CLAM - CoLlAborative eMbedded networks for submarine surveillance: An overview

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***Abstract*—This paper provides an overview of the CLAM project, which aims at developing a collaborative embedded monitoring and control platform for submarine surveillance by combining cutting edge acoustic vector sensor technology and 1D, 2D, 3D sensor arrays, underwater wireless sensor networks protocol design, advanced techniques for acoustic communication, new solutions for collaborative situation-aware reasoning and distributed data and signal processing and control for horizontal and vertical sensor arrays. The result will be a new system architecture accommodating pervasively distributed heterogeneous sensor nodes deployed at different water depths, which provides a flexible, reconfigurable, and robust platform for online surveillance of submarine environments. Horizontal and vertical collaboration between sensor arrays by means of beam forming, sensor fusion and distributed processing and reasoning enables fine-grained monitoring of the submarine environment and collaborative event detection as well as transmission of the network information to the monitoring stations such as buoys and AUVs.**

I. Introduction

Recently there has been a significantly increased need for underwater communication systems with high data rates over considerably longer distances for military, security, and civilian applications including fields of energy production (oil, gas extraction), energy distribution (e.g., oil plants, oil transport, seaport monitoring), and monitoring wellbeing of marine life. Products claiming to meet these needs are appearing, but are still not technically mature. In what follows, we highlight challenges faced by current underwater monitoring systems.

A. Challenges of underwater monitoring

Monitoring the underwater world is a challenging task due to its complexity, size and extreme harshness, and due to the limited technology we can count on today. Current state-of-the-art in underwater technology includes acoustic modems as well as sensors and autonomous underwater vehicles (AUVs). Individually, these technologies are mature enough to justify the idea of their integration into an underwater communication network. However, current monitoring solutions suffer from costly and difficult installations and sometimes dangerous operations. Once installed, collecting the data from the underwater sensing systems is by no means simple. Long cables may be needed to connect underwater sensors to sea-surface equipment from which data can be collected or transmitted. In addition very costly point-to-point communications may be required. In short, existing underwater monitoring systems have numerous drawbacks such as:

- Coarse-grained data measurements: most present-day underwater sensing systems are deployed very sparsely. The coarse-grained measurements obtained therefore do not reflect the phenomenal changes accurately. This hinders efforts to fully understand the dynamics of the underwater environment.
- Inadequacy of point-to-point communication links: operating in an insufficient data rate acoustic channels and in a single-hop network is a normal practice in existing underwater monitoring systems. This, however, is not adequate for underwater monitoring applications where higher data rates over considerably longer distances are required to deliver the necessary communications capabilities.
- Frequency dependent attenuation and refraction of the acoustic signal cause shadow zones, which pose problems to reliable communication.
- Lack of low-power acoustic sensors and transmitters for underwater: current underwater monitoring systems have high power transmitters, which need large size battery packs. The frequent battery shifts also greatly contribute making widespread deployment of the current underwater monitoring systems difficult.
- Inadequacy of current networking protocols: to sense and monitor submarine environments, sensor nodes should be deployed in 3D and their location is usually controlled (as nodes are attached to buoys and float at different controllable depths, or are anchored to the seafloor). Given their higher cost and the higher size of the areas over which they are deployed, underwater sensor nodes tend to be much sparser than in wireless sensor networks deployed on land. This demands a careful 3D topology control planning to enable node connectivity on the one hand and to optimise placement for better performance on the other hand.
- Lack of suitable heterogeneity supports for the different devices involved, including sensor nodes and AUVs.

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- Lack of collaborative in-network processing and in-situ decision making: simply storing all acquired sensor readings centrally for analysis at a later time prevents real-time assessment at the point of action and providing timely feedback. This could prevent users from, for example, predicting dangerous events well in advance.
- Unreliability in harsh environments: the fact that only a single underwater sensing system is used to cover a large geographic area means that such systems are not robust as the failure of a single sensor may result in an important event being undetected. Harshness of the underwater environment also contributes to more frequent failure and mis-calibration of the sensing devices, routing faults, failures at the network level, and loss of measurements.
- Long delays and low bandwidth: delays are longer than the ones experienced in terrestrial wireless networks and the bandwidth of an acoustic channel is much lower than over wireless RF links.
- Difficult deployment and high capital and operating costs: large size and high cost (in terms of purchase, installation, and maintenance) are obstacles towards easy and widespread deployment of current monitoring systems. In addition, periodic manual calibration needed to ensure that systems continue to operate reliably is a labour-intensive procedure and greatly contributes to this issue.

II. CLAM'S VISION

The ultimate goal of the CLAM project is to develop a collaborative embedded monitoring and control platform for submarine surveillance by combining cutting edge acoustic vector sensor technology and 1D, 2D, and 3D sensor arrays, underwater wireless sensor networks protocol design, advanced techniques for acoustic communication, new solutions for collaborative situation-aware reasoning and distributed data and signal processing and control for horizontal and vertical linear sensor arrays.

Such platform will be based on underwater wireless sensor networks made of low-cost acoustic particle velocity sensors measuring acoustic quantities, which cooperate with each other to sense the environment, and which communicate real-time information to the users about risks, hazards and events of interest. Sensor measurements will be combined both horizontally and vertically and collaboratively processed through distributed situation-aware algorithms and reasoning mechanisms. Communication of information in underwater scenarios is performed via a hybrid network combining multi-hop wireless acoustic communications with cabled communications (whenever available). Collaborative beam forming will also be considered as an option to improve link reliability or bridge otherwise disconnected network portions. The resulting underwater monitoring platform is then interconnected with centers where the information is stored and processed.

The CLAM project will directly address these challenges and will provide a constructive solution to the technical problems of meeting requirements of various underwater applications. This will entail the development of low power acoustic sensors, sensor platforms, and very innovative monitoring, communication and distributed processing and reasoning schemes at all levels (from PHY, to multiple access and beam forming protocols, end-to-end transport reliability, middleware and application design), which will make such an effort unique worldwide. In addition, the development of novel simulation and design tools will provide an effective means to evaluate the performance of the proposed solutions.

III. CLAM'S SCIENTIFIC OBJECTIVES

The scientific objectives of the CLAM project are:

- To develop an integrated miniaturized, low-cost and robust sensing and communication underwater platform that can be used both for collaborative monitoring of acoustic quantities of the underwater environment and as an active communication transceiver.
- To develop an architecture that provides an energy-efficient, robust and accurate solution for fine-grained and online monitoring of submarine life.
- To design, develop and evaluate a robust and compact underwater wireless sensor network communication protocol stack including MAC, time synchronisation, and localisation for submarine surveillance.
- To develop a robust and scalable platform for collaborative networking and beam forming.
- To design, develop, and evaluate distributed data and signal processing, situation assessment, reasoning, and event detection mechanisms for online submarine surveillance enabling learning, adaptation, and self-organization of 3D sensor arrays.

IV. CLAM'S SPECIFIC CONTRIBUTIONS AND INNOVATION BEYOND THE STATE OF THE ART

The project will provide technological advances in many respects. The scenario which will be addressed by the CLAM project, in which sensor nodes floating at different depths autonomously organise into a network, exchanging data via possibly multi-hop paths to a data collection point, or communicating to a passing by remotely controlled autonomous underwater vehicle, is highly innovative and almost unexplored so far. To be implemented, this scenario requires considerable technological advances with respect to the current state of the art in node platform design, both collaborative horizontal and vertical communication sensor arrays and sensors and AUVs, distributed networking protocols, collaborative event detection and situation awareness mechanisms, and requires the specification of modular architectures for such systems. Specific contributions of the project beyond the state of the art include:

- Underwater monitoring technology: research and development activities of the project on low power acoustic sensors for underwater are directed towards the design, calibration and development of an underwater sensing and communication platform.

- Distributed PHY and MAC: CLAM enables collaboration between nodes and will bring them intelligence and flexibility to adjust their parameters such as transmitted power, carrier frequency, time of transmission and how the water volume can best be used. CLAM performs spectrum sensing and transmitted signal shaping/frequency shifting, as well as MIMO/array processing where the suppression of noise/other sources of interference is included to have a better usage of the underwater acoustic spectrum, both in time, frequency, and space. New physical layer solutions based upon a pure temporal SISO solution (both single- and multi-carrier) or upon a combined spatial diversity/temporal MIMO solution will be assessed. In CLAM, we also develop a physical adaptive communication layer which can exploit a wide frequency spectrum and thereby make cognition possible in the frequency plane. Based on PHY specification, new schemes for MAC, awake-asleep schedules, and data link protocols will also be provided which account for the unique features of the underwater systems and of the acoustic channel.
- Error resilient topology control: CLAM offers solutions for topology control and mobility support establishing where to locate nodes, with which density, at which depths in order to optimise the network performance, how to set the transmission ranges of different nodes, and how to collectively optimise all the different aspects including topology control, acoustic transmission, and MAC. We stress the fact that building a protocol stack for multi-hop underwater sensor networks, in which 3D sensor arrays collaborate for communication, processing, and reasoning is in itself a completely innovative goal. Multi-hop heterogeneous sensor networks for harsh underwater environment require re-defining the entire protocol stack.
- Multi-hop routing in acoustic networks: CLAM offers efficient routing by online relay selection techniques that couple MAC level mechanisms with specific routing metrics so that the next hop on a multi-hop path is chosen during the very channel access phase. Through our cross-layer design, which involves PHY level awareness, higher layers (up to the application level) will be able to tune PHY behaviour so as to keep an acceptable trade off between, e.g., energy consumption, throughput and delay performance.
- Collaborative processing and reasoning: collaborative in-network data and signal processing and reasoning offered by CLAM enable situation-awareness and the ability to identify phenomenal changes at the point of action whenever and wherever they occur. Different sensor arrays in horizontal line will collaboratively fuse and process their measurements to identify interesting events. The outcome will be fused and aggregated vertically at sensors deployed at different water depth, increasing the reliability of the decision making and enabling long range communication and transmission. This will allow 3D situation-awareness. To cope with the dynamic and unreliable nature of the network and the underwater deployment environment, adaptive learning mechanisms will be designed to increase the robustness of the system. Collaborative event detection offers not only 2D but also 3D reliable fine-grained situation-awareness.
- Combining modeling, simulation, lab and real-world experiments: the project will design a framework for the evaluation of such systems, building (and using) a mixed experimental and simulation system evaluation framework. Such framework is lacking at the moment and could stimulate further research in the area allowing easy and fast benchmarking with the state of the art. Emulation will be performed porting our simulation environment on GUMSTIX platforms. This will allow to easily port the implementation of the solutions under test, written for our simulation framework, on real devices: GUMSTIX platforms can be connected to acoustic modems and embedded on real node prototypes. This methodology will therefore ease and speed up the process of going from simulated solutions to solutions which can be implemented and tested in real-world deployments, allowing fast feedback on critical aspects of the developed solutions.

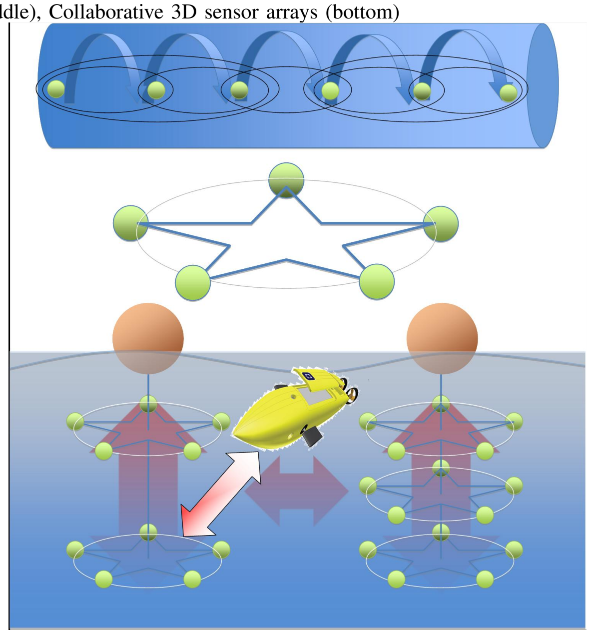
CLAM's vision of a complete collaborative embedded monitoring and control platform for underwater settings requires advances beyond the current state-of-the-art research and technical solutions in many respects. We consider the three cases shown in Figure 1, in which collaboration enables communication, in-situ processing and reasoning: (i) 1D linear sensor arrays attached to underwater infrastructures (e.g., pipelines) need to share and process their observations collaboratively to be able to provide a global view about their area of observation and reliably identify phenomenal changes. This means that instead of traditional fixed clustering techniques, collaborative dynamic clustering techniques are needed to adapt the cluster formation and information sharing to the requested quality of service and application requirements, (ii) 2D sensor arrays deployed on the sea floor or at same water depth need to collaborate to make real-time in-situ decisions, (iii) 3D sensor arrays need to collaborate to bridge their communication gap. By fusing data and decisions made locally at each 2D sensor array, collaboration between 3D sensor arrays increases the reliability and robustness of the monitoring, dealing with errors and uncertainty at various levels.

V. CLAM's Overall Methodology

The general research approach taken in the CLAM project is necessarily multidisciplinary as many of the identified challenges need to be addressed in an inclusive way that considers technology, networking, processing, and applications in close correspondence. In the CLAM project, equal weight is given to bottom-up technology-driven work on an integrated infrastructure for CLAM, and to top-down design- and industry-driven research on application settings.

The particular scientific methods to be used range from mathematical modeling (e.g., mobility and resource optimization problems), simulation (e.g., of network, distributed pro-

Fig. 1. Collaborative 1D sensor array (top), Collaborative 2D sensor arrays (middle), Collaborative 3D sensor arrays (bottom)



cessing, event detection protocols), hardware/software prototyping, and system measurements to scenario design, contextual analysis, requirement analysis and system evaluation in situ.

As an integration point for different research activities, CLAM will use validation settings in which monitoring systems and technologies will be tested and their applicability for underwater applications will be explored. CLAM's approach to enable collaborative monitoring and control platform for a submarine surveillance depends on cooperative, distributed, and reliable systems that can evolve and adapt to radical changes in their environment, in-situ awareness of occurrences of events and phenomenal changes, delivering information services that adapt to the people and the services that use them. These collaborative and distributed systems must easily and naturally integrate different devices, ranging from tiny sensors and actuators to AUVs and possibly other types of marine vehicles. Such devices will be connected primarily by underwater communication networks, as well as by high-bandwidth wireless backbones (for communication over the sea surface). The system must be able to configure, install, diagnose, maintain, and improve itself — this applies especially to the vast numbers of sensors that will be cheap, widely dispersed, and possibly even disposable.

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