Marine IoT: non-invasive wearable multisensory platform for oceanic environment monitoring

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***Abstract*— Progresses in the marine research heavily rely on gathering data about species physiology, mobility, and their habitat to understand the environmental changes and its effects using bulky biologgers and sensory networks that are invasive in nature. In this paper, we demonstrate an advanced lightweight compliant environmental monitoring system: "Marine-Skin" with enhanced sensing and logging capabilities, having soft-packaging and endurance up to a depth of 2 km in highly saline Red sea water for multiple weeks. Unlike invasive biologgers, we demonstrate a unique non-invasive attachment strategy by designing a wearable jacket from soft-polymers that can be adhered to any species irrespective of their skin type. We have successfully deployed the feather-light (<0.5g in air, 3g with jacket) wearable gadget on Wobbegong shark, Seabream, and common Goldfish to demonstrate the non-invasive and pragmatic attachment mechanism for different species of variable sizes without any hindrance to natural movement or behavior of animal tagged.**

Keywords—*flexible sensors, environmental monitoring, soft-packaging, marine ecology, Internet of Things*

I. INTRODUCTION (*HEADING 1*)

Rigorous over-exploitation by fisheries, nutrients' and pollutant run-off, direct harvesting, and pollution are a few causes contributing to the changes occurring in the oceanic ecosystem, and the impact varies with the intensity of exploitation.[1] Thus, a quantification and mapping of the human activities and the oceanic variations are needed in order to devise the policies, trade-offs, and mitigation strategies preserving the largest living space on this planet at a global scale.[2]–[4] Developments in electronic tagging devices and biologgers have facilitated the quantification and distribution of the human effect on the ecosystem. However, these animal-borne tagging devices are rigid, expensive, bulky, and heavy, which are tagged in an invasive manner by attaching anchors in the animal skin tied to the biologgers. [5]–[7] These attachment methods fail to sustain longer periods underwater due to water stream forces and not only cause injuries but also change the behavior of both tagged species and the surrounding species towards a foreign element having serious repercussions on the animals. [8]

Despite advances in technology challenges still exists for biologgers like providing animal comfort, non-invasive tagging, increasing lifetime of tag, increased sensing capabilities, conformal design, and adaptability to a myriad of aquatic species. Moreover, the advances in the field of flexible electronics are driving the technologies for the future where data, processes, sensors, and living and non-living beings are connected in synergy to form the Internet of things (IoT) and the Internet of everything (IoE). [9]–[12] CMOS technology had played the most critical role in technological developments and will continue to do so in future as well and the new devices must present the convolution of other technologies, materials with the CMOS based devices to match the high-performance.

We have engineered an advanced multi-sensory platform addressing the most advanced challenges in a very small footprint (2 cm × 2 cm × 0.2 mm), feather-light (0.5 g in air), physically compliant, with a soft-biocompatible packaging that is robust to sustain extreme pressure at the same time dramatically reducing the biofouling after prolonged deployment underwater (Fig. 1a). It is an advanced and improved version of our device known as *"Marine-Skin"* tagging system for marine environmental monitoring. [13] The device design and material optimization has resulted in drastic improvements in the sensing capabilities and enabled the demonstration of first time ever sustained performance in extremely harsh environment with extreme-pressure (~3000 psi or a depth of 2 km), long exposure to high salinity Red sea water (4 weeks, ~42 PSU), and extreme bending testing for more than 10,000 cycles. In addition, we illustrate a pragmatic approach for non-invasive attachment on species by designing a unique wearable jacket for providing animal comfort without influencing their natural behavior and is suitable for tagging most of the marine species irrespective of their skin type without any incisions.

II. RESULTS AND DISCUSSIONS

Conventionally, CTD based tagging systems have been used to monitor three fundamental parameters (conductivity, temperature, and depth) of the marine environment. In our Marine-Skin system, we integrated a system on a chip (SoC) microprocessor and a memory module with a solid-state microbattery encapsulated in a waterproof and biocompatible packaging. Great efforts were taken to make the system flexible, stretchable, and featherlight, which can be attached non-invasively using a wearable soft jacket architecture. The

SoC and memory module stores the acquired data underwater and can be retrieved from memory after the tag is retrieved by connecting it to a Bluetooth enabled device. The flexible, small, and lightweight platform combined with the wearable jacket design resulted in a sensor with minimal discomfort to any tagged species irrespective of their size or epidermal type.

A. Packaging Material, and Design:

Therefore, the first challenge in the "Marine Skin" tagging development was to have a compliant packaging material that is soft to adhere to the animal's skin, elastic to maintain the stretchability (for comfortable breathing and comply with physical deformation) of the device. Different material choices available for such soft encapsulation are Ecoflex©, and polymethyl methyl acrylate (PMMA), and polydimethylsiloxane (PDMS). We chose polydimethylsiloxane (PDMS) (Sylgard 184^{TM}) as the soft encapsulation of the sensory platform due to its hydrophobic, non-toxic, non-decomposing, and non-irritating properties. Further, PDMS is one of the most used materials in microfluidics and biosensors because of its biocompatibility.

"Marine Skin" is a stretchable and flexible multisensory platform that monitors temperature, pressure (depth), and the salinity of the marine environment. We use PDMS as a soft and compressible dielectric material for the capacitive pressure sensors. A resistive temperature detector (RTD) is fabricated for temperature measurements while the salinity sensor was incorporated by using an interdigitated electrode architecture for enhancing the sensitivity.

B. Sensory System Performance:

The temperature of seawater varies in the range from 24 °C to 2 °C from the surface to the depth of ~4000 m, hence it is important to capture the variations throughout with high sensitivity. Our design of temperature sensor with the material used Pt makes it a highly linear correlation with $R^2 = 0.99872$, in addition, we could achieve the sensitivity of S_{v2} = 358.8 mΩ/°C) which is 15 times higher than our previous version (Fig. 1b). In addition, the performance of the temperature sensor in the regime of interest (4 °C to 24 °C) is reliable and as linear it is for the higher temperatures up to 60 °C. Furthermore, the performance of the temperature sensor is comparable to the commercial reference temperature sensor from Sensirion and it matches the temperature curves and the response time as well (Fig. 1c). Thus, making it more reliable and a feasible alternative for direct integration with the SoC device.

Salinity of the water is conventionally measured using the conductivity test between two open electrodes. However, simple electrode design can exhibit variation and less sensitivity, hence we take advantage of the interdigitated electrode design for increasing the sensitivity as well as reliability. We observed a drastic improvement in the sensitivity of ~ 500% increase (19.655 kΩ/PSU) from the previous version, see Fig. 1d. Although we have observed a slight shift in the absolute value of baseline when the sensor is kept immersed in seawater with a salinity of ~41 PSU, the variation in the absolute value was < 3% without any variation in the sensitivity.

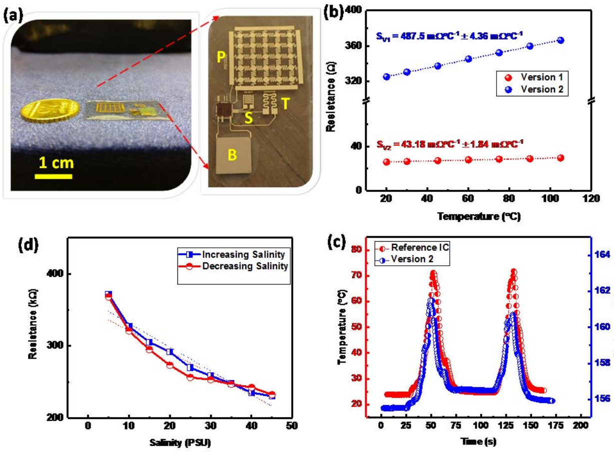

Fig. 1. Illustration of Marine-Skin tagging system (a) multisensory platform and the thin CMOS elements, (b) temperature sensor enhanced sensitivity, (c) performance comparison with commercial Sensirion temperature sensors, and (d) salinity measurements with varied saline solutions.

The most important parameter to for monitoring the environment is the depth of the water and since many of the animals swim in the depths from 200 m to 2000 m, it becomes critical to have the sensory system that can reliably perform at these high-pressure environments. We used a soft elastomeric PDMS material as a dielectric for the pressure sensing application and the overall design and choice of materials lead to a reliable and linear increase in the pressure in depths of 30 m each up to 2 km depth shown in Fig. 2a. We have also not observed any saturation in the value which implies that our device can work for higher depths which has never been demonstrated previously.

C. Rugged Performance:

The reliability of the marine sensory system can only be certified if the system shows no degradation in the performance under rugged harsh environmental conditions. We have tested our devices for understanding the effect of the orientation of the sensor after tagging the species. The device shows no difference in sensitivity whether it is tagged in a horizontal orientation or in a vertical orientation. Since the device will be applied to the animal body and we don't have control over the swim or the rotation of the tagged species, thus, it is important to observe any dependencies on orientation. Our results of pressure measurements in the laboratory environment have proved to be stable and reliable for horizontal and vertical orientation of sensors, observing no difference or dependency on the orientation. Also, the hysteresis curve for the depth measurements while submerging in and rising out the Marine-Skin from the water are extremely good fit (Fig. 2b). Hence, we achieved no significant difference in measurements showing the no dependence on the orientation which also is true for the consistency of the compliant system.

Further, for any complaint or flexible device technology, the benchmark should be formed to testing the reliability and robustness of any flexible device is the sustained performance over multiple physical deformations (bending cycles). We establish the strength and ruggedness of the Marine-Skin by performing repeated cyclic bending tests for more than 10000. The soft packing layer of PDMS, thick copper layer as metallic interconnect and modified materials and design helped in retaining the same performance for the rugged cyclic testing and prolonged exposure to Red seawater (~41 PSU). The bending tests were carried out at a minim bending radius of 1mm. each cycle bending the sensor with a radius of 1 mm and stretching. Figure 2c illustrates the device performance at the intervals of 0, 100, 500, 1000, 2500, and 10000 cycles respectively. The change in sensitivity recorded is < 4% from the value at zero bending cycles for the temperature sensor. Similarly, the robustness of the pressure sensor can be observed from Figure 5c where the sensitivity has not changed significantly due to constant cyclic physical deformations. The observed variations are mainly due to manual controlling of the immersion in water, whereas the maximum deviation observed in absolute value is < 2.6% from the initial baseline at zero cycles. Similarly, tests for the effect of prolonged immersion in saline water was necessary to establish application and feasibility for the marine species. We have not observed any significant variation in the performance of the multi-sensory system when it was subjected to immersion for 1, 3, 7, 15, and 28 days.

To summarize, Marine Skin has resulted in tremendous increase in sensitivity, reliability, and robustness of the packaging thanks to the modified design and material optimization. Furthermore, the version 2 demonstrates extremely robust and rugged performance reported for the first time, in an extremely harsh environment 10^4 bending cycles (bending radius 1 mm), high pressure (3000 psi, ~2 km), and prolonged immersion in Red Sea water (4 weeks at 41 PSU).

III. ATTACHMENT MECHANISM

Marine species have huge variations in their skin types and skeletal elements (scales). Careful consideration is required to develop a best-suited attachment method for ling time deployment. Most of the available biologgers need invasive attachment technique for tagging. Our multi-sensory platform could easily be tagged on the animals (stingray and wild shark, see Fig. 3a & 3b) by using simple waterproof glue/adhesives and due to its flexibility, the performance will not be affected. However, glue is not recommended for many species that can hurt the skin of fishes and other techniques of using clamps or suction cups are either injury prone to animals or gets detached due to drag forces.

Consequently, we present a unique, pragmatic, and universal approach for sensory platform tagging by designing a soft wearable jacket embedded with the multi-sensory system. It can be wrapped around the animal body with the strong interlocking mechanism provided by a combination of soft and 3D printed mushroom pins and holes. Presence of multiple pins on the same jacket allows adaptability to different size animal while providing enough breathing and comfort to the tagged species. The attachment mechanism is successfully tested on the Barramundi (*Lates calcarifer*) and Seabream fishes (Fig. 3d). We have observed, that this wearable Marine Skin is easy to attach even on small fishes. The lightweight of the Marine-Skin (<3g with jacket), softness, stretchability, non-invasive mechanism, and conformability presented no hindrance to their natural behavior. Hence, the feather-light and breathable wearable bracelet pattern is a pragmatic mechanism for the Marine Skin tagging system.

IV. CONCLUSION

The ocean ecosystem is affected by multiple human impacts and to facilitate policy implementations, it is important to quantify the distribution of impact. The evolution of the sensors and tracking tools in conjunction with the advances in the technology is making pivotal contributions in understanding the marine ecosystem and animal behavior and it will continue to grow further. The evolution of flexible electronics demands the focus on the development of conversion of big bulky and rigid biologgers into flexible and lightweight conformal system with the non-invasive attachment mechanism. Here, we have presented featherlight, compliant, multi-sensory stand-alone waterproof and biocompatible platform with soft-packaging for deep-sea environmental monitoring. We demonstrated a rugged and robust device that can withstand 10^4 severe bending cycles (1 mm bending radius), prolonged exposure to the highly saline (41 PSU) Red Sea water, and the extremely high pressure of ocean depths (~ 2 km deep). A unique non-invasive attachment mechanism is successfully designed by embedding a soft-wearable stretchable jacket that causes no harm and abnormal behavior in the tagged species irrespective of their skin type. This Marine Skin gadget outperforms any other entities in the domain in terms of flexibility, stretchability, non-invasiveness, comfort, featherlight (weight <0.5g for systems, and <3 g with the entire wearable gadget), with proven ruggedness and sustained performance at high pressure.

ACKNOWLEDGMENT *(Heading 5)*

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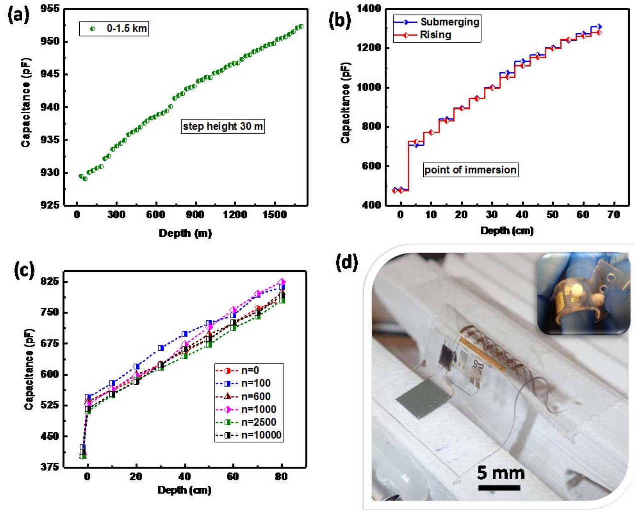

Fig. 2. Harsh environment testing of the device (a) pressure measurements up to 1500 m underwater depth, (b) hysteresis plot for submerging and rising the sensors from water, (c) rugged cyclic performance test, and (d) experimental set up for extreme bending cycles (inset shows interlocking mechanism.

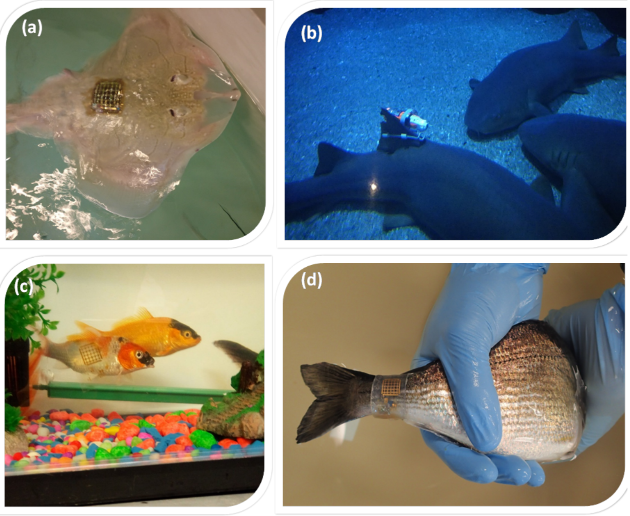

Fig. 3. Attachment/tagging mechanism for Marine-Skin (a) sting-ray host tagged using adhesive, (b) wild shark tagged by attaching sensors on cylindrical CAN device attached to fin using steel clamps, (c) scaled version attached on common goldfish, and (d) seabream wearing the soft-jacket interlocked using 3D printed and soft mushroom pins..