A Demonstrator for Future Fiber-Optic Active SMART Repeaters

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***Abstract*—The deep-sea environment still presents many challenges for systematic, comprehensive data acquisition. The current generation of SMART cables incorporates low-power sensors in long-range telecommunication cables to improve knowledge of ocean variables, aid in earthquake and tsunami warnings, and enhance coastal protection. The K2D Project seeks to expand SMART cables' capabilities by increasing the diversity of sensors along deep water cables, integrating active devices, and leveraging mobile platforms like deep-water AUVs, thereby improving spatial coverage and advancing ocean monitoring technology. This paper discusses a demonstration of these capabilities, focusing on the description of the main building blocks developed along the project, with results from a sea deployment in September 2023.**

Keywords— submarine fiber optic, optic cable repeaters, underwater communication, continuous monitoring and interaction, SMART cables.

I. Introduction

There are many outstanding societal concerns that demand systematic and reliable ocean monitoring, such as global warming, the need for carbon capture, the unknown deep sea, the pressure for deep sea mining, and the paramount importance of the whole ocean in the earth's ecosystem regulation. The deep-sea environment, in particular, poses the most demanding challenges regarding in-situ data acquisition and, therefore, presents the largest information gap as far as the ocean is concerned [1, 2].

Telecommunication cables span thousands of kilometers on the ocean floor, a significant part in deep waters where information is scarce. The concept of SMART cables (Science Monitoring And Reliable Telecommunications) was proposed as a way to take advantage of their location, by equipping their signal repeaters with low-power in-situ sensors such as temperature, pressure, and accelerometers [3]. These sensors allow for better knowledge of some essential ocean variables, early warning for earthquakes and tsunamis, and better protection of coastal regions and densely populated areas. This new generation of SMART repeaters has already been incorporated in newly deployed cables, providing the first step towards using underwater fiber optic cables as global, real-time ocean sensor networks.

The K2D Project is a collaborative effort between a group of Portuguese institutions and the Massachusetts Institute of Technology, in the USA [4]. It proposed an extension of the capabilities of these SMART cables by expanding their measuring capabilities, incorporating active devices, and taking advantage of moving platforms such as deep water AUVs [5] to expand the spatial coverage of measurements around the cables. In this new concept, each repeater can be used as a hub for more equipment, including active devices, sensors to measure physical, chemical and biological variables [6], docking stations for AUVs to charge batteries and exchange information [7], or localization beacons for AUV navigation. Regarding the localization beacons, the objective was to use from the most basic pingers to the most innovative concepts, such as active spiral acoustic sources, allowing AUVs to self-localize using a single source/hydrophone pair [8, 9].

II. Preliminary Work

The development of the K2D project aimed at giving the first steps for demonstrating this new vision of SMART repeaters, as hubs for local observatories and interaction with AUVs. Several building blocks were proposed and validated separately to conduct such demonstrations, followed by integrated experiments to validate the architecture and the whole concept [10]. The K2D interconnection with the fiber optic repeater is provided by the Repeater Interface, a device that draws a limited amount of power from the repeater and taps into the fiber optic to provide a set of power-over-ethernet (PoE) sockets. In each of these sockets, any compatible device can be connected, or a tree-like structure can be built using a set of N^{2}ODEs (Network Nodes for Ocean Data Exchange) [10]. Each N^{2}ODE acts as a hub to provide branches and extensions to the network, therefore enabling multiple topologies. Other N^{2}ODEs can be attached in a cascaded configuration propagating the power connection and including an Ethernet switch to allow the cascading of other Ethernet connections. They also include Ethernet-controlled relays, so that power to each output port can be individually switched on or off.

An initial prototype was deployed in the Sado estuary, in Portugal, for a period of 2 weeks in September 2022 [10]. In this case, a Shore Gateway provided power and a fiber optic connection over a 60m long cable. At the end of this cable, a Repeater Interface converted these into a set of PoE connectors, where a set of devices were demonstrated: an IP camera, a set of hydrophones, and a docking station for AUVs. During the deployment period, all data was available online, in real time. This initial prototype allowed the K2D team to validate the concept and to incorporate the required improvements to develop a full operational demonstrator, that was planned for deployment in September 2023, off Sesimbra, in the west coast of Portugal.

III. Sea Demonstrator Plan

One of the main goals of K2D project was to identify and develop the critical components of a cabled system that could convert subsea cable networks for telecommunications into infrastructures to support the operation of AUVs for ocean monitoring. To test and validate this concept, a wet demonstrator was designed and finally deployed in the summer of 2023, together with the Portuguese Navy. The wet demonstrator included 3 nodes with different specifications, which tried to address the requirements considered as critical for the K2D concept:

- Bidirectional communications and information exchange, as well as positioning, for AUVs;
- Discrete sensing of essential ocean variables, phased active acoustics and soundscaping;
- Continuous sensing using dark optical fibers.
- Multifunctional ports for adding other sensors or systems.

Considering the resources available in the K2D project and its demonstration objectives, the final design involved the deployment of a 2000 m cable which included 3 nodes, as shown in Fig. 1.

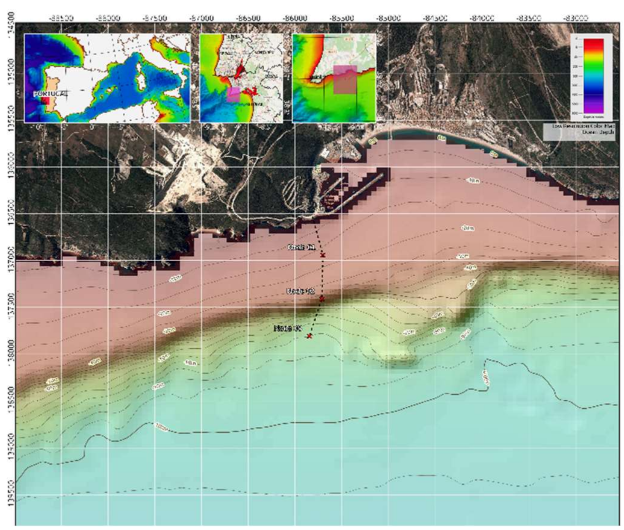

Figure 1: Chart showing the final layout and location of the cabled system and nodes deployed ashore Sesimbra, in Portugal.

Among several possibilities initially considered, the location was chosen considering several demonstration requirements, such as:

- The need to have access to power and a good internet connection (for systems control and data transfer);
- The possibility to reach depths of at least 100 m;
- The access to a rich natural environment, with interesting ecosystems and sonniferous species, and the simultaneous use for human activities;
- The existence of favourable hydrodynamic conditions for deployment and subsequent maintenance, experimentation and operation.

IV. Shore Station

The shore station was one of the critical parts of the system, considering the need to provide power supply to the cable, to control the systems located in the nodes and in the cable itself, and to exchange the data between the remote control station and the systems/sensors deployed. Since the project character was not compatible with the construction of a newly designed shore station, both due to time and resource constraints, the option was to take advantage of an existing water treatment station on the shore which could safely host the power and control station, as shown in Fig. 2.

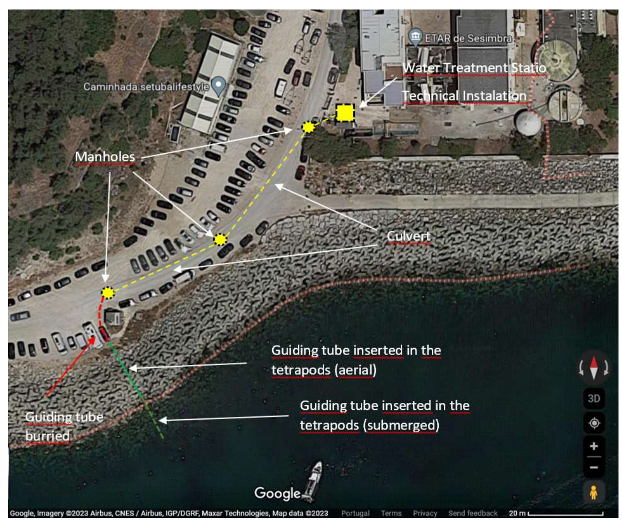

Figure 2: Map showing the components of the shore station and the landing of the cable.

As shown in Fig. 2, the yellow square identifies the installation that hosted the microprocessor, the power supply unit, and the connection with the internet, which allowed to supply the cable with the required power and to exchange the information needed to operate the prototype remotely. From this yellow square in the water treatment station, the optic cable and the conductor were inserted through the culvert, passing the several manholes identified in yellow until the final reception culvert was reached, near the red discontinuous line. Here, the optic fibers were spliced with the ones of the subsea cable, and the conductors connected with the conducting wires of the subsea cable, using a junction box safely placed. From this culvert onwards the deployed submarine cable, anchored to the final culvert, stretches to offshore. The section in air, marked in green, was inserted into an HDPE casing guiding tube, to avoid the abrasion by the tetrapods while the cable is moved by tidal and wave oscillations.This tube was previously inserted through the tetrapods, for a good protection.

V. Nodes

For this demonstration, 3 N^{2}ODEs were prepared, all similar in composition, with the only difference in the last node, which did not have an exit gland. The housings were designed to withstand pressures up to 120 bars (1200 meters) and mechanical traction of up to 10^4 Newtons. To reduce the energy loss, the cable was powered with 300 VDC.

To ensure the correct functioning of the N^{2}ODEs, it was necessary to develop the following :

- Development of a mechanical structure enabling cable traction while minimizing impact on electrical connectors and penetrators
- Design and development of stainless-steel watertight housings for N^{2}ODE electronics (140mm diameter cylinders)
- Specification and integration of DC/DC down converters (from 300 VDC to 24 VDC)
- Integration of internal electronics to control power to the PoE connectors and monitor internal status

The final architecture design of the N^{2}ODEs is presented in Fig. 3, and the final implementation of the N^{2}ODEs is shown in Fig. 4.

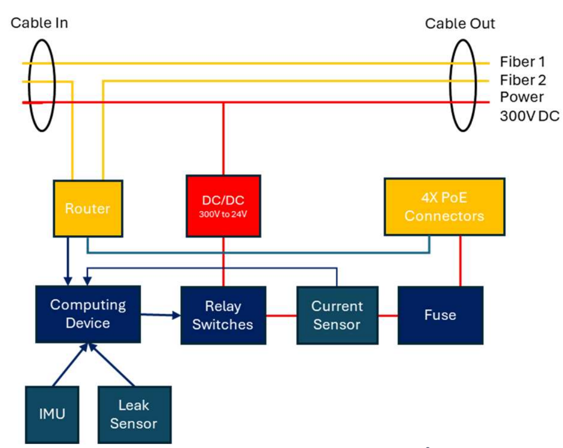

Figure 3: final architecture of the N^{2}ODEs

Before the final installation, the following validation tests were carried out:

- Watertight housing pressure testing in a hyperbaric chamber (up to 60bar)
- Individual testing of N^{2}ODEs for voltage and logical integration check
- Bench connection of the entire system (Fig. 5), including three N2ODEs and the shore gateway
- Sectioned cable testing for continuity (including power-dedicated cable and optical fiber cable).

Upon validation, the final assembly could proceed. The N^{2}ODEs were assembled aboard the Portuguese navy's ship NRP Andrómeda (Fig. 6) and tested before deployment.

VI. Sensors

Each of the three nodes featured a monitoring station, which served as a terminal for aggregating sensor data and transmitting it via the Ethernet backbone. These stations could accommodate a variety of underwater sensors, boasting advanced capabilities in signal acquisition, data processing, memory, and communication.


Figure 4: Three N^{2}ODEs with exposed electronics (top) and a closed N^{2}ODE (without cable penetrator) (bottom)

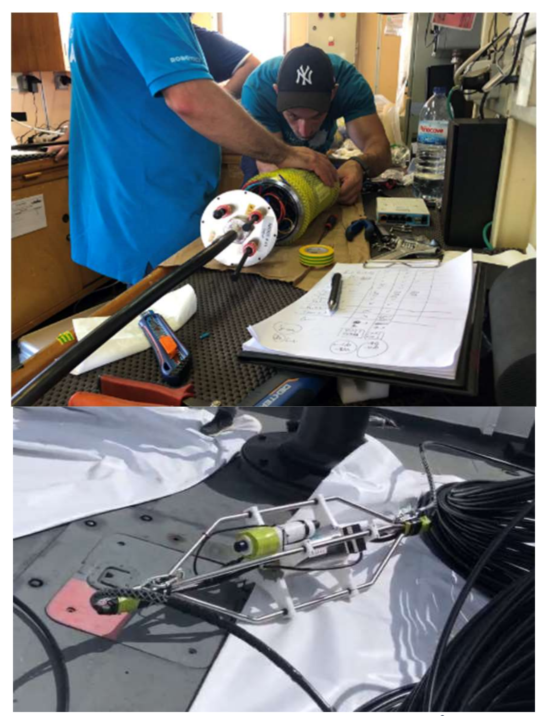
Figure 5: INESC TEC researchers mounting a N^{2}ODE on the cable (top) and a N^{2}ODE mounted on the mechanical structure, ready for deployment (bottom)

Figure 6: N^{2}ODEs were assembled aboard the Portuguese Navy's ship NRP Andrómeda and ready for deployment.

The demonstration focused on measuring water temperature (-20 to 85 ºC and 0.1 ºC resolution) and pressure (0 to 30 bar and 0.2 mbar resolution) using the MS5837-30BA sensor. The sensor stations were designed with a printed circuit board housing a stm32L056C6T6 processor, UART-Ethernet converter, and power supply circuits. The processor hosted the sensing devices and used the UART channel to transmit monitoring data to the converter, which then injected it into the Ethernet bus of the PoE. Fig. 7 depicts the electrical schematic and printed circuit board layout developed for the sensor stations.

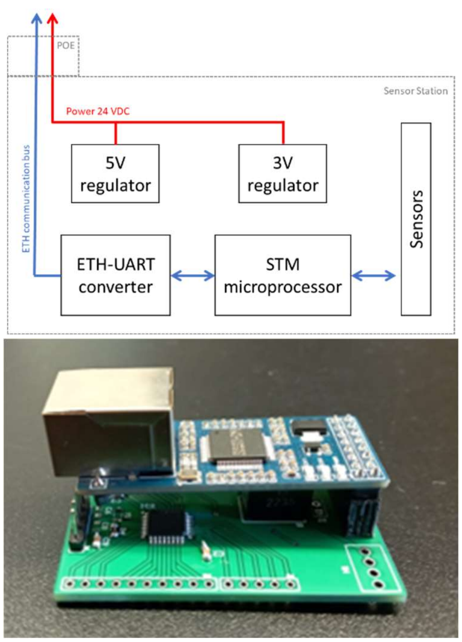

Figure 7. The top image shows the electric scheme of the Sensor station and the bottom image a photograph of the printed circuit board.

Another device installed in one of the PoE connectors of N^{2}ODE #1 was an acoustic Spiral Source. The Spiral Source satellite comprises DC/DC converters, a microcontroller that generates the transmission signals, four power amplifiers that include toroidal impedance adapters with a "full" amplification of 34 dB gain, and a hydrophone acquisition system for the spiral source calibration. All transmitted and received signals are remotely accessible via Ethernet for signal configuration or data uploading and can be used as spiral beacons for AUV navigation or as spiral sonar. Further details can be found in [8, 9]. Figure 8 (top) shows N^{2}ODE #1 and the Spiral Source satellite, which were placed together, connected with a Power-over-Ethernet cable.

Finally, all 3 nodes were deployed with digitalHyd TP-1 acoustic recorders from MarSensing (bottom of fig. 8). Each recorder was set up to perform real-time streaming, over Ethernet, of the raw acquired acoustic data to the shore station for storage and further processing. The configuration of sampling frequency and programmable gain amplifier can be set remotely in real-time, This allows for different recording scenarios. The digitalHyd TP-1 has a maximum available sampling rate of 312ksps@24bits; however, to reduce data volume, the sampling frequency was selected as 78ksps@24bits in this setup. This frequency covers not only anthropogenic noise but also biological activity of interest. As can be seen in Fig. 8 (bottom) the recorder is inside a Delrin container with an ethernet and power pigtail on one end and the hydrophone on the other. The hydrophone has a nominal sensitivity of -198dB re 1uPa and a fixed first-stage preamplifier with a gain of 32dB and a PGA with up to 36dB gain.

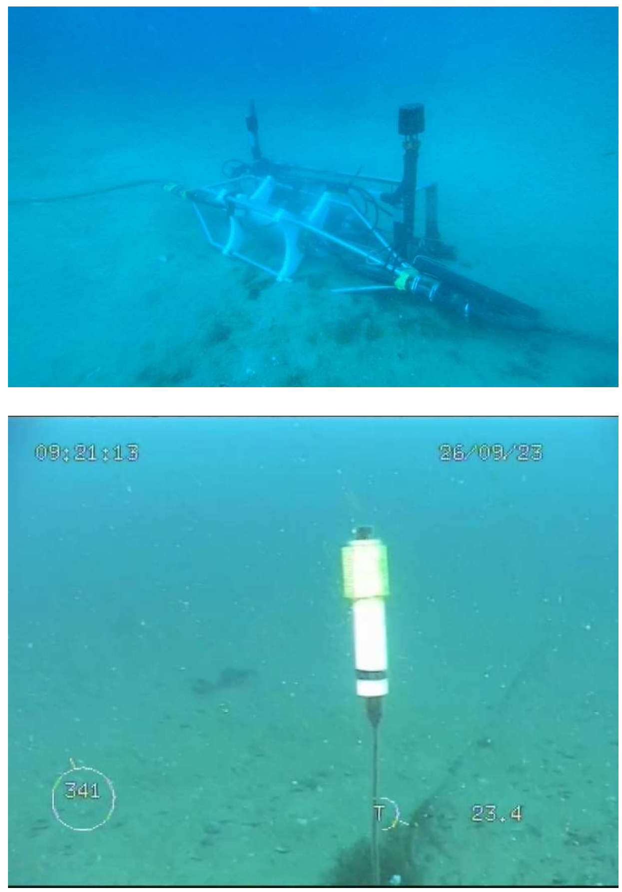

Figure 8. The top image shows node 1 together with the spiral source satellite, which also comprises a hydrophone; The bottom image shows the TP-1 hydrophone placed in nodes 2 and 3.

VII. System Deployment

This section describes the sea trial operation, where the main components of the K2D project were deployed. Since the infrastructure to be deployed comprised 2 km of electro-optic cable and 3 nodes, which were pre-installed in the cable, a relatively large vessel was needed. For that reason, the K2D consortium contacted the Portuguese Navy, who confirmed the interest in the results of the project, and agreed to use the NRP Andrómeda for the cable deployment. Given logistics constraints, the sea trial was planned to take place between the 4th and 6th September 2023.

The longest and most important part of the sea trial was the preparation, with a total time of around 20 hours, involving more than 10 project researchers. It included the setup of the shore station, preparing the 2km cable with the nodes, transferring the full system to the vessel deck, and briefing with the crew. Finally, the system deployment at sea, including the connection to the shore station, was done in a little over 2 hours, on September 6th.

The deployment of a long cable in the ocean is a relatively complex task that requires thorough preparation. The Portuguese Navy agreed to use the NRP Andrómeda for the operation (Fig. 6). Although the vessel has no dynamic positioning (DP), a feature that would facilitate deployment, it has a relatively large deck space where the cable could be laid in preparation for deployment.

For the preparation, a tarpaulin was used to cover the deck to prevent the cable from getting caught during its release into the water. The electro-optic cable was accommodated in 8's shape to allow an easy release to the water, and simultaneously the repeater nodes were assembled in the cable and placed in the right position to be released in the water (see Fig. 5 and 6).

The cable deployment took place during the morning of September 6th, 2023. In the first step, the NRP Andrómeda was moored at about 200 m from shore, and an auxiliary boat was used to carry the first segment of the cable to shore. Close to shore, the cable was introduced into a PVC tube with a guide line which was used to pull it to shore. In the second step, the NRP Andrómeda started navigating in the offshore direction, and the cable started being released into the water. At the end of the first 500 m of electro-optic cable, node 1 was released into the water, and the second cable segment started being released. The operation continued until the last node. All nodes were successfully deployed, however, the 3rd node ended up being deployed closer to the 2nd node than what was planned. The deployment finished with the addition of the Spiral Beacon to N^{2}ODE #1, which was done by the Navy divers. The same team of divers visually inspected the cable and nodes.

The deployment was completed, with minor changes, according to the plan. After the deployment, the power and the fiber-optic network were tested with success.

VIII. System Validation

All sampled data at the nodes was streamed over the fiber network in real-time to the shore station where different services recorded multiple parameters such as: temperature, pressure, conductivity and acoustic data. Additional engineering data such as node tilt and power consumption was also recorded. The high bandwidth raw acoustic data, at the selected sampling frequency, created a volume of 840MBytes of data per hour for each sensor which was timestamped and stored in individual WAV files for later processing. The acoustic data was also processed and displayed as a spectrogram in real-time on a web interface, enabling the observation of the acoustic panorama from a remote location over a 4G mobile connection. In Fig. 9, the spectrum is updated in real-time as an instantaneous value, which is used to update the spectrogram, which flows from right to left. Low bandwidth data from the other sensors was also timestamped and stored in individual text files for each sensor. The bottom part of the web interface presents the temperature at the selected nodes.

Overall a total of 20 days and 1TByte of data was acquired from the sensors on the 3 nodes. This setup demonstrated the advantage of having real-time access to configuration and raw data where it was possible to operate the sensors 24/7 without major limitations on power consumption and data volume.

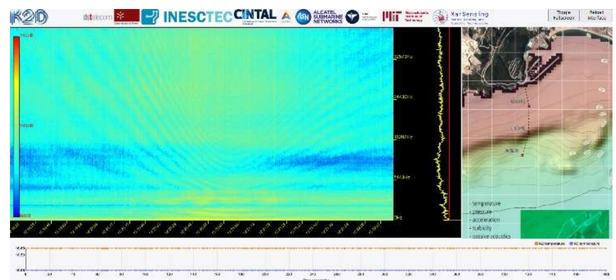

Figure 9. K2D web interface which enables the observation of the signals being acquired; on the top-left, the spectrogram of the acoustic data when a boat is passing; on the top-right, the geographic configuration of the network; on the bottom, the temperature and pressure sensors data along time.

Each one of the 3 nodes was equipped with a monitoring station designed to measure water temperature and pressure (for estimating water depth) [11]. These sensors were employed to monitor tidal cycles and sea wave conditions. Fig. 10 illustrates a sample of measurements the sensor stations took at nodes 1, 2, and 3, on September 10th, 2023.

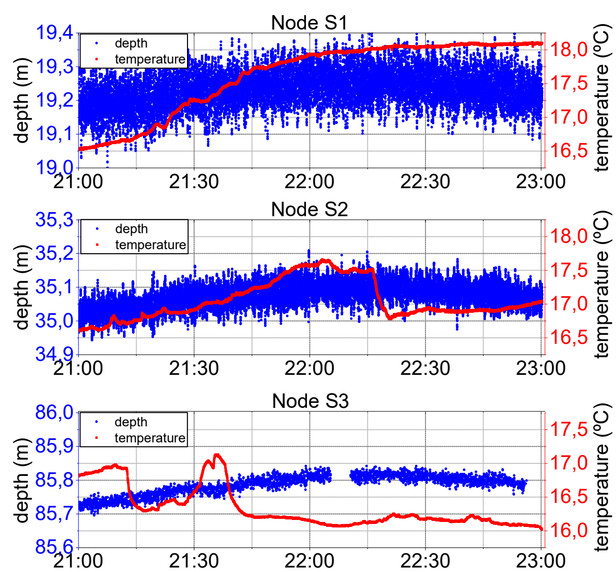

Figure 10. Measurements of water temperature and water depth of nodes 1, 2 and 3 on the 10th of September 2023.

The pressure measurements show that the stations were at different depths: node 1 at 19 meters, node 2 at 35 meters, and node 3 at 85 meters. The measurements show a high-frequency variation that is related to the sea waves (notice that this variation decreases from node 1 to 3 due to the wave amplitude sensitivity loss with depth) and a low-frequency variation related to the tidal cycles (the period of the measurements matches with the peak of the high tide). An example of the complete tidal cycle is presented in Fig. 11 and shows a tidal amplitude of 2.5 meters measured by the sensor station of node 2.

The measurements of water temperature show that the region of node 1 is the warmest and node 3 is the coldest. This matches the gradient of temperature in the ocean since the water temperature decreases with depth. It is also possible to observe slight temperature variations in the three nodes that can be explained by seashore currents.

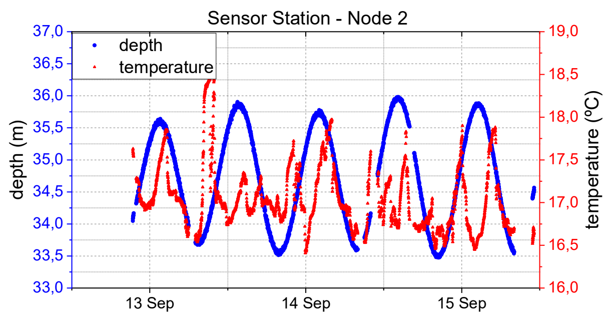

Figure 11. Measurements of water temperature and water depth of node 2 from the 12th to the 15th of September 2023.

IX. Conclusions

The global warming, the unknown deep sea, the pressure for stating deep sea mining, and the paramount importance of the ocean in the earth ecosystem regulation, pose many challenges for more systematic and reliable ocean monitoring. The emergence of smart repeaters [3] gave rise to the possibility of using underwater fiber optic cables as global real-time ocean sensor networks. These repeaters can incorporate sensors, such as temperature, pressure, and accelerometers, which provide a better knowledge of the ocean and function as early warnings for earthquakes and tsunamis and better protect coastal regions and densely populated areas.

Current fiber-optic cables equipped with smart repeaters allow for incorporating a limited number of passive sensors. However, better knowledge could be achieved if each repeater could be used as a hub for more equipment, including active devices. The K2D project aimed to take the first steps in demonstrating that such a vision is possible, and in September 2023, an "active" SMART cable demonstrator was deployed off the west coast of Portugal.

An underwater network was presented to provide power and communication lines to land through the submarine fiber optic cable repeaters. The optical repeater will connect to an N^2ODE through the repeater interface, which converts any optical fiber and power into a common configuration. The network concept is formed by a set of N^2ODEs that act as hubs to extend the number and diversity of node terminals.

The "active" SMART cable demonstrator integrated a set of passive sensors for environmental monitoring and active systems for AUV navigation, also enabling AUV operation enhancement, by allowing battery recharging and data exchange in underwater docking stations. The full system was successfully validated, although in favorable conditions - shallow waters close to shore. Future work should extend the demonstrator capabilities for deep waters.

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