IoT for Aquaculture 4.0

Smart and easy-to-deploy real-time water monitoring with IoT

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***Abstract*—While aquaculture and IoT have exponentially grown in the world in the last years, the combination of both domains still remains at its early stage. Although water monitoring is at the center of the aquaculture activity, its complexity can often push fish farmers to neglect it. We believe that developing user-friendly IoT tools for fish farming will lead to a new era of connected, responsible and efficient aquaculture. IoT for aquaculture needs to be smart, affordable, easy to deploy, reliable and highly efficient. Artificial Intelligence processing key data given by IoT can also provide new services addressing new challenges facing aquaculture (e.g be efficient but green). In this paper we describe results from European research projects that build the foundation of a new aquaculture 4.0.**

***Index Terms*—Aquaculture, IoT, water monitoring, smart systems, sensors, IMTA**

I. INTRODUCTION

A. The world-wide development of aquaculture

In 2014, the world fish supply reached 16.2 million tons, which represent 20kg of fish per person [1]. It reached a new record, mostly due to the tremendous growth of aquaculture, which provides now almost half of the fish stock (73.8 million tons in 2014), while capture production is saturating since 1990. Experts all agree that aquaculture will contribute significantly in the future to food security and adequate nutrition for a global population expected to reach 9.7 billion by 2050.

In a recent study [2], authors investigated the feasibility of sustaining current and increased per capita fish consumption rates in 2050 based on extensive data: predictions of changes in global and regional climate, marine ecosystem and fisheries production estimates, human population estimates, fishmeal and oil price estimations and projections of the technological development in aquaculture technology. They conclude that meeting current and larger consumption rates is feasible, despite a growing population and the impacts of climate change on potential fisheries production. However, it is possible only if fish resources are managed sustainably and fisheries management are effective.

The fisheries management relies totally on the water quality monitoring. Fish diseases are very frequent and impact directly the harvesting yield [3]. A low water quality can also impact the fish growth and delay the harvest. Today, the water monitoring systems are very expensive and lack of sensitivity. Implementing and maintaining this kind of system is resources consuming. A lot of small producer choose not to use it and take the risk to get a smaller yield. That is why water quality is the key to success in aquaculture and improve water quality is a big challenge, especially in small fish farms in developing countries.

B. The importance of the water quality monitoring

The fisheries management relies totally on the water quality monitoring. Fish diseases are very frequent and impact directly the harvesting yield [3]. A low water quality can also impact the fish growth and delay the harvest. The optimum fish production is totally dependent on the physical, chemical and biological qualities of water [4], no matter the type of facility. Therefore, water quality is the key to succeed a good fishery management. It is determined by variables such as temperature, turbidity, carbon dioxide, pH, alkalinity, ammonia, nitrite, nitrate, etc. Amongst them, the most critical are temperature, dissolved oxygen and pH.

Optimum temperature is dependent of the fish species, but as fish are cold blooded animals, it is vital that the temperature is controlled and maintained in the correct range. And even in the correct range, higher temperature increases the rate of bio-chemical activity of the microbiota and so increase the oxygen demand. To limit disease and oxygen consumption, temperature has to be finely regulated.

Optimum dissolved oxygen should always be above 5 ppm. Fish needs enough oxygen in the water to survive, otherwise they stay at the surface to catch up more oxygen, have slower metabolism and grow slower, and ultimately can die of lack of oxygen. It is even a bigger problem for aquatic organism to obtain sufficient oxygen than for terrestrial ones, due to low solubility of oxygen in water.

Optimum pH for fish life is between 7 and 8.5, ideal for biological productivity, otherwise fishes can become stressed in water, again slowing down their growth.

Many other parameters may be also monitored, but they generally directly influence the 3 main parameters mentioned above. Monitoring and controlling these parameters are therefore the basis for a good water quality. In addition, real-time monitor will provide faster reaction time.

C. The need of IoT for a new aquaculture

IoT has already proven its tremendous amount of applications domains in the last years. However, little are the fish farms today equipped with intelligent devices with real-time and connected water monitoring capabilities. There are many examples where IoT could help aquaculturalists to improve their working conditions. For example, some fish farms are far away from the land and using IoT to monitor water at a distance could reduce their costs. Another example is that changes in water quality can happen very quickly and at any time, so monitoring water in real-time with alerts can help to not miss any particular event.

The term Aquaculture 4.0 was introduced by European Commission in a late 2017 H2020 innovation action call[1]. It refers to 4.0 industry, that includes Internet of Things, cloud computing and data exchange. A 4.0 Aquaculture refers though to a connected aquaculture, using connected objects that are sending and analysing data in real time with cloud computing processes. Thus, with the help of IoT, we believe that a new Aquaculture 4.0 is possible. However, those progress are dependant of several aspects that need to be reinforced:

- *High performance and low-cost sensors*: sensitive water sensors can be very expensive and are often difficult to connect to the IoT world. In section II we present a new connected sensor technology based on carbon nanotube that is highly sensitive and 50 times less expensive than the current technologies.
- *Affordable and easy-to-deploy technology*: Connected solutions for real-time water monitoring in aquaculture are very expensive and complex. In section III we describe a specific use case in Ghana where we deployed very cheap and efficient solution to monitor water quality in a fish farm.
- *Smart systems for smarter aquaculture*: if the systems are smart enough (e.g big data technology at the edge, low energy, LoRa network), they could help the fish farmers to make better decisions. This is what we describe in section IV with a new project on Integrated Multi Trophic Aquaculture (IMTA) with lower environmental impact.

II. High performance and low-cost sensors

Real time sensors for aquaculture are used in both freshwater and sea water. Generally, sensors are used to monitor critical environmental parameters such as dissolved oxygen, temperature and pH. They are also used to measure nutrient levels and the build-up of wastes such as ammonia (NH_4^+) and carbon dioxide (CO_2). Such sensors are particularly vital in systems where water is recirculated and where stocking levels are high. To be of most use such sensors are often linked to alarms triggered when parameters such as dissolved oxygen or temperature are measured outside of safe limits. Oxygen sensors can be linked to oxygen or aeration banks to supply supplementary oxygen when needed.

There are a range of environments where sensors are required. In hatcheries or facilities for production of juveniles sensors are deployed within ponds or tanks within buildings. There is usually access to mains electricity, so power is not an issue. The facilities are also weather-proof and easily accessed for servicing and maintenance. At the other end of the range sensors are deployed on floating structures such as net pens or feed barges at sea and on freshwater lakes and ponds. Here they are exposed to weather and tough environmental conditions. In addition there may not be direct access to mains power. In such locations the power consumption of the sensors and of the communication system to relay the data can be a major issue.

In most environments where sensors are deployed there is a potential for fouling of the instruments by both detritus and biofouling organisms. Therefore in all cases the robustness of the sensor and its ability to withstand fouling is a major consideration. Self-cleaning or fouling resistant instruments will have a major advantage followed by those which have a simple and low frequency preventative maintenance programme.

The key considerations for aquaculturalists when considering sensors are as follows:

- *Reliability & Accuracy*: this is especially true where measuring critical environmental parameters such as dissolved oxygen.
- *Cost*: aquaculture is a food production industry often operating on tight margins and expenditure of automated equipment needs to have a proven cost-benefit before it will be availed of.
- *Maintenance schedules and costs*: this has proven to be a major issue with many systems, from feeding systems to sensors and water purification/filtering. New equipment will need to prove itself in terms of length of life and maintenance costs.

PROTEUS [5], an H2020 funded European project, has developed an innovative sensor to respond to this key considerations. It is highly sensitive and specific, thus accuracy and reliability can be mastered. The cost is up to 50 times less than classical water monitoring system. Lifetime of the sensor will be up to 2 years with 24/7 operation and real-time communication, thus reducing the maintenance costs. Moreover, the re-calibration frequency will not be higher than twice a year. Carbon nanotubes based chemical sensors have been widely studied for their high sensitivity and the large range of detectable analytes. Their main drawback is the lack of selectivity, because carbon nanotubes respond similarly to a wide range of different analytes. To counter this, functionalization of the carbon nanotubes is the classical approach: the functionalization is tuned to the target analyte, while the carbon nanotubes themselves act as highly sensitive transducers.

[1] http://ec.europa.eu/research/participants/portal/desktop/en/opportunities/h2020/topics/dt-bg-04-2018-2019.html#fn1

A patented chemical sensing strategy has been developed with PROTEUS consortium, where new functionalization molecules can be easily proposed for any given analytes based on a conjugated polymer backbone. When associated with carbon nanotubes, the result is a wide range of highly sensitive and highly selective chemical sensors.

This approach was tested along the course of the H2020 PROTEUS project on drink water quality monitoring: ohmic sensors based on percolating networks of functionalized carbon nanotube were elaborated by ink-jet printing. Using ink-jet printing yields strong process stability in an easily upscalable approach. The resulting devices showed sensitivity and selectivity to pH as well as chloride and hypochlorite ion concentrations, validating the global approach.

In addition, the devices PROTEUS proposes respond to all criteria in terms of low cost, possibility of multiplexing as well as compatibility with various technological processes (for cointegration). Such sensors work under low-operating voltages (a few volts), they can be made at low-temperature processing (and especially low-cost processing techniques such as printing), and they have a good mechanical flexibility.

The current limitation to the technology is the sensitivity of the devices, limited to a few dozens of ppb level by the ohmic transduction scheme. But the sea water use case is much more demanding in terms of sensitivity. To meet this challenge, a direct follow-up of PROTEUS work will consist in exploiting architectures based on functionalized carbon nanotube field effect transistors as an alternative to ohmic sensors. It has been recently shown that field-effect transistor-based sensors provide highly sensitive detection with stability in the marine environment. The sensitivity is notably enough for the detection of heavy metals at a micromolar concentration [6]. Based on this approach, one would expect to achieve precision of ±0.01 pH unit between pH 7 and pH 9, at temperature ranging from -5°C to 30°C.

First results of the PROTEUS chemical sensor development, shows a specificity to 5 species (pH, Chlorine, Chloride, nitrates and calcium) with 85% yield. Biofouling being a major issue for sensors in seawater, biofouling assays also showed good result on the sensor. First deployment in a pipe showed a good capacity of the sensor to reduce noise and extract the correct information.

In conclusion, using a carbon nanotube approach, the answer of PROTEUS to the water monitoring needs is a multi-parameter sensor chip for in-situ measurement with:

- Lower sensor cost, that could be reduced even further by a factor of 50
- Heavy multiplexed chemical measurements (4 different analytes in parallel validated today, over 12 possible over a only 1cm2 chip)
- Potential for considerably higher sensitivity (via a transistor approach to be validated)
- Potential for biological measurement (in the development roadmap)

III. Affordable and Easy to Deploy Technology

On February 1st 2016, a 3-years EU project called WAZIUP [7] was funded under the EU H2020 programme within the specific topic of cooperation between EU and sub-Saharan countries. WAZIUP is a collaborative research project using cutting edge technological research applications on IoT and related big data management and advanced analytic issues. It aims to provide ICT solutions, (at the lowest price possible, low energy consumption and long-range communication), corresponding to real African rural or urban use cases in order to allow them to reproduce them in a do-it-yourself philosophy.

Amongst all the project’s use cases, one of them is to help fish farmers to improve their yield of fish production. A low-cost water-monitoring system (500€) has therefore been developed and deployed in fish ponds in Ghana to measure the water quality and give some first advices to the farmers.

Data was sent from the sensors to the gateway and then to the WAZIUP platform for the first time on January 30th, 2017. It worked for 10 days until the first power outage happened. The gateway stores data in case of power lost, so when the power is back, all the stored data will be pushed on the platform, preserving the initial timestamps.

Despite the technical issues, we were able to learn about the general behaviour of the sensors and about their maintenance needs in this first version of the prototype. We also learned about the state of the water of the pond. We took a sample of 10 days from the database, where all the sensors were working correctly, to analyse the water parameters. Even with this short analysis period, we were able to retrieve valuable information about the quality of the water in this particular farm. The results will be summarized and recommendation will be provided to the farmers.

Figure 1 shows all the measured parameters with the deployed prototype. We can see that values are cyclic with clear night and day differences. This is an expected behaviour as sunlight directly affects temperature, dissolved oxygen level and pH level. It also shows that all the parameters are correlated and sometimes, acting on one parameters can affect the others. For example, too high water temperature can lead to saturated oxygen level and sunny afternoons can increase the water pH.

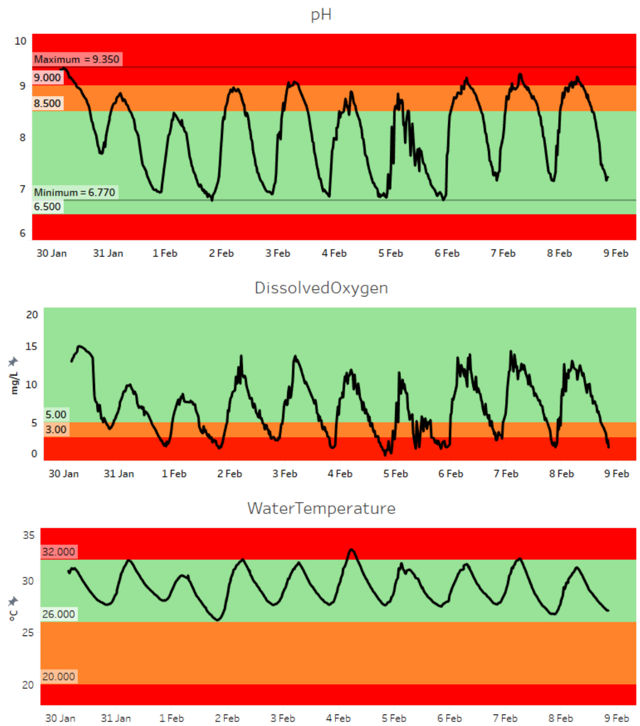

Fig. 1. All parameters on 10 days period in beginning of February 2017

A. Water pH

In Fig. 1, we can see the pH value in the water in early February 2017. The first noticeable feature is that pH variation is cyclical within a day. pH falls at night and reaches its minimum in the morning. Then it rises during the day to reach its maximum at the end of the afternoon. It is normal for pond water to have this kind of behaviour. However, pH variation per day is up to 2.5. This is way too much as it is recommended that pH does not vary more than 0.5 within a day. With the observed range of pH variation, fishes can be shocked, weakened and stop eating. We can also notice that pH is getting too high every afternoon, above the warning level of 8.5 and even above the critical level of 9.

The strong fluctuation of pH during the day combined with high level of pH in the afternoon are symptomatic of a pond with too many algae. Algae and microorganisms use CO2 and can affect the pH of the water and regular balance must be maintained to stabilise the pH. Algae grows and develop quickly when hardness (the amount of CaCO3) of the water is low.

The recommendation in that case is to add dolomite lime (100-200 kg/ha) to increase water hardness and buffering agent [8]. Water should also be changed to stabilise the growth of algae. For sustainability, it is best to closely manage phytoplankton richness by changing the water at least at a rate of one-fifth a day, avoiding overfeeding and using lower fish densities.

B. Water temperature

We can see in Fig. 1 that water temperature is also getting cyclical with natural increase in day and decrease at night. In this pond, the temperature stays most of the time in the recommended range and no particular action is needed for this parameter.

C. Water dissolved oxygen level

The level of dissolved oxygen is one of the most important factor in aquaculture, as a lack of oxygen can cause fishes to die. In Fig. 1, we can see the cyclical behaviour of dissolved oxygen level in the pond. This is an expected behaviour, as during the day with sunlight, algae and microorganisms create oxygen that will be dissolved in water. During the night, as oxygen is not produced anymore, it is consumed by fishes and rapidly decrease until the sun is high enough to allow photosynthesis to take place. In this pond, we can see that all the oxygen coming from photosynthesis during the day is not enough to last all night long for the fishes. Every morning, fishes lack of oxygen that can cause them to grow slow, stress or even die if it last too long. The only way to deal with too low oxygen level in a pond is to aerate the water with manual aerators that brasses water and increase the oxygen level. In this pond configuration, aeration must be done at night to avoid the lack of oxygen in the morning.

With this first deployment in Kumah Farms, we pointed out two major issues in the fish pond: (a) the oxygen level is too low in the morning, that can cause fishes to be stressed and, (b) the pH is too much variating and too high, because of too much algae presence. This can also cause fishes to be stressed. In that case, fishes grow slower, they do not breed and they can eventually die. Our recommendations to improve water quality (i.e. aerate water at night and remove algae with dolomite lime) should considerably improve the fish production yield of this farm. With the limited cost of the device, we proved that a connected aquaculture is suitable to all with minimum investment and maximum benefits.

IV. Smart Systems for Smart Aquaculture

While Aquaculture is booming to face increasing demand, intensive aquaculture is criticised to impact on environment and on intensive use for instance of antibiotic. There is however new approach on IMTA (Integrated Multi-Trophic Aquaculture) to create ecosystem which lead to have environment friendly aquaculture. This approach is even more demanding on information and IoT combined with AI techniques is well demanded.

In 2018, a new H2020 European funded project will be launched on Intelligent Management System for integrated multi-trophic Aquaculture (IMPAQT). It involves cultivating various species in a way that allows the uneaten food and wastes (e.g., nitrogen, phosphorus, etc.) associated with some species to be recaptured and be converted into inputs (fertilizers, food and energy) for the growth of the other species. “Multi-trophic” refers to the incorporation of species from different trophic or nutritional levels into the same system, while “integrated” refers to the more efficient cultivation of the different species in proximity of each other, connected by nutrient and energy transfer through water. The IMTA benefits are environmental sustainability through biomitigation, economic stability through product diversification and risk reduction, spatial optimisation by increasing productivity of a site, social acceptability through better management practices. Integrated Multi-Trophic Aquaculture enhanced by new/emerging management technologies can enable economically, environmentally and socially sustainable aquaculture development throughout EU and generate enhanced public and investor confidence in EU aquaculture. One of the objectives of IMPAQT is to build an appropriate management system for IMTA with advanced monitoring, IoT technology, modelling and data analytics. We hope that within this project, we will demonstrate that smarter connected systems can lead to smarter aquaculture across the world.

V. CONCLUSION

The results from these 3 different European projects showed that water monitoring in aquaculture, with the help of IoT, can be:

- *Highly sensitive* with the help of PROTEUS new sensors based on cutting-edge carbon nanotube technology
- *Cheap and user-friendly* as demonstrated with the WAZIUP use case in Ghana
- *Smart and environmental-friendly* as the IMPAQT project is aiming to.

However, water quality monitoring is not the only case of application of IoT for Aquaculture. With data analysis and prediction, we could introduce some artificial intelligence in the farms management. For example, some oyster farms are equipped with automatic machinery to take oyster out of water (for better growth). We can imagine easily how artificial intelligence could be used to take smart decision of automatically raise oyster out of water in case of bad water quality situation.

In conclusion, combining knowledge and expertise of cutting edge IoT technology can help to build the new aquaculture 4.0.

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