Design of a novel biosensor implant for farmed Atlantic salmon (*Salmo salar*)

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***Abstract*—Accessing the welfare status of animals in salmon farming is a challenge due to the large production scale and limited diversity of technologies available to quantify individuals' behavioural and physiological parameters. To increase technology diversity and facilitate rapid testing of future biosensing implants for farmed fish, we have designed and implemented a reusable and retoolable implant. The implant (9.4 g, 13 mm diameter × 47 mm length) consists of a primary module with a basic sensor suite measuring linear accelerations, rotational rates, compass heading, temperature and magnetic field strength, and a user-defined secondary module featuring a biosensor measuring heart rate and changes in tissue perfusion (photoplethysmography) enabling estimation of blood oxygen saturation (SpO_2). In this study, we describe the hardware (HW) and software (SW) of this sensor device and outline how it can be used to collect different data types from free-swimming farm fish in research and production settings. Finally, we discuss how this platform could be used as a tool for realising precision farming methods to improve animal welfare in aquaculture.**

Index Terms*—biosensor, implant, fish farming, *Salmo salar

I. INTRODUCTION

Mapping of measured behavioural physiological responses of a fish to its welfare state is a persistent challenge in aquaculture [1]. Such knowledge is crucial to avoid subjecting fish to excessive handling loads and environmental stress, which may result in poor animal welfare and even death [2].

Electronic fish sensor tags are miniaturized, encapsulated embedded computer systems which are usually surgically implanted into the peritoneal cavity of fish, where they either store sensor data locally in internal storage (biologgers/data storage tags, DSTs) or transmit real-time sensor data wirelessly using radio or acoustic signals (transmitter tags). These devices come equipped with sensors enabling collection of individual level data for parameters such as acceleration, temperature, pressure and electrocardiogram (ECG) [3]. When co-evaluated with production metadata, such data can shed light on e.g. activity levels, environmental preferences and stress [4]. Electronic tags/biosensors have recently been highlighted as potential tools for monitoring cultured fish [5], and could be a key element in achieving the aims of the Precision Fish Farming concept [6].

Several suppliers of biosensors and fish tags offer different solutions with respect to implant size, longevity, functionality and data types. However, most of these are designed with encapsulations that do not allow batteries to be replaced, have internal circuitry that is tailor-made for specific sensors, and are inherently proprietary. This reduces hardware flexibility and requires implants to be ordered and manufactured on-demand to ensure battery health. Because the battery cannot be replaced, such implants must be discarded after use which is not beneficial with respect to re-use and sustainability.

We have developed a flexible and re-usable implant with a generic primary module for power management, data storage and -processing. The design is made with connection points for attaching additional sensors using the ubiquitous I2C communication bus. The encapsulation is 3D printed and can be extended to accommodate different battery sizes. Our design therefore makes reuse and retooling possible, thereby facilitating rapid testing and deployment of new biosensors for fish in both research and operational production scenarios.

II. REQUIREMENTS SPECIFICATION

To minimize unit cost and facilitate design flexibility, the implant must be designed using standard electronic components (i.e not application specific integrated circuits). Since the implant is to be placed inside fish without negatively influencing the fish' natural behaviour and performance, it needs to be as small and lightweight as possible, and contain non-volatile memory so data are retained if the battery gets exhausted. Furthermore, the implant must be reprogrammable and retoolable so the primary module can be used with different secondary module sensors.

Motivated by the typical duration of swim tunnel trials where rapidly changing signals such as ECG need to be accurately captured, the battery is required to last at least

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30 minutes when continuously storing unprocessed raw data with a minimum sampling frequency of 200 Hz. Moreover, to enable longer lasting trials conducted at larger scales (e.g. laboratory tanks or sea cages), it should be possible to capture data for at least 5 days (120 hours) by duty cycling data capture, -processing and -storage.

The implant encapsulation must be biologically inert and as smooth as possible to prevent chafing or irritation/damage to surrounding tissues. It must also have a suture canal so it can be fixed in place during surgery both to obtain as stable sensing conditions as possible in each fish, and to enable data collection from a similar peritoneal position in different fish.

III. HARDWARE AND SOFTWARE DESIGN

A. Hardware

The hardware consists of a primary module with a basic sensor suite, a power management system, a microcontroller unit (MCU) for handling data collection, -processing and storage, and a secondary module communication interface for integration of user-defined sensors (Fig. 1).

The basic sensor suite was selected to provide measurements of motion and temperature, both representing essential variables with respect to behavioural analyses in fishes ([7], [8]). A 9-axis inertial motion unit (IMU) measuring acceleration, rotational speed and compass heading (ICM-20948, InvenSense) was included to extend the functionality beyond that of off-the-shelf implants which normally measure only linear acceleration. This enables attitude estimation, and by including compass heading, measurements can be rotated into a common reference frame allowing more accurate comparison of data between fish. A temperature sensor (TMP117, Texas Instruments) was included to log the internal temperature.

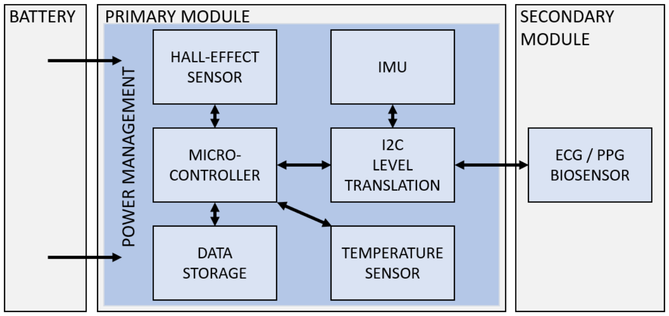

Fig. 1. Hardware block diagram. The blue background for the primary module illustrates the power management system serving all other components, including the secondary module.

The primary module was built around an ultra-low power MCU (EFM32TG11, Silicon Labs) for data collection and -processing, contains I2C level translation circuitry (NLSX4373, ON Semiconductor) for communication between the MCU and the secondary module, and a ultra-low power flash (MX25R6435, Macronix) for data storage. A Hall-effect sensor (Si7210, Silicon Labs) was included to enable device wake-up with an external magnet. The battery (CR1/3N) was connected to the primary module via a flexible printed circuit board (PCB) with battery connection pads (Fig. 2) using a conductive foam adhesive which can be peeled off and replaced along with the battery when re-using the implant. Power is managed by a switch-mode regulator (LTC3531, Analog Devices) for secondary module components requiring higher currents (i.e. $> 10\,\text{mA}$) and voltages (i.e. $> 1.95\,\text{V}$), while a low-dropout linear regulator (MAX8511, Maxim Integrated) is used for low-power components to suppress noise.

The secondary module was equipped with a biosensor (MAX86150, Maxim Integrated) measuring ECG for heart rate (HR) estimation, and the photoplethysmogram (PPG) enabling estimation of blood oxygen saturation level (SpO_2) and a (redundant) HR estimate. The biosensor was mounted on a circular PCB soldered perpendicularly to the primary module's PCB connection points (Fig. 2). This arrangement resulted from an *in-vivo* trial investigating sensing positions and orientations for photoplethysmography (PPG) in farmed salmon to provide the best chance of successful data capture using this sensor [9].

The encapsulation (Fig. 2) consisted of a 3D printed resin cylinder (13 mm diameter × 47 mm length) with a double gasket friction fit end cap, 14ct. gold ECG electrodes to prevent corrosion and bioencapsulation, and a suture canal to fix the implant's position inside the fish. PPG measurement is possible through the cylinder's transparent epoxy end seal and cover glass. The entire assembly weighs 9.4 g in air, including battery.

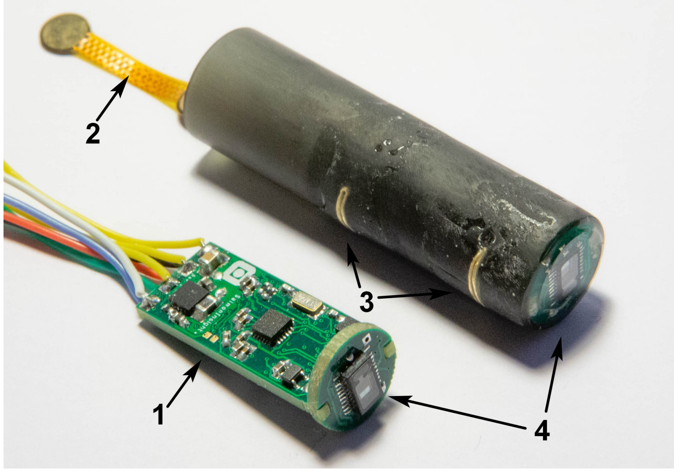

Fig. 2. Implant PCBs and encapsulation. 1: primary module PCB. Note that the wires protruding from the back of 1 is for development purposes only and are not part of the final implementation. 2: Flex print with battery connection pads. 3: ECG electrodes. 4: secondary module PCB with biosensor.

B. Software

The implant was programmed in C using the 'Simplicity Studio' IDE (Silicon Labs, Austin, Texas, USA). MCU specific functionality (e.g. I/O, timers and energy mode transitions) was handled using the emlib library functions which is part of Simplicity Studio. Proprietary drivers for handling both primary and secondary module sensor control, data processing (when relevant) and -storage for two different modes were developed in this study: Continuous operation and duty-cycling. During continuous operation data is sampled uninterruptedly from the desired sensors at a preset rate, and their respective values immediately written to memory. During duty-cycling, measurements are collected for a preset amount of time before data is processed and the result stored to memory. The MCU then enters a low energy state until a timer interrupt reactivates data collection and -storage. Data transfer to PC was implemented using Anaconda's Python 3.8 distribution (Anaconda Inc., Austin, Texas, USA).

IV. RESULTS

In-vivo trials using live, sedated Atlantic salmon (*Salmo salar*) have been carried out (Norwegian Food Safety Authority animal experiment permit no. 20/158927). Figure 3 shows a 10 s data set from these trials, illustrating the implant's ability to collect data in-vivo from live fish.

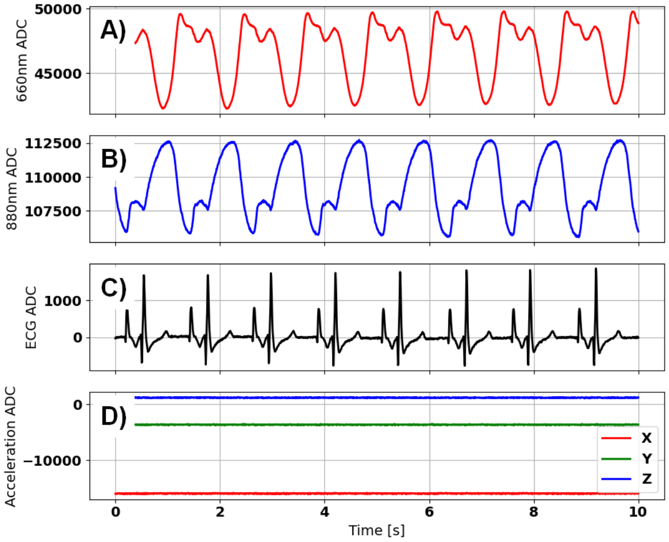

Fig. 3. A) 660 nm PPG ADC raw data, B) 880 nm PPG ADC raw data, C) ECG ADC raw data, D) Acceleration ADC raw values. Note that the lack of dynamics in the acceleration raw data is the result of data being collected using sedated fish which did not move during data collection.

V. DISCUSSION AND CONCLUSION

Although the 2% size recommendation for fish implants [3] implies that a tag of this size (9.4 g, (13 mm diameter × 47 mm length) could be used in fish down to 470 g, the implant should not be used for fish smaller than 600 g to avoid chafing against the incision so post-surgery recovery is facilitated [10]. As long as this precaution is taken, the implant could be relevant for several use cases such as aquaculture research with varying scales and levels of control (e.g. [4], [11], [12]), and in commercial aquaculture by implanting a certain number of "sentinel fish" for improved production control [13].

Technical tests of the implant indicate that all sensors can be sampled with a frequency of at least 200 Hz and that it can be operated continuously for approximately 12 hours on a single battery (170 mW h) while sampling and storing data at this frequency. This gives an average power consumption of 14.2 mW, or 4.7 mA at 3 V. However, when logging raw values from all sensors, data storage proves to be the limiting factor. For instance, with a sampling frequency of 200 Hz, memory runs full after approximately 34 minutes, which is sufficient for shorter experiments such as swim tunnel trials. Operation in this mode can be extended through careful selection of sampling rates and storing only the data types necessary for a given experiment. However, this will not be sufficient for longer experiments, implying a need for duty-cycling and onboard data processing, storing only the processing result. The MCU's intrinsic timing capabilities facilitate duty cycling of both data sampling, -processing and energy modes. When considering the requirement of 5 days (120 h) operational life for studies at larger experimental scale, this gives 6 minutes of data collection per hour, corresponding to a duty cycle of 1 minute data collection and processing followed by a 10 minute sleep period in the ideal case. A duty cycle of 1:10 minutes is reasonable when comparing data collection schedules for implants used in such contexts [4], [14], although some testing remains to validate longevity during duty cycling. Alternatively, future integration of a higher capacity nonvolatile storage may be considered, but may come at the cost of increased size and/or power consumption.

Regardless of application, our implant expands upon current sensing options and provides valuable information on the responses of fish to various stimuli (e.g. stressing) while enabling the collection and derivation of novel and objective welfare related bio-parameters (e.g. HR/SpO_2). The implant can also be re-tooled to accommodate different sensing capabilities and supports reuse by allowing battery replacement. Moreover, our device addresses the need for individual level intelligent sensor systems as highlighted by the precision fish farming concept. Given a sufficiently robust foundation of 'ground truth' data, measurements from the sensor implant can be interpreted into valuable information representative of the behavioural and physiological state of farmed salmon, which in turn can improve animal welfare through better decision support and targeted farm management actions. By adapting placement and SW, the implant can also be applied to other farmed and wild fish species.

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