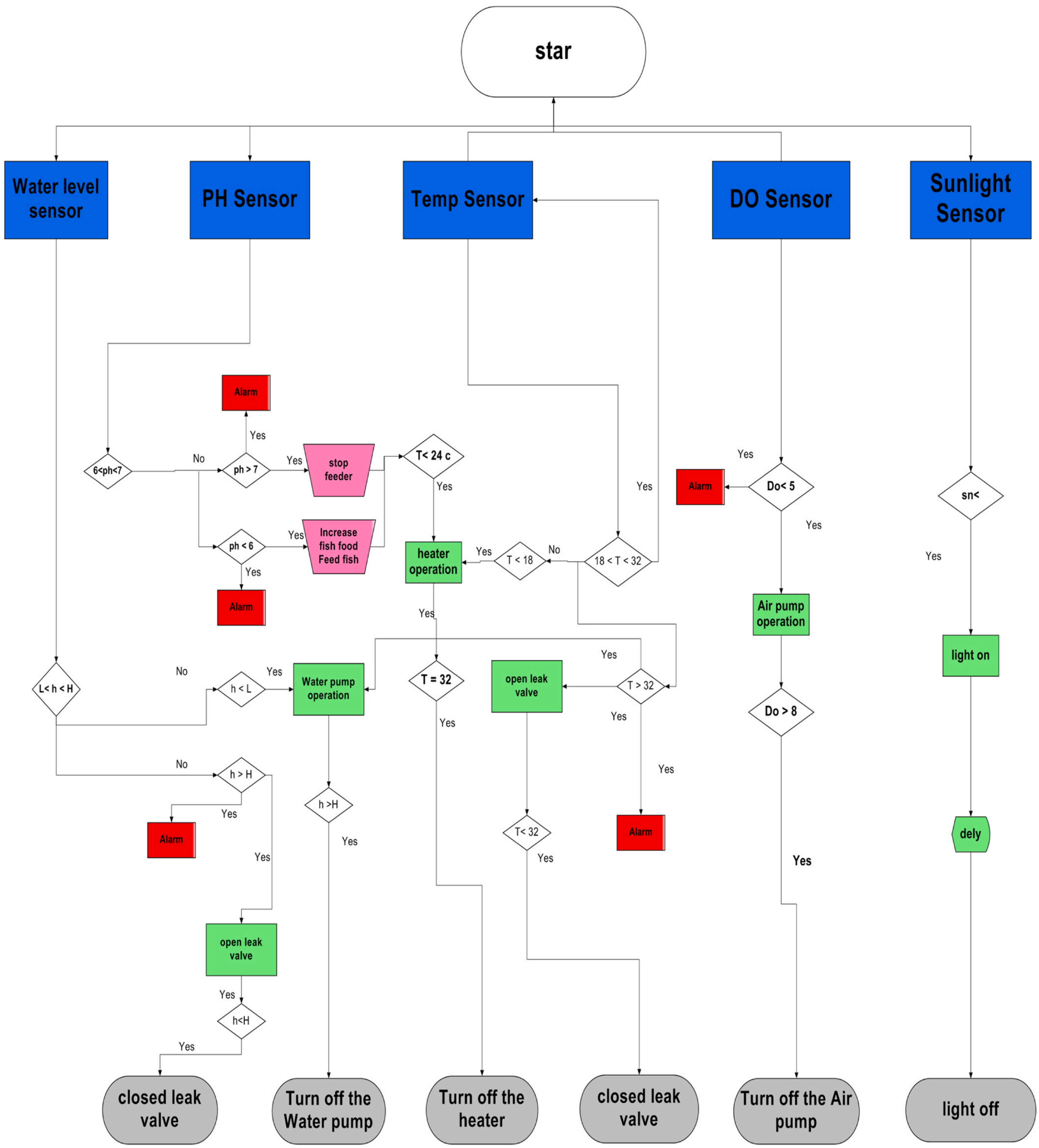

Fig. 3. Flow diagram of the system.

implemented on an actual aquaponic system installed at Heliopolis University. The system incorporates IoT as well as a digital twin of the aquaponic system.

Internet of Things

The IoT is comprised of several layer architectures, with the first layer being the perception layer. Its function is to gather information from the physical aquaponic system through sensors and upload it for processing and data analysis in subsequent layers. These layers are responsible for converting data into signals transmitted over the network and interpreted by the application layer, which then sends signals to the actuator's [8].

Technical system of IoT and digital twins for aquaponics

The system designed for the aquaponic system depicted in Fig. 2 is structured into three distinct sections. The first section, known as the

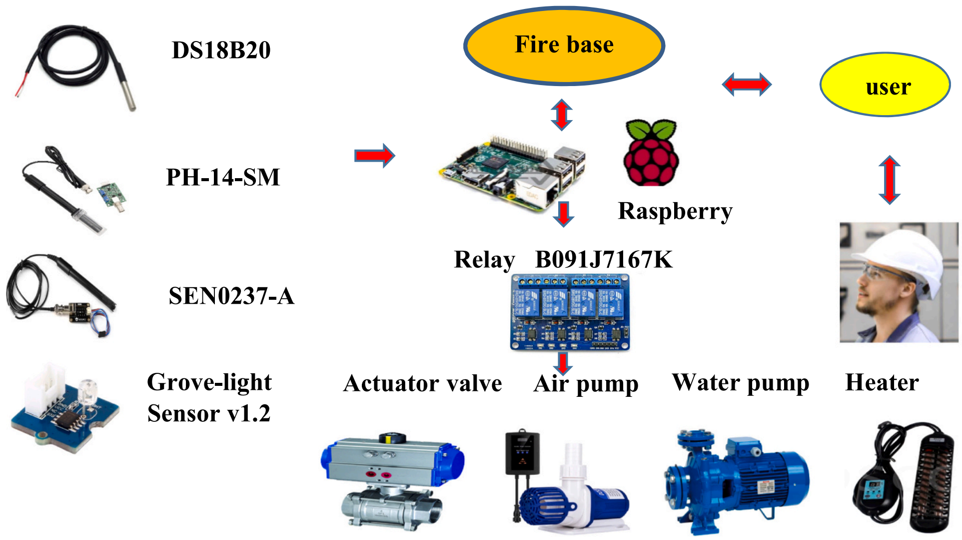

Fig. 4. System design.

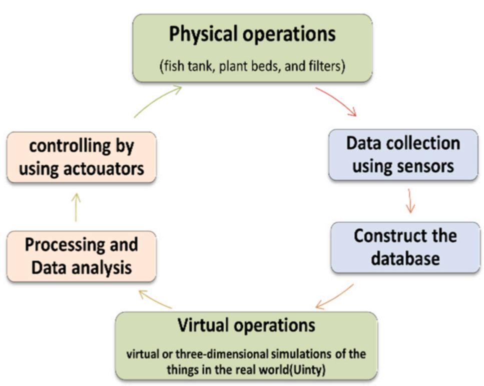

Fig. 5. Proposed foundation for digital twins.

realization layer, is responsible for collecting, calibrating, and processing the monitored data. This data includes various measurements, including water temperature captured by a temperature sensor, acidity levels monitored by a pH sensor, oxygen levels in the water detected by a dissolved oxygen sensor, and light intensity gauged by a light intensity sensor.

In the second section, the sensors readings are sent to the microprocessor, then checked and sent to the web. They are, then, linked to Unity, where the application begins and links the real system with the virtual system. This layer is responsible for processing the data and analyzing the sensor readings, and comparison with the ideal values. Then it is converted into actions that are sent to the application layer, which is responsible for translating these signals and sending them to the third section.

The third section, the actuators section, consists of various components such as the air pump, water pump, heater, and actuator valve. The process of analyzing data and sending instructions to these actuators is done offline using a Raspberry Pi. As a result, the system remains unaffected by any network interruptions. However, users can still control

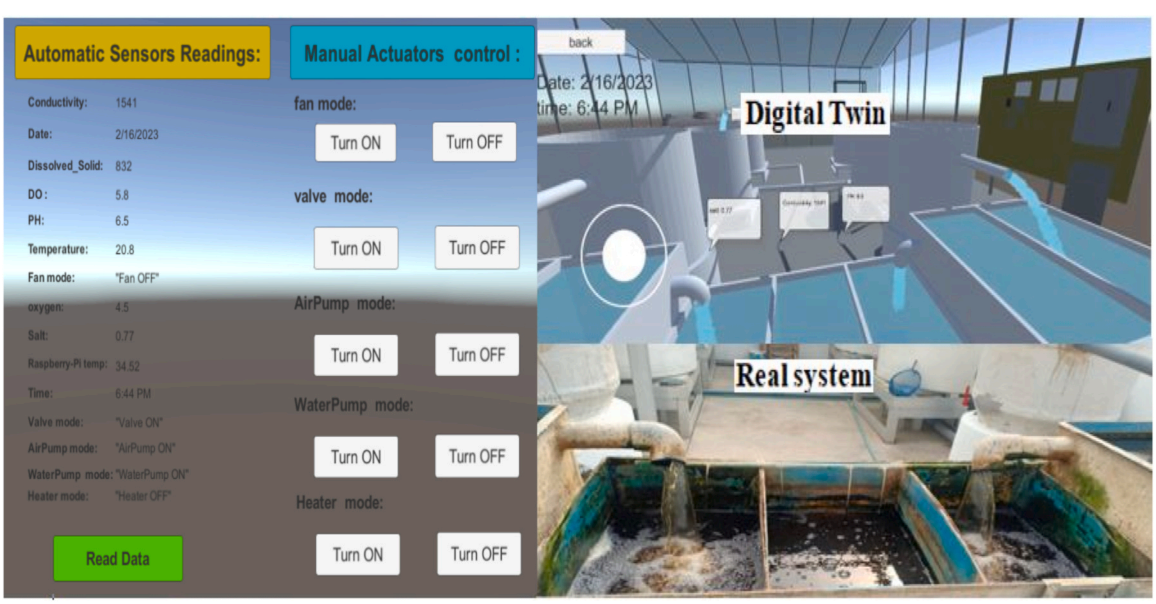

Fig. 6. Scene cam.

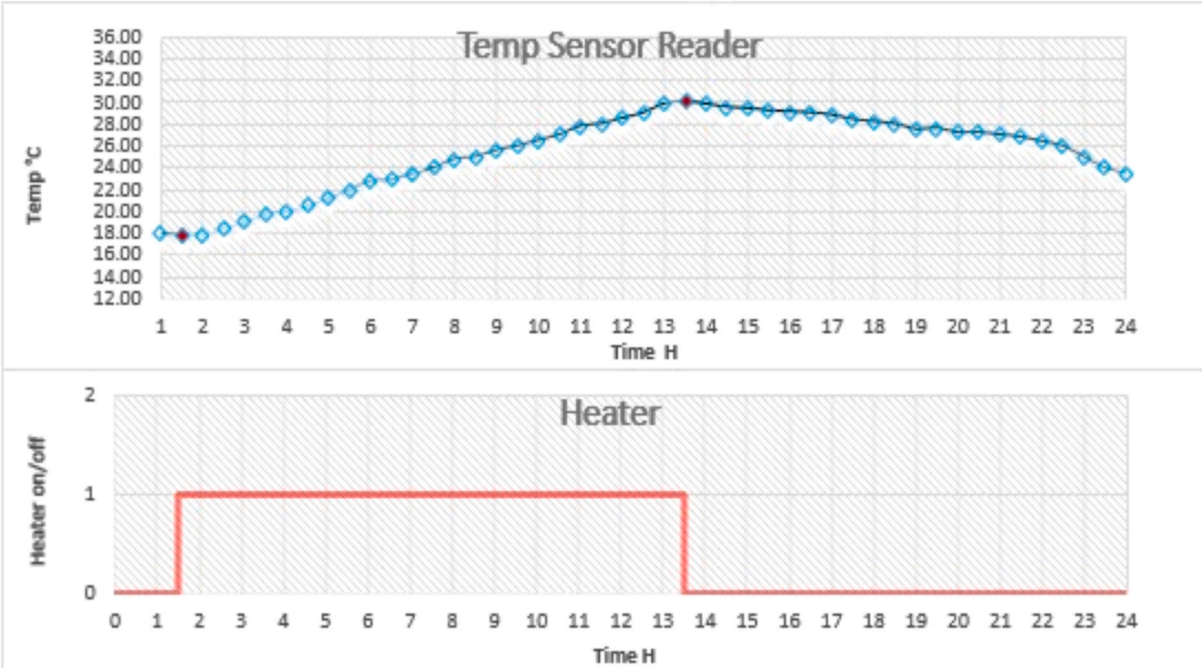

Fig. 7. Temp sensor Reader and Heater on/off.

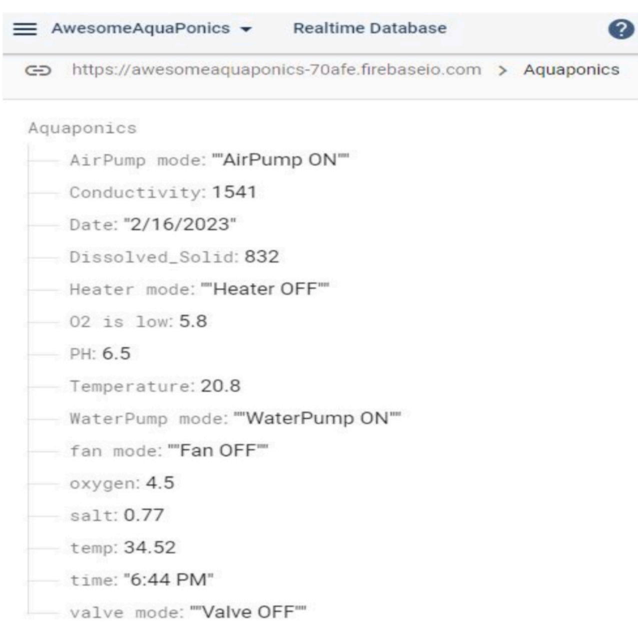

Fig. 8. Realtime database.

the pumps, monitor sensor readings, and access these functions online through an operator interface. This is made possible by connecting the Raspberry Pi to Unity via Firebase, thereby establishing a connection between the physical system and its virtual counterpart (Digital Twin).

Experimental setup

The aquaponics system used in this paper, Fig. 2, is composed of six primary parts. Firstly, there are circular fish tanks where fish are raised, mimicking their natural habitat. In the second part, there are filter tanks connected to the fish tanks by pipes. These filters remove solid waste from the water before it moves to the third component, which is the plant cultivation ponds. In these ponds, plants are cultivated without the use of soil.

The fourth component comprises various auxiliary devices essential to the system. This includes a water pump that supplies the aquaponic system with water and ensures the continuous flow of water. Additionally, an air pump is responsible for oxygenating the water, while a heater controls the water temperature. The fifth component consists of lighting units necessary for the growth of plants. Lastly, the sixth component consists of pipelines that link the different parts of the aquaponics system, facilitating the transfer of water between them. This arrangement is illustrated in Fig. 2.

Implementation

The system mechanism

The proposed system is designed using a logical flow diagram, Fig. 3, to ensure ideal conditions for the plants and fish in the aquaponics system. To effectively monitor and initialize the system, the system parameters must be carefully maintained. Once the system is initialized, the sensors begin their work and transmit the values from the system. These values are then processed according to specific conditions for plant and fish growth as stated by [9], and the resulting signals are sent to the actuators, as depicted in Fig. 3. Continuous monitoring of each system parameter generates real-time values displayed on the web server. If there is any inconsistency between the sensor ranges, the Internet of Things displays a warning message on the web server. If the data is within the expected range, the system remains unchanged. The water level sensor, for example, provides readings of the level inside the fish tank, which are compared to the tank levels set. If the water level is below the low level, the water pump operates to raise level to the desired value, Similarly, When the water level exceeds the maximum value, the system will send an alert and open the leakage valve to lower the water level. The pH sensor readings are also evaluated with the safe pH range for fish and plants is 6–7. Fish feeding will be stopped when the pH exceeds 7 and an alert will be generated to check if the water temperature is above 24 °C. When the temperature is below 24 °C, the heater is turned on, creating an ideal environment for the conversion of ammonia to nitrates, helping to lower the pH. On the other hand, if the pH drops

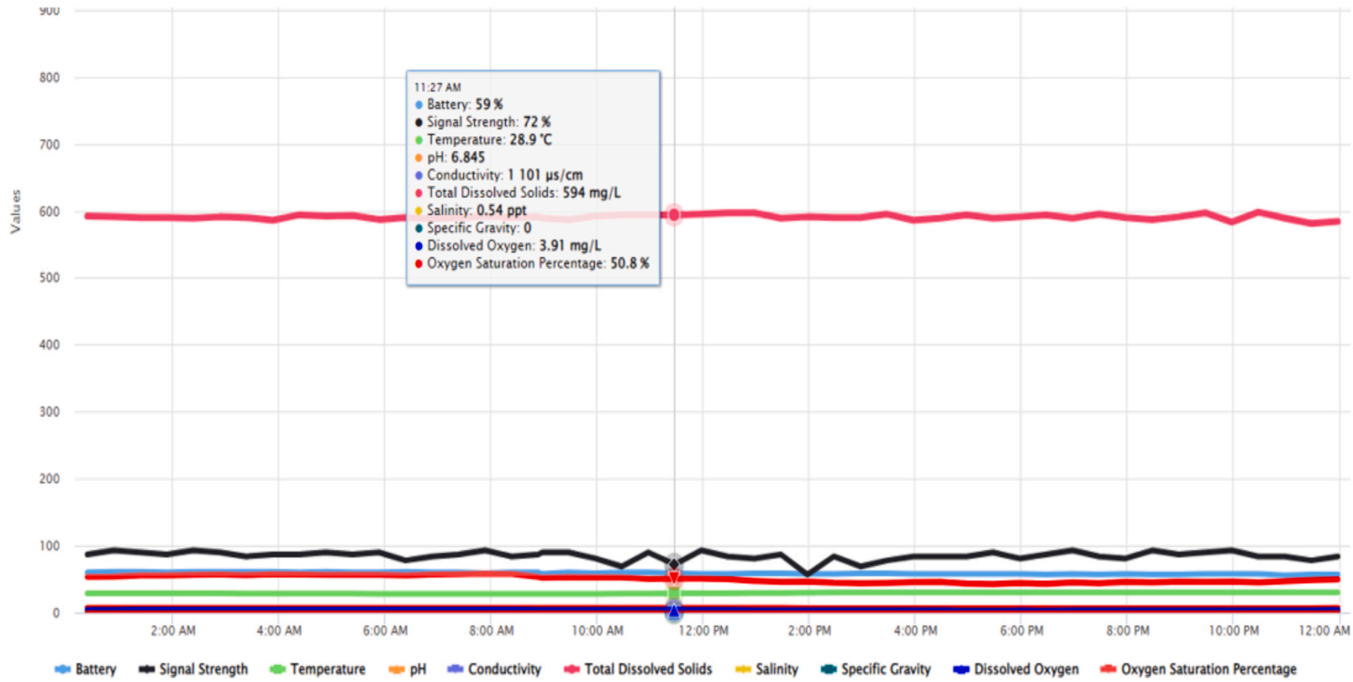

Fig. 9. Charts of data.

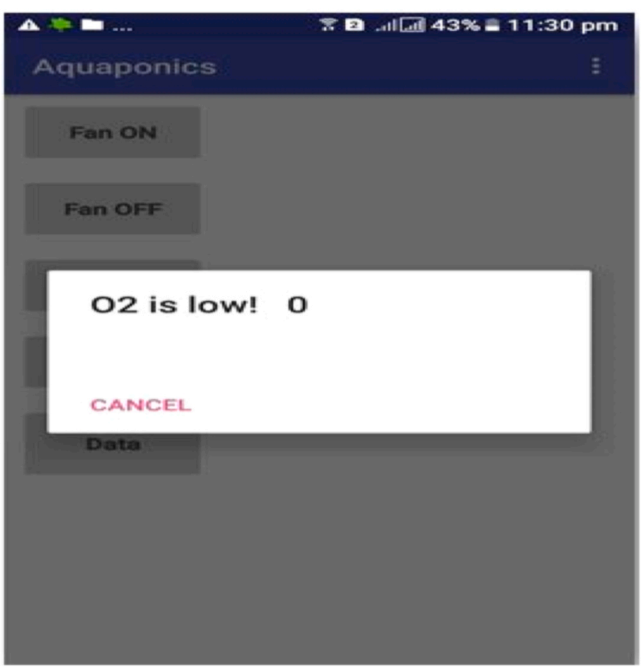

Fig. 10. Notification.

below 6, an alert will be sent, the fish will be fed more, and the temperature will be checked. If it is below 24 °C, the heater is turned on. To create an optimal environment for fish, the proportion of fish waste and ammonia production must be increased, which is subsequently converted into nitrates. The temperature sensor monitors the water temperature, with the ideal range being 18–32 °C. If the water temperature drops below 18 °C, the system activates the heater. Conversely, if it exceeds 32 °C, a warning message is triggered, and the water pump is activated while the leakage valve is opened to circulate water. Readings from dissolved oxygen sensors are analyzed and compared to the ideal range (5–8 mg/L) for aquaponics systems. If the dissolved oxygen concentration is below 5 mg/L, the air pump is activated until it reaches 8 mg/L, and then pump stops. The optimal reading range for sunlight sensors is 380–840 nanometers. If the readings fall below the plant's recommended growing time (8–12 h), the lighting system will activate to create an ideal environment for plant growth.

Design of the system

The Raspberry Pi was utilized to gather and process sensor readings and transmit signals to the actuator. The choice of Raspberry Pi was based on factors such as high speed, low power consumption, and the Wi-Fi feature, which enabled the implementation of IoT in the system [10]. By utilizing the Raspberry Pi's Wi-Fi, the system was connected to the web, where a data server stored the system parameter values, including pH, temperature, dissolved oxygen, and light intensity, in a database. The information was then submitted to the web server, where the user could access it in both JavaScript Object Notation format and graphic format. The Aquaponics monitoring system's IoT application allowed for the continuous display of system parameter values and information on the web server. To connect to the actuator systems, the Raspberry Pi was equipped with pluggable sensors, including the DS18B20 temperature sensor, PH0–14-SM pH sensor, SEN0237-A dissolved oxygen sensor, Grove-light sensor V1.2 light intensity sensor, and B091J7167K relay for the water pump, air pump, actuator valve, and lighting, as depicted in Fig. 4.

Results and discussion

Structure for digital twinning

This work proposes a digital twin approach that can be applied to aquaponics systems. The twinning method is based on the correlation between real and virtual environments, where identical events occur in both. The paper outlines essential concepts and procedures for a digital twin, as shown in Fig. 5.

Parameters that describe the type of data and information exchanged between real and virtual environments are also critical components of a digital twin system. Aquaponics systems have predefined parameters

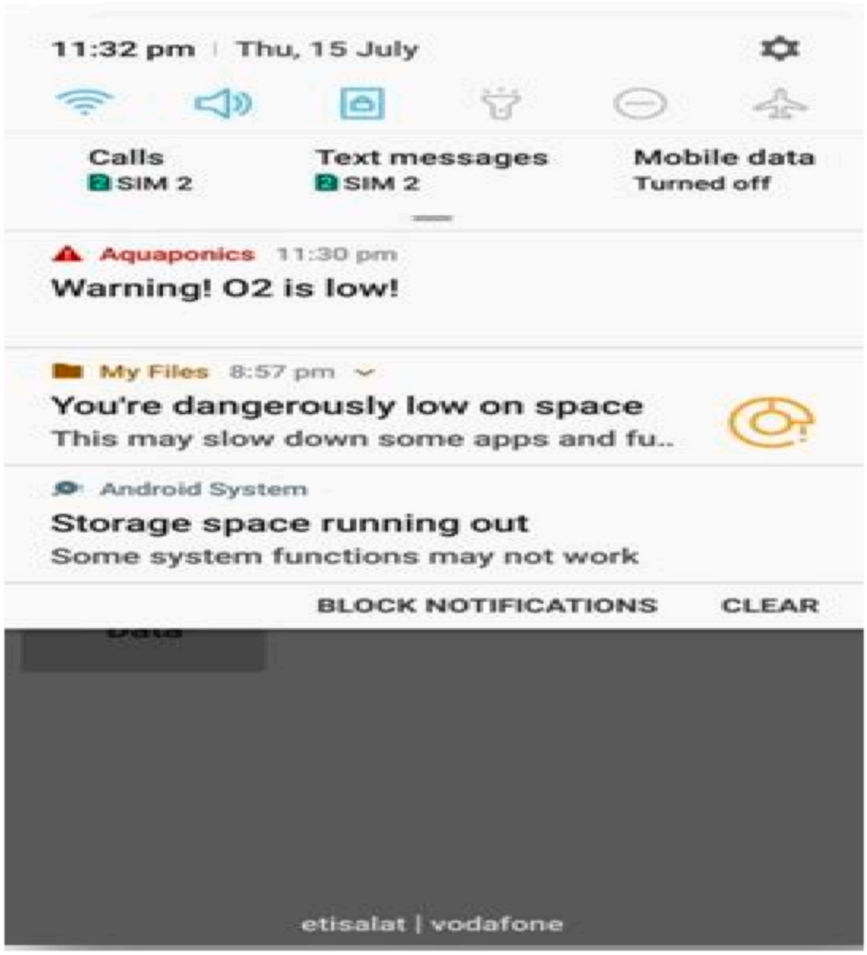

Fig. 11. Notification.

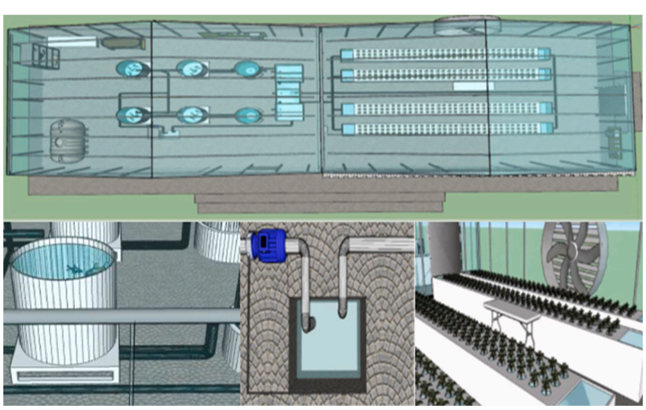

Fig. 12. Unity to simulate aquaponics system.

covering all elements such as pH, water and air temperatures, water level, dissolved oxygen, total ammonia-nitrogen, and light intensity. In some cases, the inclusion of additional dependent characteristics such as fish size, plant growth, and residual resources as parameters can enable more comprehensive system monitoring. The physical-to-virtual and virtual-to-physical connections are the other two vital elements of a digital twin. The primary difference between digital twins and other virtualization techniques, such as simulation models, is the communication and virtualization process, or the physical-to-virtual link, which transfers the status of a physical item or environment to virtual parameters such as interfaces, graphs, databases, and other elements [11].

Structure of aquaponics digital twinning

In the aquaponics system, physical elements such as growing areas or fishponds are considered physical entities, and their virtual representations are called virtual entities. In the paper, Unity Software is used to construct virtual entities of the aquaponic system described. The Unity game engine finds its application in the development of digital twins in some applications, such that in [12]. Both the physical and virtual environments include all physical elements and their corresponding virtual processes. The physical environment includes physical things such as heaters, pumps, valves, and sensors, in addition to the previously mentioned physical items. The virtual environment is provided with interfaces, buttons, alerts, graphs, tables, and other elements that create a virtual dashboard or interface that simulates the actual environment, as shown in Fig. 6.

This environment provides a visual representation of the actual and virtual settings used in this investigation. In this step, which relates to the process of digital twinning and the mechanisms for sending and receiving information, the fidelity of the information and the twinning rate are determined using four sensors that monitor the system's current state: pH, water temperature, dissolved oxygen, and light intensity. The IoT sensor module processes sensor readings and wirelessly transmits the information to the Raspberry Pi via a digital access point. The main controller stores and synchronizes data in a NoSQL cloud database, allowing real-time data synchronization across all clients. App is offline.

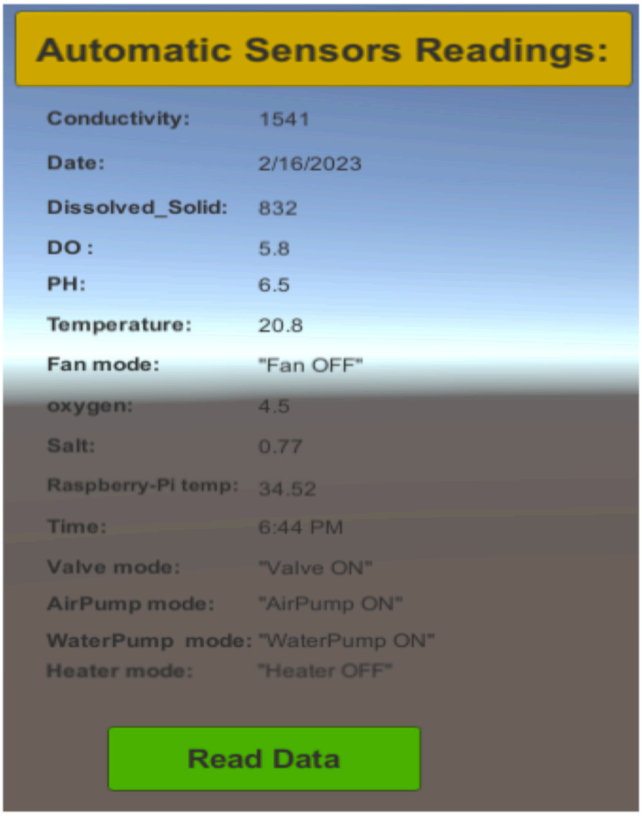

Fig. 13. Automatic sensors Readings through Unity.

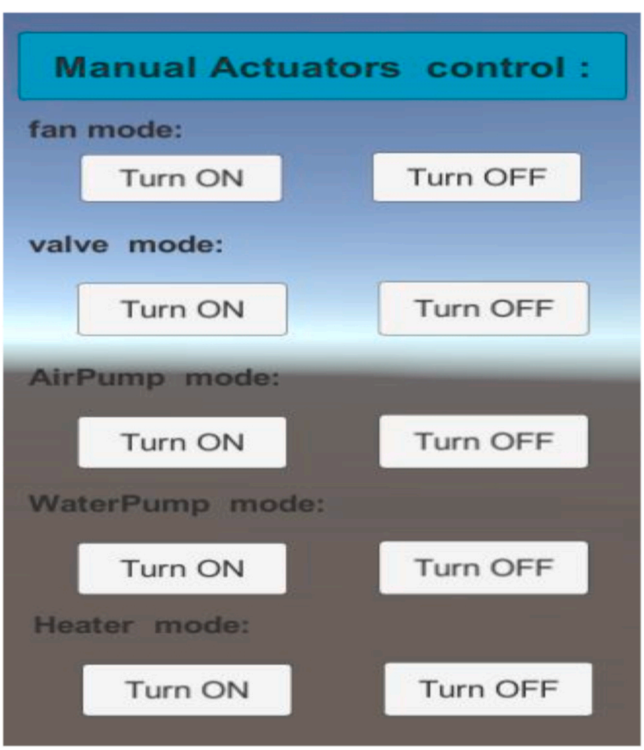

Fig. 14. Manual Actuators control through Unity.

The Firebase Realtime Database is a cloud-hosted database that stores data in JSON format and syncs it in real time with all connected clients. When building cross-platform apps with the iOS, Android, and

Table 1
The comparison between traditional and smart aquaponic systems.

Statement	Traditional control Aquaponic systems.	Smart Aquaponic systems.
Component	A set of sensors such as PH sensor, Temp sensor, DO sensor, and a set of pumps and actuators. Set of relay and timer	A set of sensors such as PH sensor, Temp sensor, DO sensor, a set of pumps and actuators. And The Raspberry pi
Data Acquisition	DO, water T, and pH	DO, water T, light, and pH
Control method	The group of actuators is used continuously using a timer and depends on the experience of the operator with the system	Each actuator is operated according to the system's need and does not depend on the operator's experience in operating this by processing and analyzing the data sent from the sensors and then sending the signals to the actuators through the Raspberry Pi
Effect	More electrical energy is used because of the continuous use of pumps by timers.	It increases the chances of system stability and removes the human element in monitoring and decision making. The aquaponic system is self-sustainable, cost effective, and environmentally friendly. Increased efficiency, automatic control, and high management accuracy
Advantages/ Disadvantages	reduced efficiency, inevitable mistakes, and increased monitoring costs.	Store data in the cloud and analyze it using smart technology. Continuous autonomous monitoring.
Cost	Higher cost due to continuous visual monitoring of the system	Lower cost due to replacing human monitoring with a microcontroller (Raspberry Pi) that stabilizes the system and allows continuous monitoring of the system through the Internet of Things and sending warnings

JavaScript SDKs, all clients share a real-time database instance and automatically receive updates with the latest data. The main component used by Firebase is the Realtime database, and Cloud Firestore allows you to store, sync, and query your app data at global scale. Therefore, real-time databases were used in both MIT APP and Unity.

Feedback control

The self-tuning principle of the aquaponics system is demonstrated by instructing the interface to enable or disable system actuators such as heaters, pumps, valves, and lights via the IoT Core module in Visual Studio. These instructions are sent to the Raspberry Pi, which activates or deactivates the relay. To test the virtual-to-physical connection and validate communication, an order to turn on the heater is sent after detecting 'Temp' values outside the set limits. The system is designed to maintain a favorable environment for the growth of plants and fish. Fig. 7 shows that the device automatically activates the heater when the water temperature falls below 18 degrees Celsius until it reaches 24 degrees Celsius, the ideal temperature for both plant and fish growth. Control mechanisms in aquaponics settings should be designed to adjust parameter values as quickly as possible to minimize adverse effects on fish and plant growth. Depending on the parameter chosen, differences in temporal response may be critical to maintaining a healthy environment. This example is an ideal method for regulating temperature in the aquaponic system and provides a clear interface for testing and optimizing controls, either by directly accessing physical systems or by building a simulated environment using database entries as a base.

Web scraping

The process of web scraping and data access leads to a hierarchical structure of data that is stored in both a real-time database and cloud Firestore, as illustrated in Fig. 8 and Fig. 9, respectively [13].

MIT APP

The app is designed to send notifications to alert users to any errors that may arise, such as low dissolved oxygen levels or low temperatures, as illustrated in Fig. 10 and Fig. 11. Patton et al., [14].

The computer software unity

The design of an aquaponics system consists of three basic components, some of which are repeated: the fish tank, the plant bed, and the filter. The design process is performed using the SolidWorks application, and the assembly file is converted to an Fbx file, a file format that can be treated as a design, as shown in Fig. 12.

The data obtained from sensors on the Raspberry Pi are matched with the data from the virtual system. The sensor readings are sent to the Firebase website, which is then linked to the Unity program. As a result, the virtual system now contains the same data as the real system in key areas such as water temperature, pH, dissolved oxygen, water level, and light intensity, as depicted in Fig. 13. The operational status of the air pump, water pump, heater, fans, and leakage valve are also displayed. All actuators were connected to the Raspberry Pi and linked to the Firebase website. They are subsequently connected to the Unity website. Buttons are created for each actuator (air pump, water pump, heater, fans, and leakage valve) on the Unity website. This enables users to open and close them. The command is then sent to the Firebase website and subsequently to the Raspberry Pi, resulting in the actuators being turned.

on or off, as shown in Fig. 14.

Traditional versus smart aquaponic systems

Aquaponics can be made more sustainable and precise by utilizing modern technologies like the Internet of Things for monitoring and control. When smart technologies are integrated into aquaculture systems, benefits include lower production times, decreased labor requirements, better product quality, and increased sustainability. In general, the primary goal is to create an intelligent and self-regulating aquaponics system. Such a system is capable of monitoring critical parameters in real time (such as pH, dissolved oxygen, temperature, light, etc.) automated [15]. Table 1 summarizes the differences of the two levels of control employed in traditional control and smart aquaponic systems. The table illustrates the evolution of the aquaponics system from early manual monitoring to the building of a smart system that employs automatic control and IoT.

Conclusion

This paper presents a novel IoT-based system which is designed to address the problem and deliver solutions in an intelligent manner while preserving process integrity under the supervision of the controller. There are several benefits to be achieved with the use of the Internet of Things for monitoring and controlling aquaponics, such as an integrated framework that can be expanded to optimize the system's functional capabilities or ensure precise performance indicators to encourage the commercialization of this technology. The proposed system has several benefits. By utilizing cloud storage and creating a database for the aquaponics system, it can help with management decisions to optimize growth inputs and conserve resources such as water and nutrients in the future. The system can also simplify operation and monitoring, which would improve the productivity of plant and fish farming. Additionally, the use of the proposed digital twin could allow for wider adoption of aquaponic technology as it requires less operator expertise. Moreover, it is essential to promote the expansion of these initiatives as they have a significant impact on water consumption, which is a timely issue in the world. The implementation of this proposed system could save about 70% of human costs, potentially leading to monthly cost savings of up to EG 12000.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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