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Coastal Marine Data Crowdsourcing Using the Internet of Floating Things: Improving the Results of a Water Quality Model

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ABSTRACT While the *everything as a sensor* is a typical data gathering pattern in the Internet of Things (IoT) applications in contexts such as smart cities, smart factories, and precision agriculture, among others, the use of the same technique in the coastal marine environment is still not explored at full potential. Nevertheless, when it comes to maritime scenarios, the application of IoT and networks of distributed sensors and actuators are still limited, even though the development of marine electronics and extreme network technologies are present for decades also in this area. In this paper, we first introduce the concept of the *Internet of Floating Things* (IoFT), which extends the IoT to the maritime scenario. Next, we present our latest implementation of the DYNAMO (Distributed leisure Yachts sensor Network for Atmosphere and Marine Observations) system, a framework for coastal data collection from sensors and devices deployed in marine equipment. To demonstrate the importance of IoFT data collection in the real-world environmental science context, we consider a scientific workflow for coastal water quality. The selected application focuses on predicting the spatial and temporal pattern of sea pollutants and their possible presence and time of persistence in the proximity of mussel farm areas in the Bay of Pozzuoli in Italy. The pollutants are simple Lagrangian particles, so the ocean dynamics play an important role in the simulation. Our results show that integrating crowdsourced bathymetry data in the workflow numerical model setup improves the accuracy of the final results, allowing for a more detailed spatial distribution pattern of the sea current driving the Lagrangian tracers.

INDEX TERMS The Internet of Floating Things, marine data crowdsourcing, food quality, mussel farm.

I. INTRODUCTION

Thanks to the extensive widespread and adoption of IoT devices worldwide, the use of crowdsourced data to solve important societal problems has recently become the norm [1]. Nowadays, among other things, we use: (i) smartphone data to monitor and predict car traffic patterns to solving several challenges, such as reducing air pollution and oil consumption; (ii) sensors scattered around cities to monitor the weather and air quality, which helps improving health; (iii) data from industrial IoT devices in the automotive sector to achieve mission-critical objectives; (iv) data from smart home devices to improve our lifestyle thanks to home automation.

In this paper, we envision the utilization of leisure and working vessels as potential instruments for collecting coastal marine data in a crowdsourcing fashion. Indeed, these vessels are equipped with on-board sensors, which can collect precious data whenever the ships are on the water following the paradigm of *Internet of Floating Things (IoFT)* defined in [2]. Moreover, in this work we show how the IoFT, and the collection of coastal marine data from on-board vessel

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instruments and sensors, can be exploited to improve the numerical forecast of pollutants transport and diffusion for marine farms' products quality assessment. Mussel cultivation and fish breeding are among the main economic activities in coastal areas and a common and affordable source for the food business in the Mediterranean area. An accurate environmental forecast is therefore required to evaluate the effects of marine pollution on coastal inhabitants' health. However, the monitoring of pollution in seawater through connected smart devices could be impracticable due to the aggressive saline environment, the low network availability, and the maintaining and calibration costs. Furthermore, in an operational context, a computational infrastructure must be dedicated to perform numerical simulations to produce high-resolution space and temporal predictions of weather and marine conditions.

The presence of pollutant substances in seawater, usually due to anthropic pollution, coastal discharges, or leakages in open sea, can adversely affect the quality of the production in aquaculture farms (fish or mussel), with the consequently influence on consumers' health. Studies have shown that the pathogen substances, such as bacteria and enteric viruses [3], transmitted by mussels [4], can affect the incidence of Hepatitis A cases, as happened in southern Italy [5].

As mitigation actions, the following have been considered: (i) planning of periodical in-situ measurements [6]; (ii) using numerical model simulations [7]; (iii) using connected smart devices for real-time monitoring [8]; (iv) a mixing of the previous solutions in the IoFT context [9], [10].

The livestock sampling and the microbiological spottily analysis fail if the goal is to collect a consistent data time series needed by any process aimed to safeguard human health. On the other hand, the availability of technologies for remote water quality monitoring using wireless sensors [11] is totally feasible in a limited extended environment. In addition to this, in open sea, the extreme weather events, the aggressive saline environment, the network and energy unavailability and, and last but not least, the need for continuous maintenance and sensors calibration could have a negative impact on the use of a technical solution entirely based on the IoT approach.

The use of water quality, numerical models can support the problem management. Nevertheless, in order to perform a reasonable model setup, the initial and the boundary conditions have to be as much accurate as possible. In the same fashion, the domain setup has to be enforced with high resolution and updated *bathymetry* in the form of a digital seafloor model. Indeed, if a numerical model is used in production, it has to pass through an accurate validation process. The validation process mitigates, or avoids in a reasonable manner, the model outputs inconsistency.

The reasons explained above justify the joint use of microbiological analysis, numerical models, and IoFT devices (the boats in this use case) in order to have the most efficient and suitable solution to the problem.

A. NOVEL CONTRIBUTION

The contributions in this paper are twofold: first, we present the software architecture of DYNAMO, the IoFT framework for coastal marine data crowdsourcing used for collecting a continuously updated dataset for environmental model simulations. Therefore, as a test-bed for the software environment, we show the improvements achieved in a real application for marine pollution transport and diffusion by using seafloor depth data crowdsourced in the Bay of Pozzuoli in Naples, Italy. These bathymetry data are used to produce an improved version of the sea bottom numerical representation used by the models affects, in a positive way, the overall results about pollution distribution details estimation. The involved numerical models are the Regional Ocean Model System (ROMS), which produces a 4-dimensional field of the sea current, salinity, and temperature [12], and the Water Community Model (WaComM),[1] which is used to compute the transport and diffusion of pollutants for assesing the water quality for mussel farming and fish breeding [7].

The rest of the paper is organized as follows: Section II describes the related work, comparing different approaches involved in the IoT context; then, the DYNAMO ecosystem is presented in Section III, followed by a formal definition of our concept of the IoFT, provided in Section IV; the use case description is given in Section V with details about the WaComM implementation, the operational application, and the improvements gained thanks to the use of the IoFT marine data crowdsourcing; finally, Section VI presents conclusions and future directions of the work.

The dotted red lines are the connection (exchange of data and information) between individual boats and between them and the ground control station. The blue box is a zoomed-in schema of the possible on-boards instruments of the single boat.

II. RELATED WORKS

The idea of using low-cost sensor networks to acquire smart cities' health parameters such as weather, pollution, noises, etc., has been exploited by many projects and in different areas has currently moved from research to production stage [13]. In 2012, [14] proposed the use of a network of smart sensors for in situ and in continuous space-time monitoring of seawater (temperature, salinity/conductivity, turbidity, and chlorophyll-a concentration).

To the best of our knowledge, one of the most successful projects in this area is the *Array of Things* [15], managed by Argonne National Laboratory and the University of Chicago. In this case, some sampling stations have been deployed over the City of Chicago area. In this scenario, the citizen scientist is motivated to use the collected open data to learn how to extract and share knowledge and algorithms with the pairs.

In 2013, a different approach to volunteer city science has been proposed in [16], related to computing urban air temperatures from smartphone battery temperatures and

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[1] https://github.com/CCMMMA/wacomm

crowdsourcing the estimated data for further analysis mainly related to weather, pollution containment, and energy management. This work demonstrates the remarkable potential of these kind of crowdsourcing applications for real-time temperature monitoring in densely populated areas.

As previously remarked, while the use of crowdsourced data on the land, performed by processing user-generated web content, data from mobile apps, or leveraging on citizen scientists acting on a voluntary basis, is a common way to gather large amount of social, economic, and environmental data [17], [18], the same kind of applications in the sea have not been explored yet at the full potential, opening new frontiers for research opportunities.

The authors of [19], in 2012, proposed a volunteers crowdsourcing program devoted to monitoring the color, the transparency, and the fluorescence of the sea. The authors propose to use the volunteers' smartphone cameras to get the sea/ocean color and then infer the other water properties using a post processing stage once data are uploaded on cloud-based storage systems (Dropbox or Google Drive). Other considered sensing devices are low-cost moored sensors and wearable underwater cameras or remotely operated vehicles (ROVs).

The concept of ''Common Oceanographer'' is widely defined in [20], which could be considered a sort of marine data crowdsourcing *manifesto* because the authors propose a crowdsourced effort of oceanographic data performed mainly by leisure yachts and charter vessels cruising around the world. Considering the Lagrangian and Eulerian approach on ocean observation paradigms, the authors evaluate the cost of about 30K USD (2014) per day for operating a dedicated ocean research vessel, excluding the full cost of scientists, engineers, and the cost of the research itself.

In a recent paper [21], a crowdsourcing methodology for collecting and sharing weather data for typhoon forecast and warning in the South East Pacific ocean region is proposed. The authors make use of the Automatic Identification System (AIS), adopted internationally to facilitate ship-ship and ship-shore data exchange, to developed a communication link between ship/shore and buoys, in order to facilitate the weather data collection and sharing via the shore-based AIS network to ship-borne application platforms.

At the best of our knowledge, there are some business applications leveraging on bathymetry crowdsourced data in order to improve marine digital maps such as, but not limited to, Navionics Sonar Maps.[2] From the open data point of view, the project run in the context of OpenSeaMap[3] has the aim to collect leisure yachts GPS positions and depth data from the on board echo sounder on a volunteer basis. Table 1 compares and contrasts these last two applications and DYNAMO.

Signal K[4] is an open data format designed for marine electronics. Although marine electronics leverages on industrial standards for decades such as NMEA0183, SeaTalk, and NMEA2000, among others, none of those is completely open and usable free of royalty charges. Signal K is a community initiative supported by marine electronics companies, computer scientists, and engineers and expert sailors, recognised by the National Marine Electronics Association (NMEA). From the technical point of view, it is built on standard web technologies, including JSON, WebSockets, and HTTP. Strategically, Signal K has been designed in order to facilitate the development of IoT and home automation on board of leisure and professional vessels.

A. DISCUSSION

The proposed DYNAMO vision can be compared with the system described in [20]. We identify the main difference to be how the concept of ocean sampling and data collection is defined. The idea of depicting the ''Common Oceanographer'' model to take into account a nearly invasive refitting of leisure and charter vessels in order to host *ad-hoc* ocean sensors such as, but not limited to, conductibility-temperature-depth sensors and water sampling bottles. Even though this vision could be engaging for both oceanographers (having data familiar to manage) and wealthy yachtsmen (a new toy on board), a real-world application could be limited by the fact that it is focused on a small size of potential crowdsourcing contributors. On the other hand, DYNAMO is targeted to small boat users more than yacht ones. That means having a potentially bigger audience of participants that can be involved, because of the lower costs of small yachts and boats. DYNAMO is not invasive since the concept of IoFT leverages on on-board sensors that are already present, usually connected to each other using commonly spread industrial standards that are stable, resilient, and reliable.

Moreover, what is described in [21] is also similar to the DYNAMO idea, but limited to weather data, which are just one of the many data types that can be sampled using the DYNAMO approach. Nevertheless, the use of the AIS infrastructure for transporting small amount of data, as performed by [21], could be explored for future DYNAMO developments.

The business oriented bathymetry data crowdsourcing is made possible thanks to high quality marine mobile maps applications or custom devices, leveraging on jealously protected custom protocols with no chance for a user to share data with other peers or institutions in an open data fashion. The OpenSeaMap *''Depth''* project works by leveraging on a simple logger. Users have to manually upload the logged data to the OpenSeaMap resources in order to contribute to the project. At the time of writing, the total amount of the shared bathymetry data appears to be quite limited.[5]

Despite the similar applications in both business and open data contexts, the proposed IoFT paradigm is not limited to the bathymetry data, but it is entirely agnostic about the devices and sensors installed on board. In particular,

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[2] http://webapp.navionics.com

[3] https://depth.openseamap.org

[4] https://signalk.org

[5] http://map.openseamap.org/?layers=BFTFFFFFFTF0FFFFFTTT

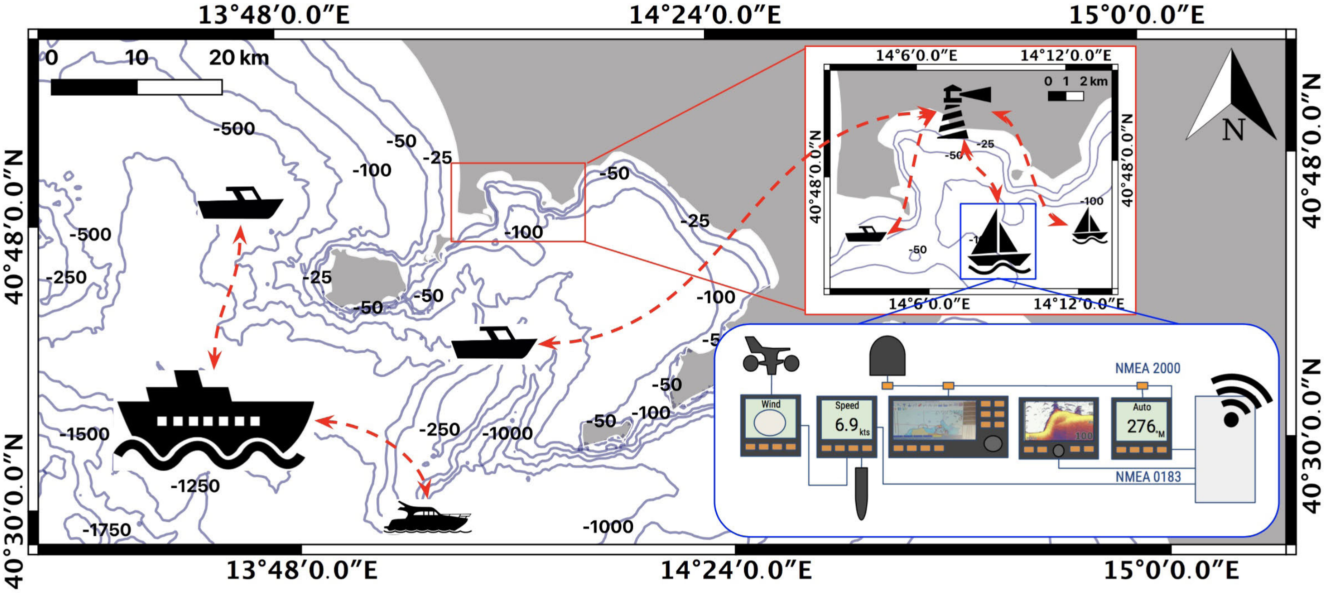


FIGURE 1. A high-level representation of The Internet of Floating Things (IoFT) in the Gulf of Naples, Italy.

TABLE 1. A summarised comparison of distinctive features of the proposed DYNAMO with other related work.

	Open Data	Automatic Data Upload	Secure Data Transfer	Signal K	Data					
					Depth	Navigation	Weather	Engines	Sailing	Attitude
Navionics Sonar Map		✓			✓					
OpenSeaMap "Depth" Project	✓				✓					
DYNAMO	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

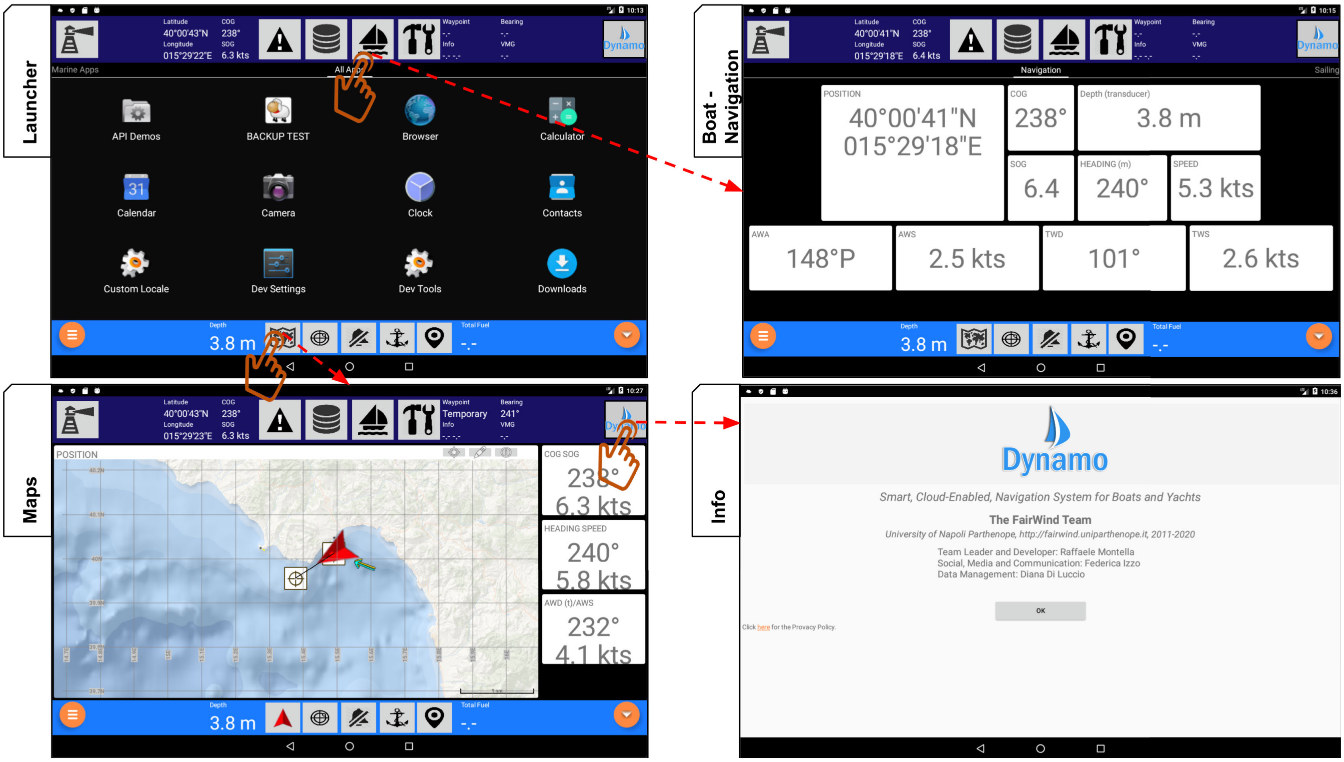
the DYNAMO IoFT implementation leverages on a scalable and cloud-based infrastructure in which the instruments and the sensors on the vessels are loosely coupled with the cloud-hosted databases with no need for the user to interact with complex procedures for data uploading. Differently from other bathymetry crowdsourcing initiatives, DYNAMO leverages on a secure, high performance, and dedicated protocol designed for data movement from vessels to shore [22], which transparently handles the intermittent and unstable network connection vessel-shore. The distinctive features of the proposed DYNAMO are summarized in Table 1 alongside a comparison with other related work.

As for the internal data format, we choose Signal K because of its ability to represent sampled data as delta messages devoted to change the part of the Signal K document interested in the update. Leveraging on this feature, we store and forward only data changing the status of the sampling platform. This approach simplifies the local storage, the security management and, last but not the least, the data movement because groups of delta messages can be grouped in data parcels.

III. DYNAMO

Marine sensors and actuators are closely connected to each other in a close and limited environment. Figure I-A shows a high-level representation of the IoFT using boats. In this specific actualization of the IoFT concept, the "floating things" are vessels, remotely operated vehicles, unmanned underwater vehicles, and similar scientific or offshore industry sampling platforms. The connectivity between the sampling platforms can be rare, intermittent, low performance, insecure, and expansive, due to the extreme operative conditions. In this paper, we try to address two main technological problems: on one side, the sampling platforms are heterogeneous, spatially, and temporally distributed in a sparse fashion; on the other side, they are barely connected to each other and with the Internet, with intermittent and costly services.

The *Distributed leisure Yachts sensor Network for Atmosphere and Marine Observations* (*DYNAMO*) is an open-source marine electronics ecosystem being under continuous development at the Department of Science and Technologies of the University of Naples "Parthenope" (Italy) since 2011. Leveraging on our previous experiences in grid computing enabled instruments [23], in 2011, the idea of *BoatApp* or *Bapp* was born in the context of the design of *sensing instrument as a service* leveraging on the emerging cloud computing technology in order to turn physical tools into ubiquitous services [24].



Dynamo

Smart, Cloud-Enabled, Navigation System for Boats and Yachts

The FairWind Team

University of Napoli Parthenope, http://fairwind.uniparthenope.it, 2011-2020

Team Leader and Developer: Raffaele Montella
Social, Media and Communication: Federica Izzo
Data Management: Diana Di Luccio

Click here for the Provacy Policy.

FIGURE 2. The Dynamo attractive user interface designed to be familiar to old salty users accustomed to interaction with marine electronics but also to be compliant with the mobile applications' user experience. Launcher: Dynamo acts as an application launcher; navigation data are shown alongside the installed apps; the *BoatApps* can be launched browsing the application carousel or from the upper system bar and the lower tools bar. Maps Boat - Navigation: are two of the *BoatApps* installed by default; Maps supports different cartographic data sources (this app is not intended as a primary navigation aid, but just as a support to official marine charts); Boat - Navigation displays all data acquired by on-board sensors with different gauge types; Info: the usual screen with information about the developer team, the supporting institution, and the licenses.

In 2012, the first research prototype was released under the name *Open Sailing Processor (OSP)*, a web-based Internet of Floating Things embryo, which enabled the basis for the technology needed for the convergence between the Internet of Things and the High Performance (Cloud) Computing to be developed [25].

In 2015, the architecture of the OSP project was completely redesigned in order to match the idea of a regular Android device that could act as a hub for IoFT-enabled sensors and actuators and released as *FairWind* in 2016, an Android application compliant with the Signal K standard,[6] which was being developed at the time as an open-source community standard for marine electronics data applications. Nevertheless, the behavior of the Android Garbage Collector management [26] and of the Android scheduler enforced by the Android Low Memory Killer [27], drastically affected the performance, and the real usability, of the FairWind application. That was due to FairWind's heavy CPU usage and RAM needs, which caused unrequited (and almost unpredictable) Android Service and background Activities process killing. Even if mitigated by the use of a watchdog Android Service, often this behavior compromised the usage of FairWind in a real-demanding environment such as sailing at sea. FairWind reached the end of rails in our research effort and then discontinued on the Google Play Store.

Although the early results in IoFT data crowdsourcing were remarkably encouraging [28], thanks to a fast, secure, reliable, and resilient data transfer framework, we abandoned the idea of using a regular Android running on any device in order to implement Android native components to be executed as daemons and libraries on a single board computer provided by an open-source version of the Android operating system [29].

Finally, we released these components under the name of DYNAMO (Distributed leisure Yachts sensor Network for Atmosphere and Marine Observations) ecosystem [30].

The DYNAMO ecosystem is our proposed implementation of the Internet of Floating Things paradigm as on board data processor and store-and-forward data mover from vessels to cloud. In this work, we describe in details the DYNAMO reference implementation of IoFT because: (i) it fosters the most novelty in our overall contribution for both architecture and data management; (ii) it is attractive for the user because the user interface is designed to share both the marine electronics and the mobile applications' user experience (Figure 2); (iii) the concept of **BoatApp** is exploited and transparently

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[6] http://signalk.org

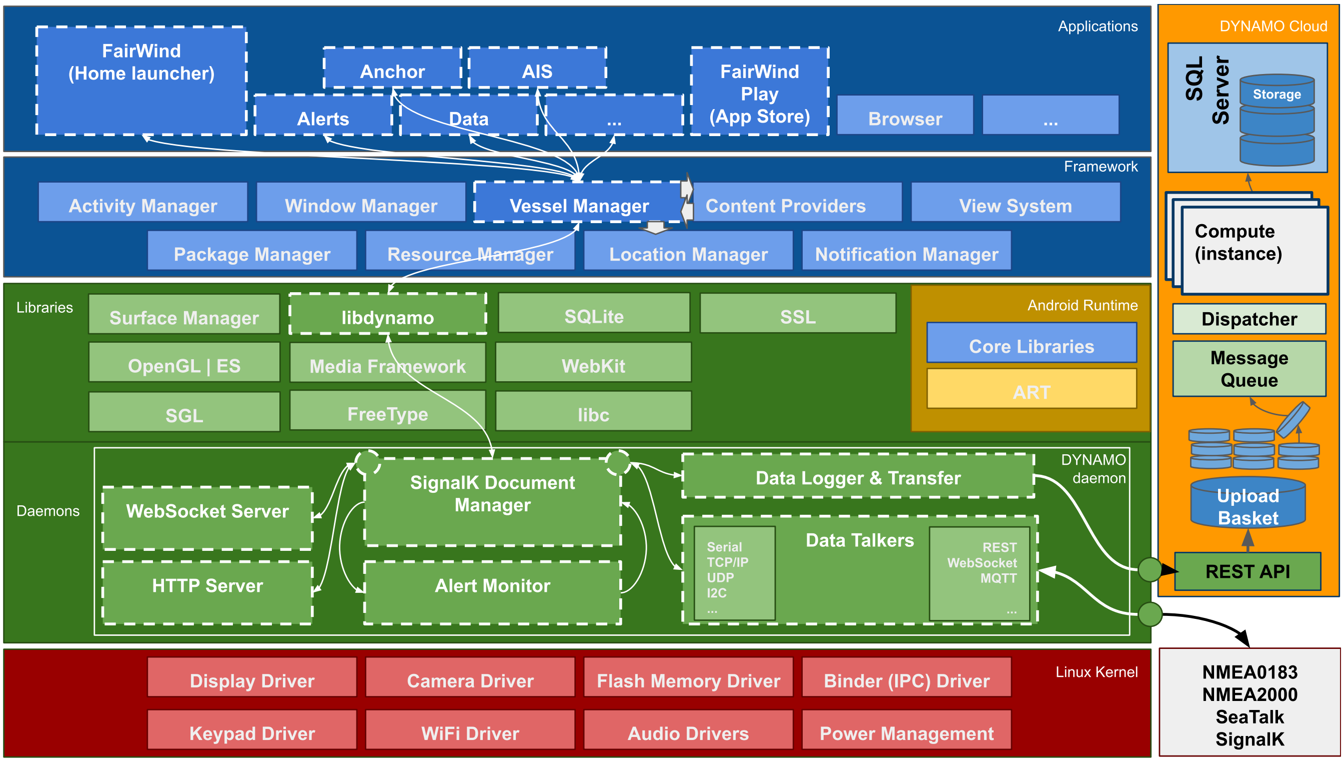

FIGURE 3. The DYNAMO architecture and data flow between components.

integrated into the regular third party developed Android applications.

From the marine electronics point of view, a principle innovation is FairWind, and DYNAMO is the concept of Boat Apps, which can be used to extend their basic features, allowing for integration with the already present on-board instruments and straightforwardly interactions with industrial or self-made IoT-based instruments.

DYNAMO collects data from on-board sensors and instruments connected to different local network protocols acting as data logger, router, and gateway for NMEA0183 and NMEA2000,[7] SeaTalk,[8] and Signal K data. Even small leisure vessels routinely produce a large amount of data that, if collected on a routine base, could be of considerably important for science, engineering, and management of natural resources. They can include large amounts of geolocated data about the marine coastal environment (weather and sea conditions, surface sea currents, water temperature, water depth, etc.), boat engine status, boat performance (speed, heading, pitch, roll), presence of board water and waste management, fuel consumption and, above all, safety at sea and search and rescue systems.

In order to avoid the pitfalls of the FairWind application related to the Android service unreliability for this kind of near real-time application, in DYNAMO we implemented the whole data logging and routing using a daemon running in the privileged unmanaged run level. The Figure 3 shows the DYNAMO data flows and the overall system architecture. The role of each involved component in this big picture schema is detailed below. In order to maximize the portability across Android versions, we enforce a policy of no modifications to the operating system source code, adding our components to a plain Android Open Source distribution.

Data are homogenized using the Signal K format by the **Data Talkers** component, which handles the parsing of most part of NMEA0183,[9] NMEA2000 over NMEA0183 $PCDIN,[10] and SeaTalk1 over NMEA0183 $STALK[11] sentences. The Data Talkers are bi-directional components because it also acts as data repeater or data forwarder on the same or different interface. The same Data Talker can be instanced multiple times, enabling massively multi-sourced data scenarios. Data Talkers can be network-oriented (TCP/IP, UDP, WebSocket) or device-oriented (USB Serial, Bluetooth).

Signal K data are stored in a key/value data structure that supports thread safe access, insertion, and deletion by the **Signal K Document Manager**. Each value is marked by its source and timestamp in order to allow discarding of obsolete data.

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[7] www.nmea.org
[8] www.raymarine.com
[9] https://www.nmea.org/content/STANDARDS/NMEA_0183_Standard
[10] http://www.seasmart.net
[11] http://www.raymarine.com

The **Alert Monitor** is invoked each time a Signal K data value is updated to check whether the new value matches a criterion used to trigger notifications. If it happens, the related notification is added to the Signal K data structure. Notifications via the `libdynamo.so` are handled at a higher level by the software components implemented in the Vessel Manager Framework.

The **Data Logger** handles the data for long-term storage on-board and for vessel-to-cloud transfers. Data are divided into parcels of Signal K update, then they are signed, encrypted, and moved to scalable cloud resources when an Internet connection is stable and persistent. More details about DYNAMO Data Transfer Protocol from both vessel side [28] and the DYNAMO Cloud side [22] point of view have already been evaluated.

The **Web Server** and the **WebSocket Server** enable remote access to the device via either a regular web browser, or via the Signal K compliant REST APIs, or via the Signal K delta update via WebSockets.

The interaction with the Android managed components is performed using an intermediate shared library, `libdynamo.so`, accessible from the Frameworks using the native interface provided by the Android SDK/NDK integration. In order to decouple the accessing privileges between the DYNAMO daemon and the frameworks, the library leverages on a request/response mechanism based on POSIX AF_UNIX sockets.

The **Vessel Manager** is an Android framework providing SDK like features such as shared components, enabling the DYNAMO applications such as the launcher FairWind-Home to interact with the DYNAMO Daemon. Using the Vessel Manager, developers can contribute to DYNAMO apps leveraging on foundation software components. Android applications not explicitly designed for DYNAMO can use the vessel data querying on the Content Provider or using default provided position and attitude data via the Location Manager, making the access to boat data from virtually any already available Android application. The Vessel Framework exposes the Signal K data using the same interfaces provided by the Signal K Artemis server[12]: an instance of the `DYNAMOModel` class implementing the `SignalKModel` interface. The `SignalKModel` interface has been defined and largely used in the Signal K Server Java and represents a sort of standard way to consume Signal K data in Java. A Kotlin API is also provided in order to match the new Android programming language requirements.

The launcher FairWind Home has the same user interface of the previously developed stand-alone FairWind app. However, its features are limited to basic interactions, configuration, data browsing, DYNAMO Data Transfer Protocol monitoring and launching other applications: all the data gathering is delegated to the DYNAMO Daemon. In this way, DYNAMO achieves the near real-time behavior (in the context of our use case) via a tighter integration between the application and the rest of the system [31]. Other features such as map browsing, anchor alarms, AIS control, alerts, depth profiling and data gauges are implemented in different applications using the Vessel Manager framework. Android applications developed using the Vessel Manager framework can be installed using a dedicated DYNAMO application. Regular Android applications can be technically installed and productively used, but this is out of the scope of our research.

Figure 4 shows two stable versions of the DYNAMO core IoFT already installed on some vessels: (i) in (a) the DYNAMO lite version based on Raspberry Pi3 computer and designed to be headless (the user interacts with this device using a smartphone or a tablet); (ii) in (b) a version built on top of (a), but provided by a touch web-based user interface for data browsing, vessel-to-cloud data transfer control and statistics and system configuration.

IV. MARINE DATA CROWDSOURCING

The use of cloud-based services reducing the total cost of ownership and accelerating the democratization of science [32] is a common approach in the field of environmental monitoring and modeling [33]. The value of numerical weather and marine predictions is increased by the need of products dedicated to specific application fields: the final user needs for advice rather than numbers to convert in information. To have more robust and accurate models, detailed, high resolution, space-temporal dense data for model initialization and validation are needed.

Due to the nature and the resolution needed by those kinds of truly vertical applications, the data assimilation rises as a first-class component of the computational workflow. Unfortunately, data required for model assimilation can be hard to obtain from traditional sources, due to the lack of available public data in some coastal areas, challenges of surveying large areas, and other technical constraints.

In the field of ocean modeling, the need for computational and storage resources is currently satisfied by the availability of cloud-based services that reduce the total cost of ownership and accelerate the democratization of science [32]. Nevertheless, to have more robust and accurate models, there is a need for detailed, high resolution, spatio-temporal data for initialization and validation [34]–[36]. While data can be hard to obtain from traditional sources [37], [38], or using satellite, suitable for large scale applications [39], [40], but they do not reach the adequate resolution and quality when approaching the coast.

These difficulties increase due to the lack, in some cases, of available open-source data. These data can be easily obtained using the Internet of Floating Things based crowdsourcing tools. The idea is to use professional vessels and, above all, leisure boats and yachts to collect coastal marine data. Most of the nowadays leisure boat fleets are already provided with a large plethora of sensor instruments that collect weather, marine, and performance data as navigational aids. The core of the system is an on-board data collector gateway running on low-energy and low-cost single-board computers.

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[12] https://github.com/SignalK/signalk-java

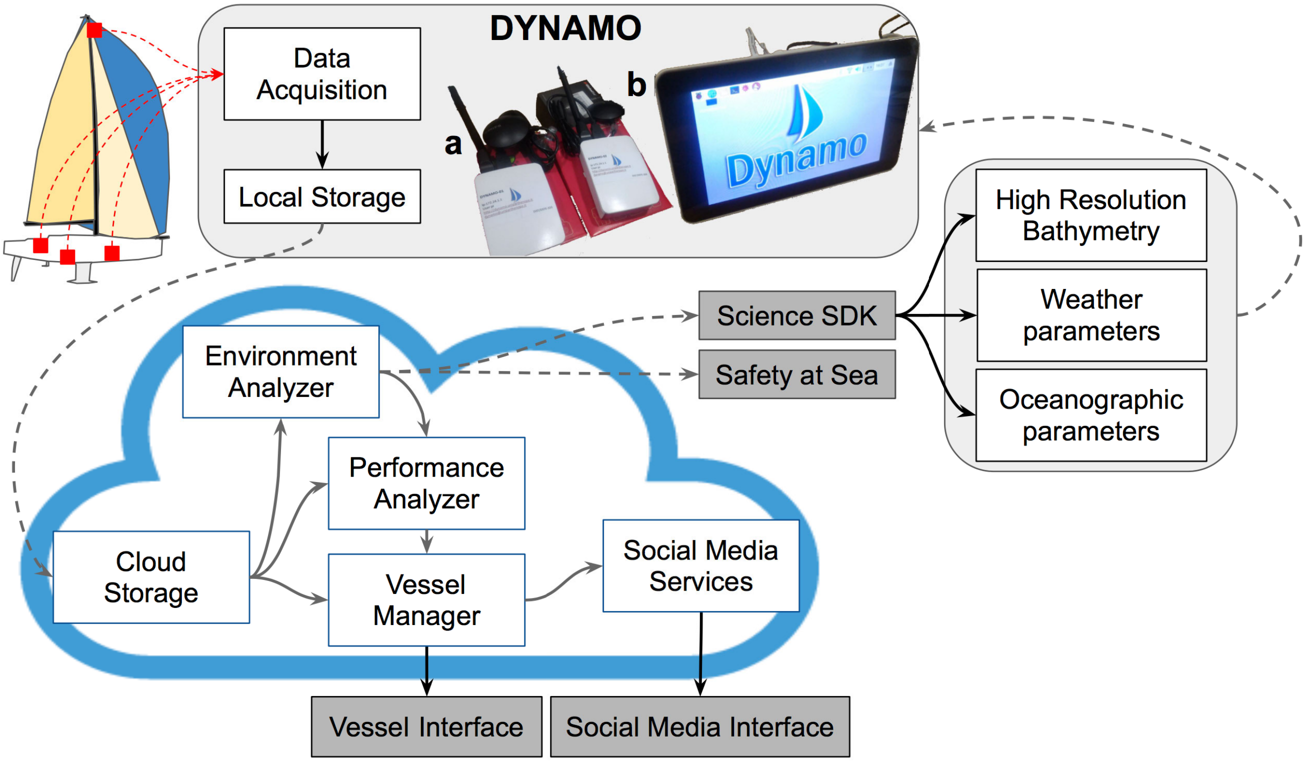

FIGURE 4. Smart devices' schema in the context of IoFT makes data crowdsourcing affordable. The red squares in the figure represent the possible vessel sensors devices. The DYNAMO box reports the lite DYNAMO version (a) and the same enriched with the touch-screen monitor (b).

An IoT core system is an integrated and multi-functional navigation device based on open technologies designed and developed by a multidisciplinary team in order to maximize the benefits and the advantages of a conceptually new on board marine electronics item.

The dataset collected on board is a scientifically intriguing source of huge amounts of geolocated data (big-data) such as: (i) marine coastal environment (sea and weather conditions, water temperature, surface sea currents, water depth, etc.) (ii) boat engine status (boat performances like heading, speed, pitch and roll, fuel consumption) (iii) boat management (presence of board water, waste management, safety at sea and search and rescue systems.

Due to the peculiar environment setup, data is collected on board and, when possible, sent to cloud storage and computing facilities using reliable, affordable, and safe technologies such as the transfer methodology based on the store-and-forward paradigm. When data are moved to the cloud and the consistency is verified, data can be analyzed and processed in order to extract sensor calibration, then evaluated with a quality model comparing it with data acquired by trustful equipment and, finally, made available as open data for ocean model initialization and/or validation.

V. USE CASE: IMPROVING WATER QUALITY MODEL RESULTS

The focus point of the described test case is the Water Community Model (WaComM), improved with the crowdsourced weather-marine data (bathymetry data in this case) to enforce the decision support system and enable the simulation and prediction of pollutant spills, transport, and dispersion in both inshore and offshore environments [6], [41]–[43].

A. WATER COMMUNITY MODEL

As described in [7], WaComM is a three-dimensional Lagrangian model, designed and implemented as evolution of the Lagrangian Assessment for Marine Pollution 3D (LAMP3D) model [44]. In WaComM, several basic algorithms have been optimized and, in order to improve its performance on a High Performance Computing environment, some features like restarting and parallelization techniques in shared memory environments have been added. In the following, we describe the underlying mathematical model as explained in [10].

Pollutants are modelled as inert Lagrangian particles. No interactions with other particles or feedbacks are included in the model. In more detail, each particle is defined by:

- an initial position $r_0 = r(0) = (x_0, y_0, z_0)$ at the initial time $t = t_0$;
- a position $r(t) = (x(t), y(t), z(t))$ at time t $(t > t_0)$;
- a velocity $v(r(t), t) = U(r(t), t) + \eta(r(t), t)$ at time t, where $U(r(t), t)$ denotes the deterministic velocity. Conversely, $\eta(r(t), t)$ represents the stochastic fluctuation obeying the Langevin model describing the Brownian particles motion [45].

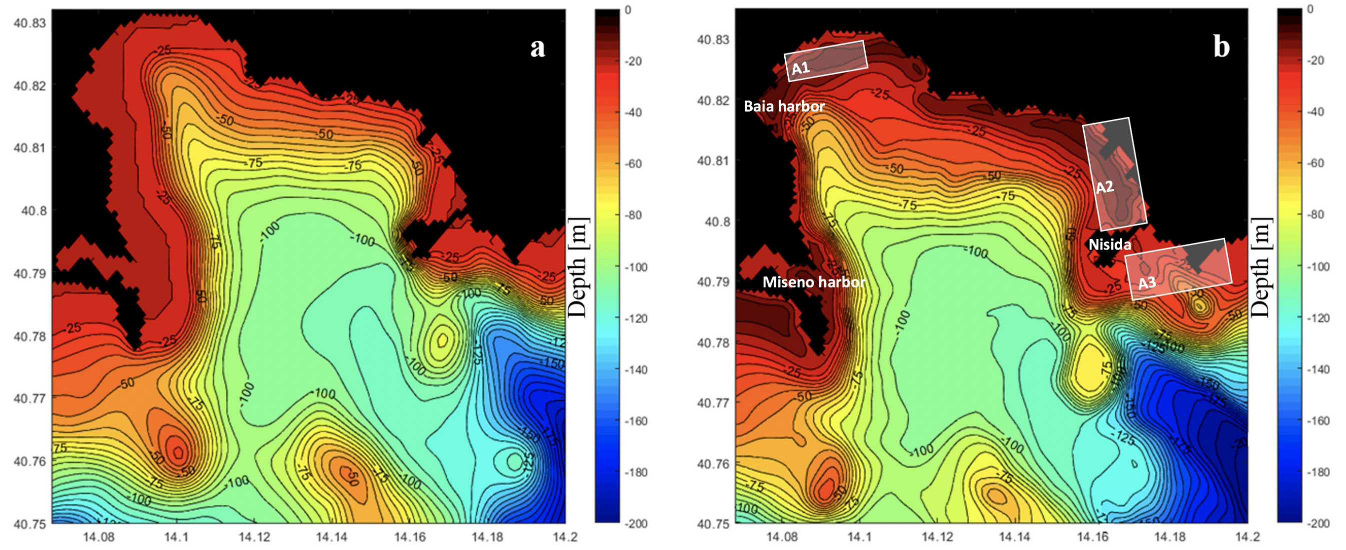

FIGURE 5. **ROMS model Arakawa-C grid bathymetry in B_{LR} (a) and B_{HR} (b) versions clipped on the considered study area. The white boxes evidence the position of a thermal submarine zone (A1), a touristic harbor (A2), and a zone characterized by some navigation restrictions (A3).**

The particle motion in the time interval $[t_k, t_{k+1} = t_k + \Delta t]$ (where $\Delta t > 0$ measures the time interval length) from a starting position $r(t_k)$ to the final position $r(t_{k+1}) = r(t_k + \Delta t)$, is described by:

$$r(t_k + \Delta t) = r(t_k) + \int_{t_k}^{t_k+\Delta t} v(r(t), t)\, dt, \quad (k = 0, 1, \ldots) \tag{1}$$

Numerical integration of (1) could be made in several ways but, in our approach, the Euler method is used. It considers a discretization of the time interval $[t_k, t_{k+1} = t_k + \Delta t]$ in the grid $\tau_{j,k} = t_k + j \cdot d\tau \quad (j = 0, \ldots, N)$, where $d\tau = \Delta t/N$ denotes the discretization time step. To this aim, the evaluations of $U(r(\tau_{j,k}), \tau_{j,k})$ and $\eta(r(\tau_{j,k}), \tau_{j,k})$ are required at each step time τ_j.

$U(r(t), t)$ was provided by ROMS, a free-surface, terrain-following, primitive equations ocean model used by a broad scientific community [46]–[48] to produce mesoscale and sub-mesoscale ocean dynamics. Since ROMS provides sea current velocity values only at some discrete timestep and on a discrete irregular three-dimensional grid (Arakawa-C grid), it was necessary to include in the WaComM software an interpolation algorithm. Considering the ROMS water column schematized in Figure 6, each cell is an irregular polyhedron defined by its assigned eight vertexes.

The WaComM numerical scheme requires the values $U(r)$ at each particle position r (unstructured grid) and desired time t_k, to do this we applied a trilinear interpolation approach based on barycentric coordinates [42]. In order to estimate the U and V components of the sea current value of $U(r(\tau_{j,k}), \tau_{j,k})$, two trilinear interpolations at t_k and t_{k+1} have been performed. In particular, by referring to the notation shown in Figure 6, the following computational steps were performed:

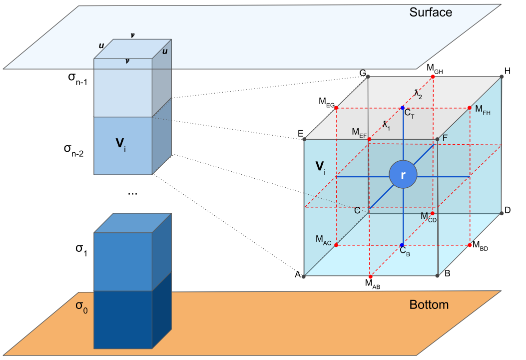

FIGURE 6. **Example of ROMS 3D unitary section water column and a zoom-in version of the single Arakawa-C grid cell.**

- $\tilde{v}(C_T(t_k), t_k)$ is evaluated using a linear interpolation: $\tilde{v}(C_T(t_k), t_k) = \lambda_1\, v(M_{EF}(t_k), t_k) + \lambda_2\, v(M_{GH}(t_k), t_k)$, where λ_1 and λ_2 are the barycentric coordinates of C_T with respect to M_{EF} and M_{GH}, respectively. $v(M_{EF}(t_k), t_k)$ and $v(M_{GH}(t_k), t_k)$ are known values provided by the ROMS model as solutions of the momentum equation at the given time and sigma level;
- in the same fashion we used the values $u(M_{EG}(t_k), t_k)$ and $u(M_{FH}(t_k), t_k)$ to compute $\tilde{u}(C_T(t_k), t_k)$;
- the same linear interpolation algorithm was applied to the bottom face in order to get the estimated values $\tilde{v}(C_B(t_k), t_k)$ (starting from the ROMS value of $v(M_{AB}(t_k), t_k)$ and $v(M_{CD}(t_k), t_k)$) and $\tilde{u}(C_B(t_k), t_k)$ (starting from the ROMS value of $u(M_{AC}(t_k), t_k)$ and $u(M_{BD}(t_k), t_k)$);
- re-applying the linear interpolation model between the points C_T and C_B, we computed the estimate $\tilde{v}(r(t_k), t_k)$ and $\tilde{u}(r(t_k), t_k)$.

All the previous steps are re-applied at time t_{k+1}. Finally, values $\widetilde{v}(r(t_k), t_k)$ and $\widetilde{v}(r(t_{k+1}), t_{k+1})$ are linearly interpolated, with respect to the time variable to estimate $v(r(\tau_{j,k}), \tau_{j,k})$. The same interpolation was applied to $\widetilde{u}(r(t_k), t_k)$ and $\widetilde{u}(r(t_{k+1}), t_{k+1})$ to estimate $u(r(\tau_{j,k}), \tau_{j,k})$.

The simulation of the stochastic fluctuations is based on the standard 'K-theory', with a diffusion coefficient which is estimated during the ROMS pre-processed data. Decaying processes are included in the model, assuming an exponential decay which uses the T_{90} parameter (time required to degrade 90% of the biodegradable matter in a given environment). A sedimentation velocity $w_{\text{sed}} = (0, 0, -w_{\text{sed}})$, is added to the deterministic velocity component to simulate settling particles. At the end of each time interval, a scalar concentration field $C_{i,j,k}$ is obtained by counting the number of particles found within each grid cell (i, j, k).

The larger the number of Lagrangian particles involved in the simulation makes the WaComM model computationally expensive, so parallelization techniques [49]–[55] are needed for its practical applications in the real world. To this aim, the WaComM main cycle (involving the interpolation and computation of the 3D momentum and dispersion parameters) used a GPU implementation, adopting the parallel design schema hierarchical and heterogeneous [56]. The GPGPU enabled is based on the NVIDIA CUDA programming model and uses both the CPU and GPU with an MPI based distributed memory approach [57], [58].

The WaComM system can be used in more ways: as a decision support tool [59], [60], to aid in the selection of the best suitable areas for farming activity deployment or in an ex-post fashion in order to achieve a better management of offshore activities [39], [61].

B. OPERATIONAL APPLICATION

Figures 5a,b show low B_{LR} and high B_{HR} resolution ROMS model bathymetry, respectively. Figure 7 shows the depth differences between B_{HR} with respect to B_{LR}, evidencing an increase in bathymetry accuracy near the boat routes.

In this section, we describe a real application, evidencing the importance of models' initial and boundary conditions and its improvement obtained integrating crowdsourced ocean data in the simulations. The test area is the Pozzuoli Bay in the Campania Region, Italy. This area is characterized by the presence of some coastal mussel farms (mainly with the *Mytilus Galloprovincialis* species) dedicated to human consumption, which is one of the main economic activities related to the sea in this zone.

The WaComM initial condition, in terms of sea current, is provided by the ROMS model, which in turn uses: (i) the meteorological forcing of Weather Research and Forecasting (WRF) model operative at University of Napoli "*Parthenope*"[13]; (ii) the ocean forcing the global data provided by Copernicus Marine Environment Monitoring Service[14]; (iii) the geological constraints of the ETOPO1 global relief model of Earth's surface that integrates land topography and ocean bathymetry, provided by NOAA.[15]

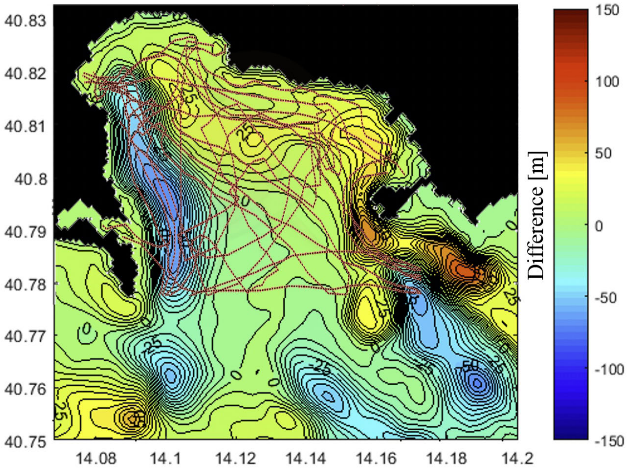

FIGURE 7. **Differences between ETOPO 1 dataset and the same dataset improved with crowdsourced seafloor depth. The overlapping dotted red lines represent the ship routes.**

In this way, WaComM can be considered the last component of a complex models workflow (WRF-ROMS-WaComM).

The considered crowdsourced parameter is the depth because the morphology of the seafloor has a significant role in the hydrodynamics definition, mostly in the coastal area.

Not being able to use the depth data collected in crowdsourcing mode directly within the WaComM model (as it is based on an unstructured model grid), we decided to use these data to configure two versions (B_{LR} and B_{HR}) of ROMS model geological constraints: (i) B_{LR} is an Arakawa-C grid based on ETOPO1 dataset, with mean spatial resolution equal to 80m; (ii) B_{HR} is the same grid described before, improved with crowdsourced bathymetry data collected along the casual ship routes (red lines in Figure 7).

From a first visual analysis, it is evident that in B_{LR} dataset the minimum depth is around -20 m while in B_{HR} we can also observe areas with depths ranging from -2 m and -20 m. This allows us to identify, for example, the thermal complex [62] with a depth ranging from -2.5 m and -3.5 m (A1 white box in Figure 5b). B_{LR} underestimates, also, the sea depth in the shallow area between Baia and Miseno harbors. Around Nisida isle, the morphology is more complex by the presence of a tiny touristic harbor (A2 white box in Figure 5b) and some coastal protection structures, so the crowdsourced depth measures gain more importance in the real shape of the seabed definition. Nevertheless, the same area has some navigation restrictions due to the presence of a protected marine area (A2 white box in Figure 5b), a mussels farm, and a jail for underage criminals (the whole Nisida

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[13] http://meteo.uniparthenope.it

[14] http://marine.copernicus.eu

[15] https://www.ngdc.noaa.gov/mgg/global

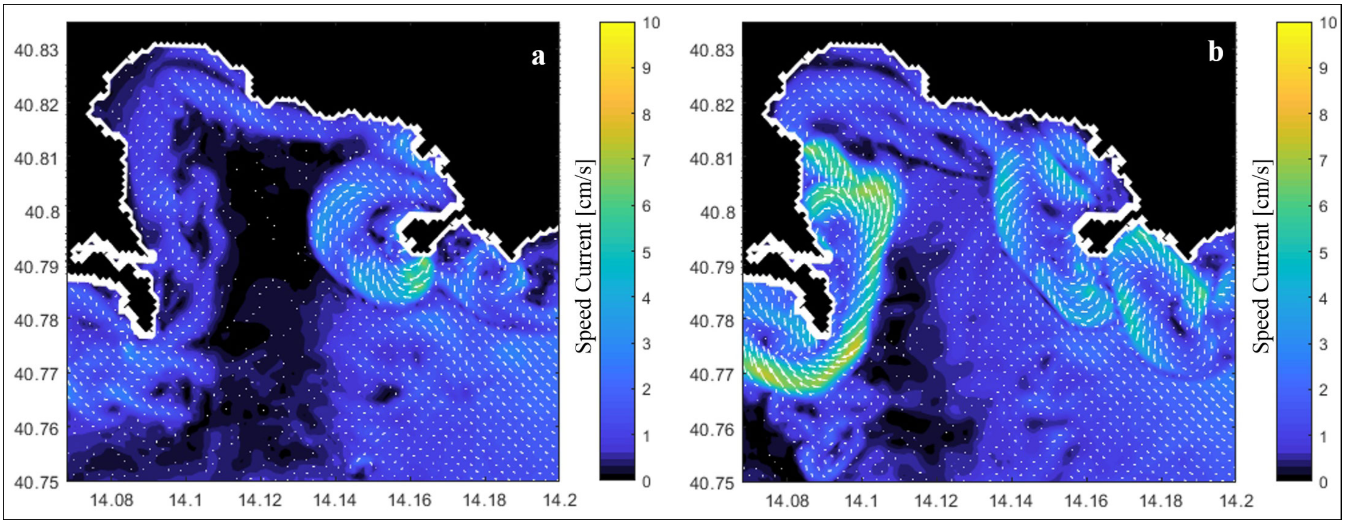

FIGURE 8. Sea surface currents speed and direction (vectors) simulated by ROMS model constrained with (a) B_{LR} and (b) B_{HR}.

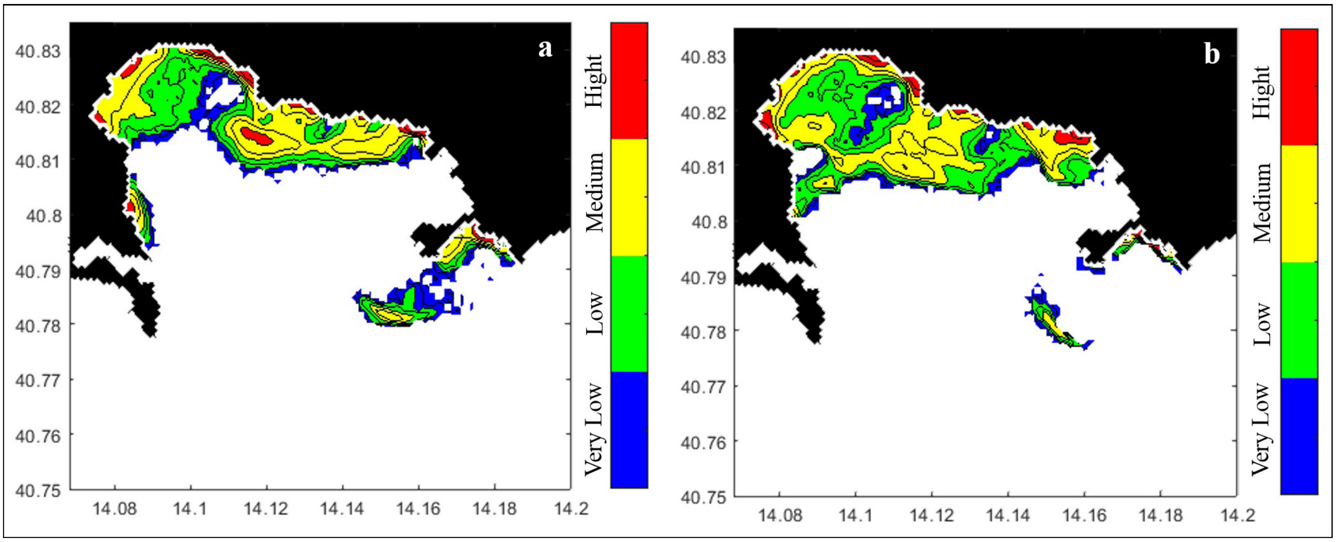

FIGURE 9. Lagrangian particle surface concentration qualitative classes (Very Low, Low, Medium, and Height) simulated by WaComM model constrained with: (a) the native ETOPO 1 dataset and (b) ETOPO 1 dataset improved with crowdsourced seafloor depth.

island). Those restrictions limit or completely avoid any use of crowdsourced data. This highlights the importance of using not only vessel sampled bathymetry data. Figure 7 evidenced that in the offshore zones, the differences between B_{HR} and B_{LR} are very small (close to zero).

A change in the bathymetry accuracy used to initialize a hydrodynamic model, such as ROMS, can be relevant on the evolution of the water column variables. This concept is applicable in any case, regardless of the duration of the simulation and the reference time. However, generally, it is more critical during winter, when the water mass variations are more sudden and the flows are more energetic.

As a result of improved bathymetric details, all ROMS model hydrodynamic variables shown a variation in their spatial distribution. In particular, Figure 8 shows the sea surface current patterns using as geological constraint B_{LR} and B_{HR}, evidencing that in the eastern part of Pozzuoli Bay there is an increment of the sea surface current using B_{HR} as a topographic constraint (Figure 8b).

Starting from these considerations, we configured the WaComM model considering pollutant sources as coastal points, spilling out in the sea 100 lagrangian particles hourly [7]. We use, alternatively, the ocean forcing obtained with the two versions of the ROMS model described above in this Section. In order to link the concentration of the Lagrangian particles with the human dangerousness, the tracers in Figure 9 are grouped in four qualitative classes: high, medium, low, and very low concentration. As shown in Figure 9b, the distribution of the Lagrangian tracer has undergone an improvement in detail, which are no visible using a low B_{LR} in ROMS model configuration, as already evidenced in [2].

VI. CONCLUSION AND FUTURE WORK

In this paper, we presented the DYNAMO architecture, which can be used for different IoFT applications related to ocean monitoring and modeling, among others. In order to demonstrate the results obtained using crowdsourced bathymetry to improve the numerical ocean model simulation quality, we considered the ROMS-WaComM scientific workflow configured at the *Meteo Center of University of Naples "Parthenope"*. Currently, these models are used to evaluate the sea currents and the pollutants dispersion around the mussel farms in the Gulf of Naples in order to improve the overall health of these shellfish and, as a consequence, its quality when served as food.

The geographical constraints in this environment, such as type and orientation of the coast, presence of coastal defense or harbors, and seafloor morphology, among others, influence the circulation model and, indirectly, the pollutants' patterns. Moreover, high-resolution bathymetry data are costly and difficult to obtain. This paper showed that an IoFT-based crowdsourcing system in this coastal area is a viable solution to collect such important data thanks to volunteering leisure vessels and small boats.

Our experimental results showed that it is possible to improve the computed coastal details by using a finer bathymetry. These results will drive our research plan to the next steps to perform an extensive water physics and microbiological data sampling in order to support a more consistent numerical evaluation. Finally, we are aware about the hidden information we can extract applying data science methodologies on the collected data as the number of DYNAMO users will increase.

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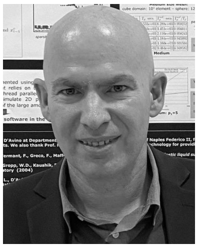

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