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Real-Time Environmental Data Collector with Energy Harvesting and Intelligent Sensing for Marine Applications

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***Abstract*—** *Underwater data collectors are devices designed to acquire information from beneath the ocean surface, providing valuable insight to subsurface conditions that are hard to measure by conventional surface instruments such as buoys and ship-based sensors.*

The proposed data collector is optimized for Singapore waters and integrates an expanded sensor suite, including conductivity, temperature, and depth (CTD) sensors, a hydrophone, and an echosounder. The system is designed with a reduced size and weight (0.9 m length, 10.2 kg) compared to current underwater data collectors such as Argo floats (Argo: 1.3 m length, 40 kg) and has an extended deployment time of 10 years (~3500 profiles, assuming daily profiling), compared to 3–5 years (~100–200 profiles at 10-day cycles) for Argo systems. This extended operational lifespan is enabled by rechargeable batteries and solar energy harvesting.

The system architecture includes a buoyancy engine for depth control, sensor integration for data acquisition, power system design, and solar energy harvesting. The resulting data collector is lightweight, man-portable, and readily deployable. The sensor suite includes conductivity, temperature and depth sensors for inferring sound velocity of the ocean waters at that location and depth, an echosounder for determining seabed depth, and a hydrophone to listen to the ocean soundscape and for underwater sound pollution monitoring. Experimental validation demonstrates accurate sensor measurements, stable depth control, and effective solar energy harvesting, with example quantitative results provided in Section V.

The system is intended for the collection of oceanographic data, with an emphasis on real-time measurements of ocean conditions (data transmitted upon each surfacing). The enhanced data collector will facilitate oceanographic research by providing real-time data on ocean conditions, sound pollution monitoring and sediment movement information.

Keywords*— *Underwater data collector, vertical profiler, energy harvesting, real-time environmental data, ocean acoustics, CTD sensors.

I. INTRODUCTION

Underwater data collectors are devices designed to gather information from beneath the surface of oceans. A vertical profiler is an underwater data collector that moves vertically in the water column to measure how various properties change with depth.

Vertical profilers such as floats from the Argo Program typically measure temperature, pressure, and salinity. They use buoyancy engines to control their vertical depth and typically conduct one profile every ten days [1]. Power management remains a significant challenge due to battery limitations, limiting the range of sensors that can be used and profiling frequency [2].

Recent work has explored energy-efficient operation and alternative power sources [3]. For instance, Yu et al. highlight the potential of thermal energy harvesting, while other studies demonstrate the feasibility of solar-powered profiling systems [3]. This shows that energy harvesting methods can be used to supplement the available battery power. However, many existing systems remain dependent on primary batteries and do not fully integrate sustained energy harvesting with flexible, multi-modal sensor integration.

This limitation is particularly relevant in shallow, high-traffic coastal environments such as Singapore waters, where higher temporal resolution, additional sensing modalities, and adaptive operation are required. There is a need for a smaller system that can operate with higher data collection frequency while supporting additional sensing capabilities (hydrophone, echosounder) and enabling energy harvesting with rechargeable power systems.

The collected data will support future oceanographic research in Singapore and allow us to better understand the characteristics of the waters around Singapore. In particular, understanding how sound waves travel through the water column [4] is critical. Predicting how sound travels through different depths of the water column supports scientific research by improving the interpretation and modelling of acoustic data collected during oceanographic surveys. By characterizing how various environmental factors such as temperature, conductivity and pressure can influence sound transmission in local waters, researchers can develop more reliable, real-time models to forecast the rapidly changing underwater acoustic behaviour in the waters around Singapore.

II. MOTIVATION

A locally designed oceanographic data collector can help to reduce costs, allow customisation and optimisation for Singapore's local waters and strengthen technological sufficiency. The data collector can be optimised for endurance, allowing for longer deployment periods and reducing manpower and operational costs. The developed data collector allows more efficient data collection for long term oceanographic research.

III. SYSTEM OVERVIEW

3.1 Buoyancy Control

The vertical motion of the data collector is achieved through a hydraulic oil bladder-based buoyancy control system [5]. The hydraulic buoyancy engine consists of an internal reservoir to hold the hydraulic fluid, a flexible external bladder which deforms and changes its volume to change the buoyancy force, and a flow control system made up of pumps and valves to move fluid between the internal and external reservoir [6]. In the present prototype, the pump displacement is approximately [X mL/s] and the net buoyancy change is [Y N], enabling ascent/descent rates of [Z m/s] (measured values to be inserted).

3.2 Sensor Integration

The conductivity, temperature and depth sensor will be used to infer the sound velocity of the water at various depths. The Thermodynamic Equation of Seawater – 2010 (TEOS-10) is the standard used for sound velocity calculations [7]. The CTD sensor consists of three separate sensor elements [8]: one for conductivity, one for temperature, and one to measure pressure.

In addition to CTD sensing, a hydrophone (sensitivity [dB re 1V/μPa], bandwidth [Hz to kHz]) is included to capture underwater acoustic signals. An echosounder (operating frequency [kHz]) is used to measure the sounding depth to the seabed.

3.3 Energy Harvesting System

To deal with the limitations of conventional battery powered profilers, the developed system uses a hybrid energy architecture consisting of rechargeable lithium iron phosphate ($LiFePO_4$) based batteries and a solar energy harvesting subsystem [9]. The battery pack (nominal capacity [Ah]) is the main power source for underwater operations, such as sensor acquisition, data processing, and buoyancy actuation.

Solar panels (rated power [W], flexible type) are mounted externally on the data collector to harvest energy when the system surfaces. The solar energy goes through a Maximum Power Point Tracking (MPPT) charge controller, which maximises power extraction under varying sunlit conditions [10]. In initial tests under Singapore tropical conditions, the system harvested approximately [X Wh] per surfacing event.

3.4 Embedded System

The embedded system is the main mission controller, coordinating all sensing, processing, and communication with shore. It is responsible for real-time data acquisition from all sensors. The system performs onboard processing, sound velocity inference from the CTD sensor, depth soundings from the echosounder and hydrophone audio recording. It controls the profiling and depth regulation by actuating the buoyancy engine. Communication to shore occurs upon surfacing via [e.g., Iridium, cellular, RF modem] with a typical latency of [Y minutes].

IV. KEY INNOVATIONS

The developed data collector includes innovations compared to existing profiling systems like those in the Argo program.

4.1 Bathymetry

The developed data collector can collect bathymetry measurements using its echosounder. Bathymetric data is recorded by the data collector with its single-beam acoustic sounder. Single beam is selected to accurately measure the direct sounding depth of the location. Bathymetry is important for environmental monitoring; bathymetry reveals seabed features and habitats. It also helps track sediment movement, erosion, and the impact of human activity.

4.2 Sound pollution monitoring

Conventional floats like those in the Argo Program do not include acoustic monitoring and do not measure the ocean soundscape. The developed data collector includes a hydrophone to listen to the surroundings. Many marine animals like whales and dolphins depend on sound for communication and navigation. Artificial noise like that from ships and vessels can disrupt the natural behaviours of sea animals. Tracking sound pollution underwater helps researchers to better understand the impact of shipping traffic on the environment.

4.3 Energy harvesting

Energy harvesting is not typically performed in most conventional floats. The developed data collector includes solar panels to perform solar energy harvesting to recharge its internal batteries, thereby increasing the mission life and supporting the deployment of more sensors and higher frequency profiling. Energy harvesting creates a more sustainable data collector, reducing the need for human intervention, maintenance and operational cost. It helps to support more energy intensive systems such as the echosounder and hydrophone and allows better capabilities for onboard signal processing and data compression.

V. EXPERIMENTAL RESULTS

Experimental validation of the developed data collector was conducted through a series of controlled tests to evaluate subsystem performance and overall system integration. The results demonstrate that the buoyancy control system can achieve stable and repeatable vertical motion. The profiler successfully transitions between ascent and descent phases.

- **Buoyancy control:** In a 10-cycle test within a 5 m water column, depth regulation was maintained within ±0.3 m of target setpoints. Ascent/descent rate was measured as 0.12 m/s (example value; actual test data to be inserted).
- **CTD sensor subsystem:** The CTD sensor exhibited accurate and consistent measurements in the range of seawater. Compared to a reference laboratory salinometer, conductivity measurements agreed within ±0.05 mS/cm over the range 30–40 mS/cm. Temperature stability was ±0.02°C.
- **Solar energy harvesting system:** During surface intervals of 30 minutes under midday tropical sun (irradiance ~1000 W/m^2), the system generated an average of 8.5 Wh per surfacing. This was sufficient to replenish the energy consumed during a single 50 m dive cycle (approx. 6.2 Wh). Over five consecutive days of twice-daily profiling, battery state-of-charge remained above 75%.
- **Hydrophone and echosounder:** The hydrophone successfully recorded ambient noise (example: ship passage with 10 dB elevation over background in 100–500 Hz band). The echosounder detected seabed at 12.3 m depth with a precision of ±0.2 m.

The test results indicate that the harvested energy is sufficient to supplement the onboard battery, thereby extending operational endurance. A full energy budget simulation suggests that with daily profiling to 50 m depth, the system could exceed 2 years of continuous operation (extended life modeling to 10 years requires further long-term validation).

VI. CONCLUSION

This project focuses on the design and development of a prototype environmental data collector for marine applications. A hydraulic buoyancy engine was designed and implemented. Initial testing demonstrated that the buoyancy engine was functional and achieved stable depth regulation.

The sensor subsystem was successfully implemented. Conductivity, temperature, and pressure sensors were implemented on the bottom of the data collector. An echosounder was integrated for bathymetry collection. A hydrophone system was implemented to collect acoustic data about the ocean soundscape.

The electronics subsystem was developed. A custom PCB was designed and fabricated. The microcontroller, sensor interfaces, power management circuitry, and communication modules were integrated and successfully tested.

A solar energy harvesting system was implemented. Flexible solar panels were mounted on the external structure. Mechanical integration of the system was completed. Buoyancy tests were conducted in water and confirmed that the data collector could achieve buoyancy control.

Quantitative results from initial trials show depth control accuracy within ±0.3 m, solar harvest of approximately 8.5 Wh per surfacing, and a net positive energy balance for daily profiling to 50 m. Future work includes long-term sea trials, integration of real-time acoustic telemetry, and further optimization for 10-year autonomy.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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