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Multisensor Platform for Underwater Object Detection and Localization Applications

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***Abstract*—Reliable object detection and localization in various underwater applications is still challenging. Existing sensors are limited to particular applications and/or environmental boundaries. We present an architecture with a uniform communication protocol for a multi-sensor platform that enables a robust integration of different sensor systems. Further, we propose an extensible modular multi-sensor platform prototype to detect and localize objects with different properties in all environments. Our prototype combines magnetic, acoustic, and electrical sensors for object detection and localization. The functional prototype is ready for first measurements outside the laboratory environment.**

***Index Terms*—Underwater, Localization, Multisensor, MQTT**

I. Introduction

In underwater applications, reliable detection and localization of obstacles and objects is required, for example, to navigate safely even in poor visibility conditions. For the exploration of underwater ground structures in deep-sea mining, the salvage of unexploded ordnances (UXO), and the route planning for underwater cables and pipelines, detailed information on the nature of the subsurface is required. Specialized methods and sensor systems for object detection and localization are already available for these various applications. However, these are optimized to the conditions of the environment and the respective application and are not flexibly applicable.

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In underwater applications, acoustic systems are often used, which, depending on the application, operate in the frequency range from 1 kHz to 200 kHz [1]. Echo sounders, altimeters, side scan sonars, and multibeam sonars visualize the bottom structure and measure water depth or distance to the bottom. The sound waves from these instruments penetrate only slightly into the seafloor and are therefore used to image the water column. Acoustic exploration of the seafloor is performed with subbottom profilers (SBPs). These emit low-frequency acoustic sound waves in the lower kHz range, penetrate deep into the seafloor, and reflect off interfaces with high acoustic impedance contrast. SBPs are flexible with AUVs, remotely operated vehicles (ROVs), and mother vessels [2], [3]. Similarly, parametric methods with higher frequency and better directivity are used for buried object detection [4]. Acoustic methods are limited by backscatter and reverberation and are thus highly dependent on the particular subsurface structure, especially in ground exploration [5]. The penetration depth of sound waves varies from a few meters to a hundred meters, depending on the sediment.

Magnetic field sensors are also already used in underwater applications, for example, in the navigation of autonomous underwater vehicles (AUVs) [6], [7]. These sensitive sensors are used to measure magnetic dipoles and their magnetic fields. Electrical impedance tomography (EIT) is described in the literature as another imaging technique for the localization of buried objects [8], [9]. In this method, an electric field with electrode pairs is generated with an array of electrodes measured. The electric field distribution depends on the environment and is shaped accordingly by impedance differences of water, sediment, and objects. In EIT, the electric field distributions are measured for different excitation modes, and a cross-sectional image of the conductivity distribution is reconstructed.

In this work, we present the architecture and the implementation of a multi-sensor platform for reliable and flexible object detection and localization. The advantages of different sensors and sensor systems are combined to achieve better results than single sensor systems. When using different sensor systems, especially the varying protocols and interfaces are a problem. For this purpose, we present an event-driven solution approach to process control and measurement data uniformly in the system. The chosen communication protocol increases the scalability, flexibility, and modularity of the distributed overall system. Algorithms and software modules for data fusion also communicate via the selected protocol. When using different sensors and sensor technologies, mutual influences are also possible, negatively affecting the measurement results. We present a time-division-multiplex (TDM) approach to avoid cross-talk between sensors. By centralized allocation of time intervals for the respective sensors, mutual interference is excluded.

The contributions of the paper are:

- We present an event-driven architecture for a multi-sensor platform.
- We present a time-division-multiplex (TDM) approach to avoid cross-talk and increase robustness.
- We demonstrate the implementation of a multi-sensor platform with acoustic, magnetic, and electrical (EIT) sensors.

The paper structures as follows: We first describe the architecture for a modular and extensible multi-sensor platform. Then we present the implementation of our multi-sensor platform prototype. Finally, we describe the control of the sensors and data processing and conclude our work.

II. Multisensor Platform Architecture

A multi-sensor platform with unified data and control flow is shown in Figure 1. It consists of N sensors, a sensor controller, and the data fusion. All components are connected with a central data unit, which distributes the data. We assume the sensors as components that communicate with a unified protocol. Therefore we apply adapters to connect off-the-shelf sensors as a component to the multi-sensor platform. The adapter is used to pass both sensor data and control messages. An adapter component includes the software and, in most cases, embedded hardware with an appropriate sensor interface.

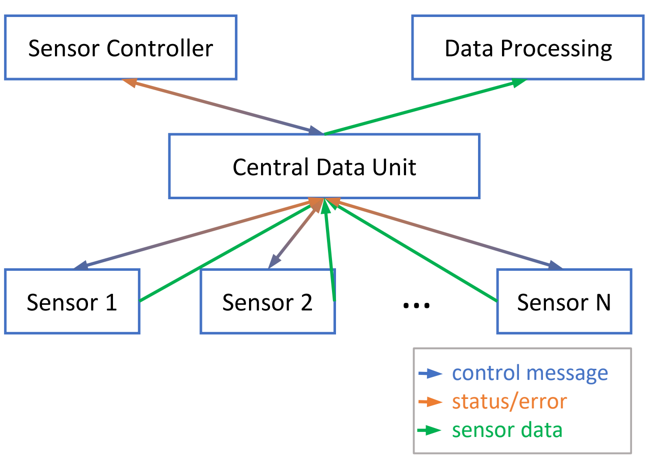

Figure 1: Structure of a multi-sensor platform with unified data and control flow.

We assume the multi-sensor platform to be operated with an ROV and real-time data processing on the mother vessel. Thus, the sensors are located underwater, and a communication link to the mother vessel with the sensor controller and data fusion components is needed. The central data unit is also supposed to be on the mother vessel. The structure shown in Figure 1 is also applicable for AUVs. Then the central data unit and sensor controller are located in the AUV, and data fusion is performed either offline on the mother vessel or online on the AUV.

A. Uniform Communication Protocol

We propose the message queue telemetry transport (MQTT) protocol for reliable, flexible, and event-driven communication. MQTT is a lightweight communication protocol based on the publish and subscribe principle. We apply an MQTT broker as a central data unit that handles the clients' connections and distributes the MQTT messages. An MQTT message is built with a topic and the payload. Clients subscribe to their required topics on the broker and will receive the published messages from clients publishing messages to those topics. MQTT typically uses TCP/IP as a transport protocol, and therefore the IP address of the broker must be known by the clients to connect to the broker. On the other hand, the client addresses are not needed because the broker forwards the messages. For detailed information on the MQTT protocol, we refer to [10], [11].

Our proposed multi-sensor platform communicates over the MQTT protocol, and therefore all components are connected to a TCP/IP network. To establish the connection, it is required that the broker (central data unit) is started before the clients. The sensor controller and data fusion algorithms are software modules running on PCs. Sensor initialization, error handling, sensor status display, and scheduling of the sensors are handled by the sensor controller. The control, status, and error topics are defined as:

```
SensorN/CONFIGURE
SensorN/STATUS
SensorN/ERROR
```

where `SensorN` is the name of a sensor component. Equally, the data fusion algorithms and display subscribe to the topics `SensorN/DATA`.

The sensor components must provide matching adapters to process the control messages and forward status, error, and measurement data. An additional (embedded) hardware and software adapter is applied to adapt to the uniform communication protocol for off-the-shelf sensors. The adapter translates the messages from and to the sensors, and all protocols or analog sensors are connectable. For the integration of analog sensors, we refer to our reference implementation of a universal underwater sensor box in Section III-A. The integration of sensors with serial communication protocols as RS232 is adaptable to our adapter implementation for the altimeters in Section III-D.

To operate the multi-sensor platform, avoiding mutual influence between the sensors is required. We fulfill this requirement with geometrical spacing and, if necessary, with the scheduling of the sensors.

B. Sensor Control and Error Handling

Reliable operation of remotely controlled sensors underwater is a challenging task. For the starting, initialization, and in case of errors, the sensor components need an implementation with automatic restarting and reconnecting routines. First, the clients connect to the MQTT broker and then provide their status information to the topic `SensorN/STATUS`. If the connection to the MQTT broker fails, no information are available in the sensor controller, and manual debugging, for example, via ssh, is necessary. The adapters shall be designed to restart the components in case of fatal errors, like missing MQTT or sensor connection. If possible, all errors shall be reported via MQTT to the topic `SensorN/ERROR`, using the retained flag for persistent messages. Then the sensor controller displays, logs, and responds to errors.

To solve problems with a sensor component, the adapter must implement a restart routine that is triggered with the MQTT message `Topic: SensorN/CONFIGURE, Payload: RESTART`. Sensor-specific control commands are implemented in the adapter and published from the sensor controller via the topic `SensorN/CONFIGURE`. To avoid mutual influence between the sensors, all sensors must start in idle mode. The activation of the sensors is controlled by the sensor controller scheduling, which is described in the following Section II-C.

C. Scheduling

This section proposes a time-division multiplexing (TDM) approach to operate our multi-sensor platform without cross-talk between the sensors. Our implementation, for example, includes multiple acoustic sensors, such as altimeters and analog wideband ultrasonic transducers that operate in the same frequency range. The parallel operation of multiple sensor systems is a challenge concerning possible mutual influence between the systems. With TDM, we define time slices for the sensors to operate. For an efficient TDM design, it is necessary to determine the sensors that interact with others, and their operation needs to be divided in the time domain.

In a multisensor system with six sensors S_j, where sensor S_1, S_2, and S_3 interact; and sensor S_4 and S_5 interact, we define the following interacting groups G_i:

$$G_1 = \{S_1, S_2, S_3\}$$
$$G_2 = \{S_4, S_5\}$$
$$G_3 = \{S_6\}.$$

Let N_i be the number of elements of each group G_i, we calculate the number of time slices $n_{\text{TDM, slices}}$ with the least common multiple (lcm) of N_i. For the given example we calculate $n_{\text{TDM, slices}}$:

$$n_{\text{TDM, slices}} = \text{lcm}\{N_1, N_2, N_3\} = \text{lcm}\{3, 2, 1\} = 6$$

The sensors S_i are operated in the slices shown in the slicing scheme in Figure 2. The slicing scheme must be known by the sensor controller only. Then the sensor controller publishes a start message to the sensors that are active in the current slice: `Topic: SensorN/CONFIGURE, Payload: "START"` .

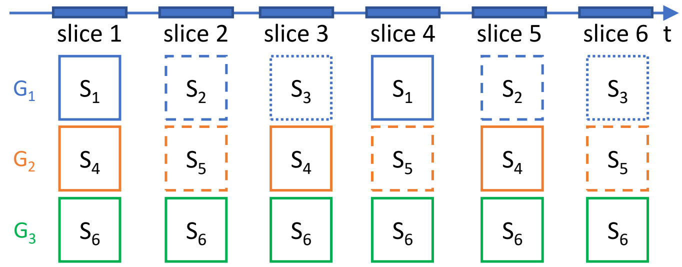

Figure 2: Slicing scheme for an exemplary multisensor platform.

At the end of a slice, we propose to deactivate all sensors: `Topic: SensorN/CONFIGURE, Payload: "STOP"` .

We propose dynamic time slice sizes that require a status message from the active sensor components: `Topic: SensorN/STATUS, Payload: "FINISHED"` .

When all active sensors in a time slice reported their `FINISHED` state, the next slice is supposed to be started. To prevent infinite locked slices, we further propose a slice timeout $t_{\text{TDM, max}}$, that is checked in the sensor controller. The proposed TDM is expandable to a more complex implementation to increase the system performance, where the time slices for sensors in an interacting group must not overlap.

The event processing of the incoming data will be covered in the next section.

D. Data Event Processing

We included a TDM-based slicing scheme for communication over the links to avoid cross-talk between our single sensors. But for data analysis, the incoming messages of each interacting group G_i need to be handled together. Communication via MQTT enables data storage of all published topics' latest data. With the topic chosen as shown in Section II-A, all sensor data is available at the MQTT-broker.

For data processing, we apply an *event-driven architecture* (EDA). The EDA is very popular in the financial sector to estimate stock market prices and investment management. In our system, it is included to process and fuse the event sensor data. It is based on three elements which are shown in Figure 3. In the following, we interpret each arriving sensor data message at the MQTT-broker as an event. So, the *Event Creation* is given by our basic multi-sensor system.

The most crucial part of data processing based on the EDA is the *Complex Event Processing* (CEP). The CEP checks for concatenation of asynchronous events. In the following, a complex event is a composition of multiple events defining a *state* for the system. To determine this state, the latest sensor data of the group G_i are combined and evaluated together. The CEP is following a rulebook for queries in the *Event Processing Language* (EPL) to implement this. The EPL is

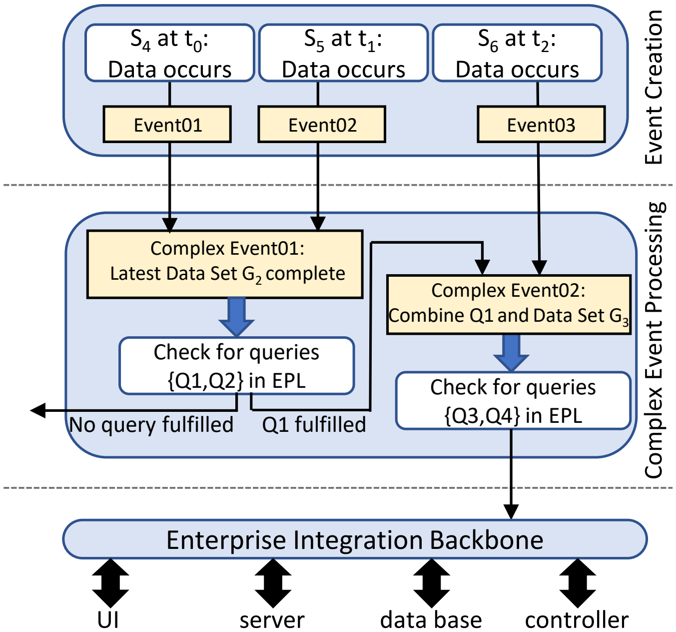

Figure 3: Event driven architecture for data processing.

an extension of the Structured Query Language (SQL). The narrow structure of the EPL simplifies the implementation of the evaluation of one or multiple queries.

In Figure 3 we see set of events as data resulting from sensors S_4 and S_5 of group G_2. This complex event triggered by events *Event01* and *Event02* is evaluated against the queries Q1 and Q2 of the EPL. If one of the queries matches, the complex event is recognized and can be forwarded to the subsequent matching with other (complex) events. Here, Q1 is fulfilled, and the result of Q1 is combined with the latest data of group G_3, creating another complex event. After evaluating Q3 and Q4, this can be the end of the query comparison and trigger another event, e.g., another measurement, a statement about a nearby metal object, or a display on a UI. Data that does not satisfy any query is dropped. So, the CEP handles data while live measurement and provides cleaned events as states. On the other hand, it eliminates the unwanted or redundant source events by fulfilling no query.

The third element, the *Enterprise Integration Backbone* (EIB), is representative of the interoperability of various interfaces. EIB enables the communication between multiple service devices (e.g., UI, server, databases, controller) without a bilateral communication initialization between all devices. So, no data wrapper or parser is needed for direct data exchange. Since all devices and the sensors are connected via MQTT protocol, we transform the idea of the EIB into an overall connectable data broker and add a parser when needed.

After introducing our general multi-sensor platform, we will take a look at the integration of the platform in the upcoming section.

III. Multisensor Platform Implementation

This section presents a multi-sensor platform implementation for underwater object detection and localization applications. The system is operated on an ROV, and we assume an existing wired communication link to the mother vessel. Figure 4 shows the multi-sensor platform with an EIT array, analog ultrasonic sensors, altimeters, and magnetic sensors.

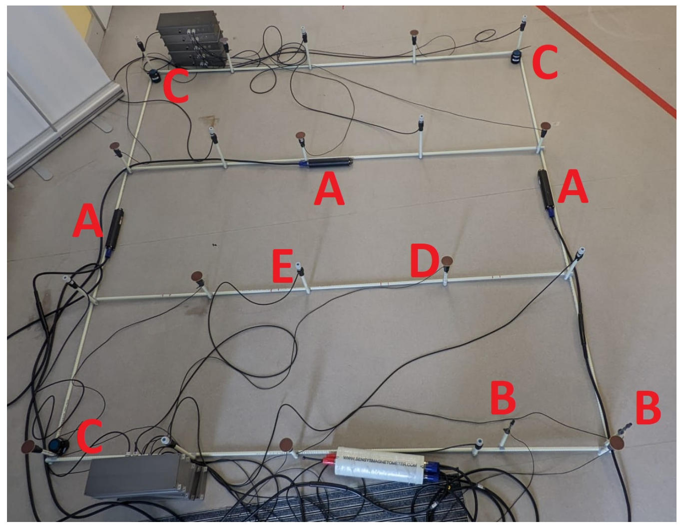

Figure 4: Multi-sensor platform prototype for underwater object detection and localization. A: magnetic sensors, B: ultrasonic transducers, C: altimeters, D: EIT source electrode, E: EIT measurement electrode.

All sensors are connected via adapter components to the underwater telemetry unit that provides the Ethernet connection to the sensor controller and data processing on the mother vessel. The structure of our multi-sensor implementation is shown in Figure 5.

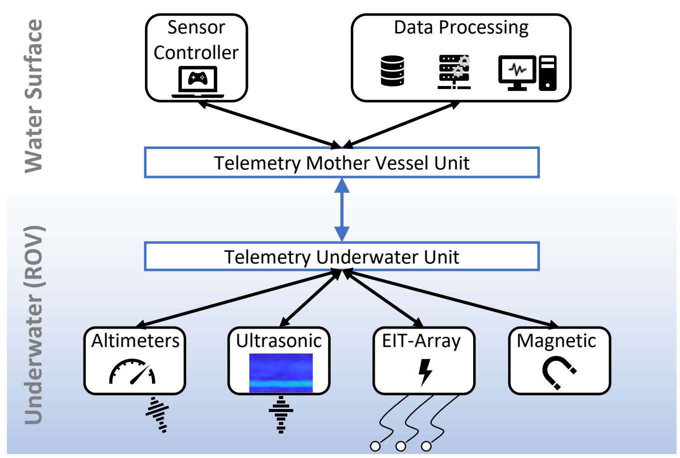

Figure 5: Structure of our multi-sensor platform.

Our modular multi-sensor setup is extensible with new sensors that communicate via the proposed MQTT protocol, with the defined control and status messages in Section II. The top-level components, sensor controller, and data processing are described in Section IV. The uniform communication protocol allows flexible and parallel operations, such as data storage, display, and calculation.

We present the sensor components with their adapters in detail in the following sections. First, we introduce our universal underwater sensor box used for the EIT electrodes and analog ultrasonic transducers in the system. Then we show the integration of the altimeters with their serial communication protocol. The magnetic sensors are connected via Ethernet, and we present our adapter to connect them via MQTT.

A. Universal Underwater Sensor Box

We developed a universal sensor connection box that provides two analog input and output channels to connect various analog sensors. The box implements our proposed unified communication protocol and is directly adaptable to our multi-sensor platform. Figure 6 shows the structure of our universal underwater box, which contains two DCDC converter boards for power supply and a RedPitaya for data processing. The DCDC converters provide 5 V @ 1.6 A and ±15 V @ 1 A output from the variable DC input voltage $18 - 25$ V. The RedPitaya is an embedded signal generator and oscilloscope device with 125 Msps and 14 Bit resolution. The components are mounted in a waterproofed case, with space left for additional analog signal processing circuit boards.

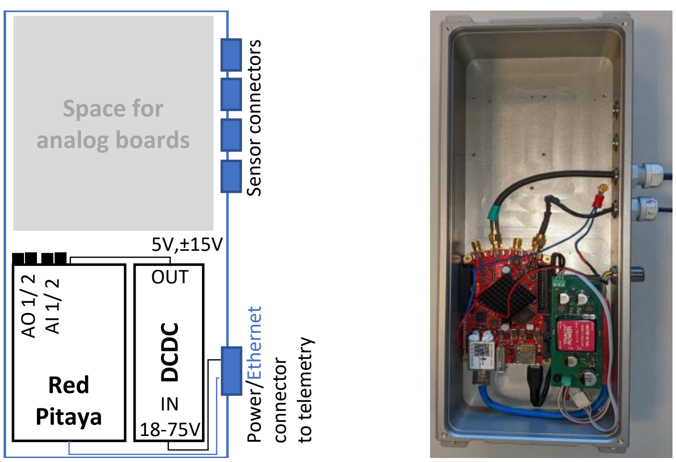

Figure 6: Universal underwater sensor box structure and photo.

Please refer to our publication for detailed information about the universal underwater sensor box [12]. Our Sensor Box achieves data rates of up to 2.73 MB/s with an underwater weight of 0.2 kg.

B. EIT Array

We integrate an EIT array on our multi-sensor platform for underwater object detection and localization. The EIT is formerly known for medical imaging applications, where the reconstructed image provides information on the conductance distribution in the region of interest. An EIT array consists of electrodes that apply an electrical current to the environment and measure the distribution of the resulting electrical field. EIT arrays for underwater object localization were evaluated with a resolution in the range of the electrode spacing in [13], [14], [8].

We implemented an EIT array with dedicated source and measurement electrodes. We chose this design to reduce the complexity of the electrical circuits needed to operate the array. Furthermore, this design enables the use of electrodes with an increased electrode area for the current sourcing with low transfer resistance and electrodes with a small conduction area to measure the electric field distribution. The EIT electrodes are operated with our universal underwater sensor box described in Section III-A. We operate one sourcing electrode and one measurement electrode with each sensor box. Figure 7 shows the block diagram of our EIT sensor box with a controlled current source and an analog signal processing PCB for differential and amplified measurement of the electric field distribution and the current.

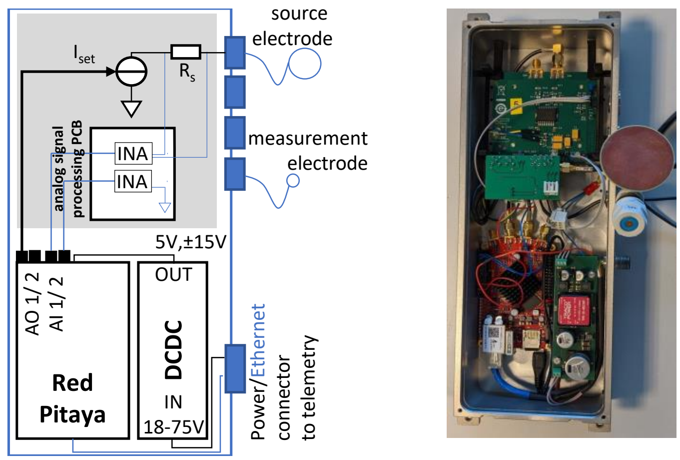

Figure 7: Block diagram of the EIT array sensor box.

Our analog signal processing PCB is designed for flexible analog input filters and provides a variable gain adjustment. Our EIT sensor boxes are flexible for other analog sensors, with very small measured signals.

We set up a multi-sensor platform with ten source electrodes and ten measurement electrodes operated with ten sensor boxes. For the synchronization of the electrodes, we use a central digital trigger signal that starts the signal output and acquisition on all boxes simultaneously. From the measured signals, we get the amplitude and phase. The electrodes are operated with sinusoidal signals with an adjustable frequency f_0. To reduce the necessary data rate for transmission to the data processing modules on the mother vessel, the RedPitaya firmware calculates the amplitude and phase for the given frequency f_0 with a Fast Fourier Transformation (FFT). Only the amplitude and phase information are published via the MQTT broker. Compared to publishing 16384 recorded floating-point samples, we reduce the required data rate to a minimum with the two calculated floating-point values (amplitude and phase).

The 10 EIT electrodes are arranged in an array with the size of $2\,\mathrm{m}{\times}2\,\mathrm{m}$ and space between the electrodes of $0.8\,\mathrm{m}$, as shown in Figure 4.

C. Analog Ultrasonic Transducers

The analog ultrasonic transducers are also operated with our proposed universal sensor box in Section III-A. For the analog signal processing of the ultrasonic pulses, we apply another self-designed PCB. The signal processing and the ultrasonic system are described in earlier publications [15], [12], [16]. Our ultrasonic sensor system applies wideband pulses in the range of $90 - 150\,\mathrm{kHz}$, and we use a spectral model for flat buried object localization. The localization algorithms require performance that is not met with the RedPitaya, and therefore, we publish the measured raw data floating-point array with 16384 samples for each ping. Then the localization algorithms are calculated on the mother vessel's data processing PC.

The ultrasonic transducers are located at a corner of the multi-sensor platform shown in Figure 4. We ensure a maximum distance to the altimeters on the three other corners to reduce mutual influence between the acoustic sensor systems. Also, the operating frequency of the altimeters is in a higher frequency range (refer to the next Section III-D). The ultrasonic transducers are triggered with an MQTT message from the mother vessel's sensor controller. When the trigger message is received, the signal output and acquisition are started. When the 16384 samples are received, the measured buffer is published via MQTT, and the analysis of the data on the mother vessel is performed.

D. Altimeters

We apply three altimeters on our multi-sensor platform to acquire detailed position information of our system. The distance to the seabed is an additional parameter used for the data fusion algorithms later and precisely close to the ground operation of the multi-sensor platform. The three altimeters also help to position the platform parallel to the seabed.

The altimeters provide a serial interface (RS 232) for control and data acquisition. To communicate with such sensors, we developed an adjustable adapter to pass through data to serial interfaces via MQTT. The software configuration includes the serial port name, baud rate, and flow control parameters. The lightweight software automatically connects to the broker and serial device on startup and is operable on Windows and Linux systems. On our multi-sensor platform, the altimeters are connected to one of the RedPitayas in the EIT sensor boxes.

E. Magnetic Sensors

The magnetic field sensors are located in the center and at the edges of the multi-sensor platform. This arrangement is used to perform differential measurements to locate the origin of magnetic dipoles. The magnetic sensors push their data continuously via Ethernet. We developed an adapter to pass through the measured magnetic field strength values of the tri-axial magnetic sensors from sensys. The raw data are processed on the mother vessel's data processing PC.

IV. Multisensor Control and Data Processing

We describe the multi-sensor control and data processing components in this section. The overall system consists of multiple software components that interact on an event-driven architecture. Each software module subscribes to the relevant topics and publishes its results to the broker. This architecture increases the scalability, allows computation on distributed hardware resources, and decouples the visualization from the processing algorithms. With this modular software architecture, the system's robustness is raised, and additional modules for debugging are applicable in case of unexpected errors.

The adapters of the sensor components publish their `STATUS` and `ERROR` messages as described in Section II-B. To observe the health state of the sensor components, they publish periodic alive messages. The status monitoring system lists the time of the last received alive message for each sensor by subscribing to the topic `+/STATUS/ALIVE`. Also, the errors of the sensors are displayed and logged by subscribing to the `+/ERROR/#` topic.

We developed a scheduling software for our multi-sensor platform that works with three slices. The magnetic sensors, EIT electrodes, and ultrasonic transducers build an interacting group. We perform the measurements of each sensor component in a dedicated slice. The adapter of the magnetic sensors publishes data to the broker after its activation via the message `Topic: magnetic/CONFIGURE, Payload: START`. The system itself measures continuously, but the values are published to the broker only in the slice when no other interacting system is active. The EIT sensor boxes are activated in their slice, and the electric current and the electrical components in the box don't interact with the magnetic system. Each possible combination of sourcing electrode pairs is activated and triggered sequentially during the EIT measurement. An EIT measurement with ten electrodes takes several seconds. In the third slice, the analog ultrasonic transducers are activated and perform a set of pings (the number is adjustable). The measured data are published and processed on the mother vessel's data processing unit.

The data processing for each single sensor approach is integrated into the data processing. Our data fusion algorithms are still in the development phase, and the proposed multi-sensor platform prototype is ready to perform its first measurements outside the laboratory environment.

V. Conclusion

We presented a multi-sensor platform prototype for underwater object detection and localization in this work. Our proposed system is ready for first measurements in underwater environments, and data fusion algorithms are still in the development phase. We presented an extensible and scalable system approach with our modular architecture and the uniform communication protocol. Also, debugging during the runtime and parallel data processing with various algorithms is possible with our approach.

Next, we perform object localization measurements with the multi-sensor platform. We will evaluate the data fusion results and the single sensor measurements for this sensor platform.

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