MARLIN: An IoT Sensor Network for Improving Maritime Situational Awareness

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Abstract—Maritime situational awareness pictures are mostly collections of interfaces for particular sensors, showing a one-on-one relationship between sensors and their interface. The internet of things has broken with this pattern, using unified and open interfaces on sensors and services to instead create modular, interconnected networks to handle the recording, processing and interaction of and with data.

The MARLIN project adapts these patterns to create a modern maritime situational awareness picture. This paper illustrates the structure and design decisions of this network, showing how modern web technologies can be used to rapidly create reliable and flexible situational awareness tools in the maritime domain.

Index Terms—IoT, sensors, data analysis, visualization, microservice, situational awareness

I. Introduction

With the increasing connectedness of maritime systems, maritime infrastructures aggregate more and more interconnected devices [8, 24]. These devices are not only expected to seamlessly interact but also to provide integrated data processing to reduce the amount of input for the operators [7]. The Maritime Awareness Realtime Instrumentation Network (MARLIN) project aims at these aspects, demonstrating how Internet of Things (IoT) devices, Machine Learning (ML) algorithms and resulting situational awareness pictures can interact to provide a manageable information flow for maritime infrastructures.

The project focuses on measuring, assessing and representing the protection status of maritime infrastructures in real-time. For this purpose, novel sensors and state-of-the-art data processing and analysis methods will be used to provide users with both a compressed representation of complex information on the situation and recommendations for action on different kinds of user terminals.

This paper illustrates how specific, maritime requirements and practices impact the design of an IoT network for the usage in a real-time situational awareness picture. The "maritime" used in this paper also includes land-based infrastructure, such as ports or sluices.

II. Requirements

There are several requirements which apply to maritime infrastructures but are not dedicatedly maritime – e.g. the competitiveness of the maritime industry [17, 22, 6] requires approaches to be cost-effective and maritime infrastructures often involve a lot of different stakeholders [2, 5, 16], requiring open, established standards and the ability to connect and disconnect at will.

Opposed to that, the mixture of critical and non-critical infrastructures that is prevalent in larger maritime infrastructures is rarely found in non-maritime environments [3, 1]. With imports and exports often being considered of systemic importance, maritime infrastructures may house some elements with stricter rules and regulations.

Additionally, maritime infrastructures are often placed at country borders, resulting in a delicate mixture of public and commercial interest and partners [12]. Border security, state representation and borders between national and international territories, each with different duties and responsibilities and according authorities requires any technological framework to be able to reflect these interests and necessities.

III. The Maritime IoT

While the network itself obviously needs to be modular and based on established standards to easily integrate a wide range of sensors and services, there is a wide variety of options available that seemingly all provide the requirements for the given use case (e.g. zeroMQ [13] or Robot Operating System (ROS) [15]).

A detailed comparison of all options is beyond the scope of this paper, but the MARLIN project relies on established web technologies and consists of a variety of microservices to provide connectivity. These web services have the advantage of being ubiquitously applicable. They use wired and wireless LAN and WAN connections which can be considered as a foundation of essentially all connected infrastructures. Libraries for providing and accessing corresponding Application Programming Interfaces (APIs) are available in essentially all programming languages. These, of course, have certain disadvantages concerning questions such as authentication of users, "proper" real-time application and interface stability and control.

The goal of this paper is not to have a silver bullet for all issues of microservice-based interconnected systems but instead have a discussion on the possible mitigations of these concerns and their relevance and priority in a maritime environment.

IV. Architecture

This section, together with Fig. 1, presents the architecture of the MARLIN project. It consists of three main aspects represented by layers. Each layer consists of different modules, which are considered as closed systems. All inter-module communication is done using microservices. The communication between these layers is done using state-of-the-art protocols that offer a sufficient level of cybersecurity.

The first aspect is *data acquisition*, which is realized by the *instrument layer*. This layer uses both novel and established sensors and monitoring systems such as optical near and remote reconnaissance, radar, and Automatic Identification System (AIS). Next is the *middle layer*, which reflects the
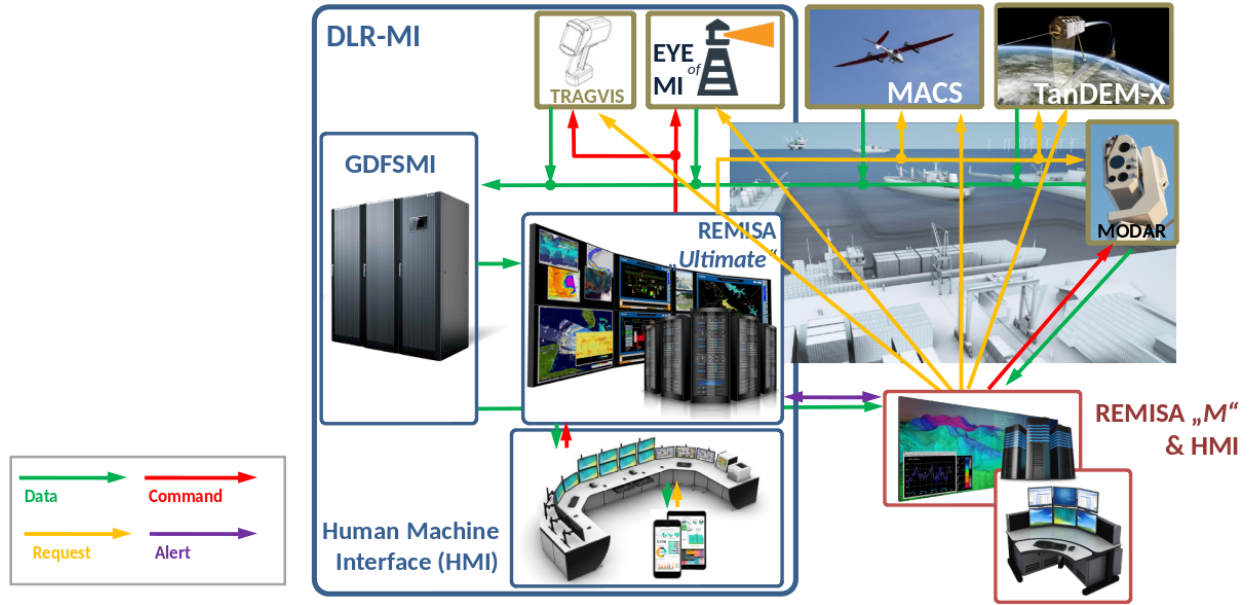
Fig. 1. MARLIN architecture: The top right shows sensors of the instrument layer (beige-colored boxes). This can be sensors developed at the German Aerospace Center and also external sensors. The middle layer is shown on the left with the Global Data Fusion System for protection of Maritime Infrastructures (GDFSMI) and Real-time Engine for Maritime Infrastructure Situational Awareness (REMISA). Data from the instrument layer is going (green arrows) to the GDFSMI and will be stored for data analysis. The data will be analysed in the REMISA. On the bottom is the HMI, where data from the middle layer are be presented and recommendations for actions based on KPI are given. The HMI can send commands to the middle layer to start data analysis processes and to the instrument layer to start data acquisition processes. All communication, represented by the arrows between the modules, is done via microservices.

second aspect of the *data analysis*. The middle layer includes tasks such as data analysis as well as data handling and data storage. For example, this layer performs data fusion and contextual data analysis for object or person identification as well as anomaly detection. The third and last aspect is the *monitoring* handled in the *user layer*. Analysed data is displayed in near real-time in a Human Machine Interface (HMI), which can be run on different devices like usual workstations or also mobile devices. In addition, recommendations for actions based on Key Performance Indicators (KPIs) are integrated into the situational awareness picture. To ensure interoperability, all modules communicate via web-microservices. This allows modules to be built on and for a broad range of underlying operating systems and programming languages.

V. INSTRUMENT LAYER

This section describes more in detail the instrument layer, and some sensors involved in MARLIN project. The instrument layer consists of multiple Independent Sensor Networks (ISNs) shown in Fig. 2. An ISN performs data acquisition and can perform local data processing, data fusion or partially automated detection. Each ISN handles and controls the containing sensor appropriate and offers a unified interface for requests and commands by the *Control* component. This component checks if the requesting module or user have the permissions to perform the desired requests and commands. The resulting data is stored at the GDFSMI from which existing data can be fetched by other modules in the MARLIN network.

Data processing can be performed locally. The data can be preprocessed for better subsequent processing and analyzing steps of other MARLIN modules. One example for local data processing is geo-referencing of image data or converting

image data from a raw data format to a standardized image format. This aligns well with the requirements in Section II.

An ISN can also contain local partially automated detection. This can be the detection of data that allows the conclusion to identities of persons or direct images of persons. In this early step of the tool chain, personal data can thus be filtered out or anonymized.

The chosen microservice pattern fits the sensors well: The IoT structures that are used in the MARLIN network are often used for small cyber-physical devices as well, allowing them to easily provide their data via push or pull mechanisms. Encryption and authentication is done via common standards, allowing simple web-based login methods and https channels to be used to securely transfer data and handle access control.

The given list of sensors represents a non-exhaustive list – these are the sensors that have been implemented for and integrated into the given proof-of-concept network, but as the whole idea of the open structures is to allow for easy integration of additional sensors, this should be seen as a starting point for the sensor network.
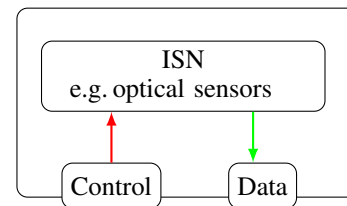

Fig. 2. Independent Sensor Network: The sensors logic is placed to the box labeled with ISN and can be considered as black box for the MARLIN network. As interface the ISN has a *Control* component, which receives commands and requests and forward them to the sensor. The resulting data are stored at the GDFSMI by the *Data* component from where requesting modules can fetch the newly created data.

Fig. 3. Three HarbourCam with a view to a maritime infrastructure.

Fig. 4. Example image of detected persons, cars and vessels from a video stream like from the HarbourCam. Geo-referencing the detections allows to draw shapes on a map corresponding to the location (see Fig. 9).

Fig. 5. The TRAGVIS sensor with the illuminator (left) and the synchronized camera (right).

Fig. 6. A captured picture with objects reflecting the illuminated light at a distance of 200 meter.

A. Optical Camera

The HarbourCam (see Fig. 3 and Fig. 4) consists of a low-cost fixed camera system with privileged views to the maritime infrastructure. It essentially represents closed-circuit television (CCTV) devices, webcams or any other "ordinary" optical sensor to give access to an infrastructure's situation. The current implementation offers an interface to both, control and retrieve the video stream and comes with an integrated object detection algorithm [20] that can be enabled or disabled via the control interface, allowing the operator to rely on a state-of-the-art preprocessing to help with the assessment of the situation. In addition, detected objects are geo-referenced using the position and view of the cameras as reference [23], allowing the positions to be used in abstract maps or other situational awareness interfaces.

B. Range Gated Vision

The TRAGVIS instrument, shown in Fig. 5, is a compact range-gated-viewing sensor, consisting of an illuminator and a synchronized camera [14, 18]. It allows measurements of illuminated scenes in specific distances (shown in Fig. 6). The distance is determined by the speed of light, and the delay between emission of a laser pulse and opening of the camera shutter (called the camera gate). TRAGVIS is currently developed and configured as a night-time-sensor. The maximum distance of the gate position is 450 m.

The TRAGVIS module offers an interface to record new image series. After pictures are taken, they will be stored at the GDFSMI for all other MARLIN modules. It is also possible to enable and disable object detection for images produced by the TRAGVIS sensor with the interface.

C. Third-Party Optical Sensors

The Motion Stabilized Optical Detecting and Ranging (MODAR) system is a commercial multi-sensor platform from OptoPrecision, containing a visual and a thermal camera and a gated-viewing sensor. Mounted on a vehicle it ensures mobility and facilitates the determination of the protection status as well as occurring risk factors. Monitoring in darkness or during bad weather conditions such as fog, rain or snowfall is possible because of the presence of the range-gated and the infrared camera.

The Modular Airborne Camera System (MACS) consists of a geometric and radiometric calibrated industrial 16MPx camera with a high end positioning receiver in combination with an industrial grade inertial measurement unit (IMU) and an embedded computing board with exchangeable storage module. The Micro version of this module is meant for lightweight mapping and as monitoring solution [10, 11].

The live imagery produced by the MACS module is continuously put to a geo-server where new images are added to a Web Map Service (WMS). By periodically fetching the data of the WMS an up-to-date view of high resolution imagery in near real-time is possible.
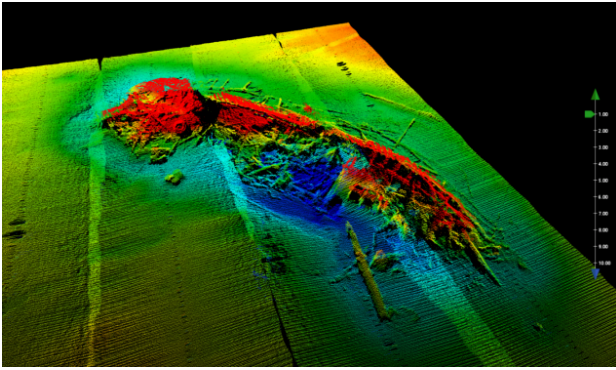
Fig. 7. A side-scan sonar image of the Voitja, sunk in the early 1940s. It is also easy to see the four lanes that the AUV needed to get a full sonar image of the wreck.

Fig. 8. A pointcloud of our institute's building generated out of the drones imagery. It is shown in the situational awareness software developed in the MARLIN project.

D. AUV

The Autonomous Underwater Vehicle (AUV) is a subsea instrument platform. A live stream is not possible because no communication can be established during operation. The route for the AUV has to be planned beforehand, then it will record data along the route. After finishing the recordings on the route, the data can be obtained for further post-processing steps. Fig. 7 shows a sonar image from a sunk ship near Kieler Förde.

E. Drones

A better overview for complexly structured, inaccessible or extensive areas can be ensured by drones.

The drone interface offers to receive the cameras live video stream. In addition, if required the drone module sends the current position. Thus, the drones' location can be drawn and updated on a map during live operation.

Independent of live video footage, the drone imagery may be processed to create map tiles or photogrammetric 3D models which are stored on geoservers running in the middle layer of the network.

F. AIS

The maritime AIS is used to communicate the vessels' information in open seas to prohibit collisions and provide basic information on a given vessel in the surrounding but has evolved to be a source of data for all kinds of maritime situational awareness pictures [21, 4]. The messages are sent periodically from the vessels transceiver and are received by an AIS receiver which is connected to the MARLIN network.

VI. MIDDLE LAYER

While structuring the sensors as a set of microservices is rather straightforward, the same pattern is applied to the middle layer as well. This allows other modules to use the same or similar implementations for most services, regardless of the data presented coming directly from a sensor or being retrieved from a database.

While this unified approach to services comes with several advantages concerning e.g. API access or there are of course trade-offs to be made. A prominent issue with independent modules forming processing chains in middleware environments is the lack of synchronicity – while synchronous data acquisition improves the results of data fusion algorithms

significantly [25], independently running web services are inherently difficult to synchronize. Ultimately, this problem is not yet solved for IoT networks in a general way. While meta data such as precise time stamps (e.g. via GPS clocks) for recorded data at least somewhat remedies this issue, the problem remains prominent. For sensors that are known to create data that is to be fused, synchronizing the time of recording data via pre-communicated timestamps and global navigation satellite system (GNSS) clocks on the sensors is currently used, albeit this remains a non-standard solution in the network. Experience has shown that especially in maritime environments, actors usually move slowly, allowing larger margins for non-synchronized data acquisition, again making the microservice-based architecture viable for the given use case.

This section focuses on the middleware modules that are used in the exemplary sensor network and the design decisions that were made in the process. Modules include data analysis and storage solutions. The centerpieces of this layer are the Global Data Fusion System for protection of Maritime Infrastructures (GDFSMI) and the Real-time Engine for Maritime Infrastructure Situational Awareness (REMISA). While GDFSMI modules store data and provide interfaces for easy data retrieval, REMISA processes, analyses and fuses various data.

A. Photogrammetry

Photogrammetry is a technique of contactless measurement and interpretation to indirectly determine the position and shape of an object through image measurement and to describe its content through image interpretation. Fig. 8 shows a 3D-pointcloud generated with photogrammetry using recorded imagery from a drone in the situational awareness picture.

B. Machine Learning

For data analysis, ML is heavily involved in MARLIN. One use case is object and person detection, as shown in Fig. 4. Regarding the european data privacy regulations, such a detector will detect people and blur them live on the video stream, before the data will be stored anywhere.

Most detectors are based on Neuronal Networks (NNs) and trained beforehand [20]. Afterwards, it can be used on every video stream of the MARLIN network.

Another use case for ML is the predictive analysis. Again, NNs are trained with historical data, and the algorithm learns to predict the behaviour of specific situations and is able to detect abnormal behaviour for example with AIS data.

Often, vessels that behave "as expected" are not particularly interesting – the core question is, if there is a vessel that behaves "oddly", whatever this may mean.

The number of vessels – especially surrounding coasts or maritime infrastructures – is usually high [9] and the movement slow, which makes it hard for operators to detect suspicious behaviour by simply looking at the current state.

In order to detect an anomalously behaving vessel, the movement of existing vessels is analysed via ML algorithms (long short-term memory networks in particular) to learn patterns which define "ordinary" behaviour for a certain vessel class. This allows the prediction of tracks of specific types of vessels. If the predicted track shows abnormal behaviour a warning or an alert can be given.

Additionally, a vessel's trajectory can be used to classify it and compare the result to the classification that is testified via AIS. This is a possible measure for an anomaly: a vessel that does not behave like it is supposed to do should be observed by the operator.

C. Data Fusion

Data fusion is the merging of data from heterogeneous sensors. One problem that comes with data fusion is the synchronicity of the different data sources [25]. At the moment, we do not directly handle this problem either. The data streams to be processed produce data slowly enough that they can simply be fused as soon as new data is generated.

Fig. 9 shows an example for data fusion at MARLIN. The results of boat detection with ML algorithms on a HarbourCam video stream and the AIS signal are put together. The AIS signals are sent infrequently enough for the ML algorithms to keep up well with detection and geo-referencing.

D. Data Storage

All data is stored in the MARLIN middle layer. An example for this data are the AIS messages that are received and recorded. With this data being sent by all larger vessels on earth every few seconds, the amount of data that has been generated is already large and keeps growing at high rates. A situational awareness picture may easily display the last message received – but providing access to a vessel's historic data may be vital to interpret its current state.

In order to provide such information, the existing information must be searchable and the interface must support existing geo-information standards. Both issues are not easily solvable, with GIS standards for rapidly moving POIs being either unavailable or not generally supported and several, fundamentally different back-ends being viable options.

VII. User Layer

The HMI is located in the user layer and is the core component of it. It visualizes various data from sensors of the instrument layer as well as results of various data analyses and the fused data sets from the middle layer. Recommended actions generated in the middle layer based on KPIs are displayed, also.

With MARLIN's modular system, it is easy to display the situational awareness picture even on different devices at the
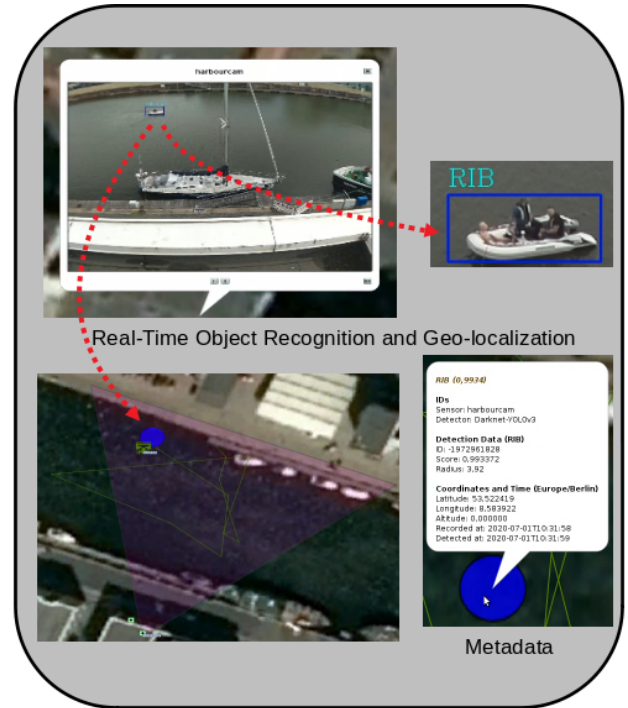

Fig. 9. On the top an image of a HarbourCam video stream with a detected rubber boat is shown. Around the detection a bounding box is drawn (see top right image). Each detection will be geo-referenced. The bottom shows a map where the rubber boat's AIS signal and the corresponding geo-referenced detection is drawn on it. Both data sources positions matching well. The picture on the bottom right shows additional data corresponding to a detected rubber boat like position or record time.

same time, no matter if it's a regular desktop environment with multiple screens or a mobile device such as a tablet. On a tablet, only a reduced version of the situational awareness picture is displayed. In other words: Only the information that is relevant for the person in question is shown.

With the microservices being run over standard web-interfaces, the time it takes for information to travel between modules until it reaches the user in it processed form cannot be guaranteed in any way, right to the point of packages being lost in transit. Real-time applications are therefore not possible in the strictest sense (as real-time requires these guarantees for maximum amount of time for data to be fully processed). The decision to nonetheless use web technologies is essentially based on the assumption that slight delays are acceptable and errors in data transfer are preferred over non-standard communication interfaces in areas that would not necessarily benefit from them.

VIII. Ethical, legal and social aspects

Data protection and privacy have been considered from early stages of the MARLIN project – detailed concepts for the protection of personal data, including most prominently avoiding recording personal data in the first place, have been put in place. In an image produced by an ISN (see Section V), for example, people will be blurred directly inside the camera module. This ensures compliance with local data protection regulations and allows forwarding the data for storing without any concerns.

Interestingly, modern ML methods may very well be (and are) used to *increase* the level of data protection. The MARLIN project e.g. relies on face recognition methods to remove faces from video streams before the data leaves the sensor, improving the privacy of the people that are recorded while at the same time reducing the amount of work that later needs to go into securing said data.

Data storage in the context of the MARLIN project is a subject to the legal requirements determined by European and German privacy laws and therefore data is stored in encrypted form. An authorization concept is used to ensure that only people or services that are related to a specific scientific task have access to this data. A data protection concept and a data protection impact assessment considers these aspects and summarizes the legal requirements and privacy matters.

IX. Conclusion

MARLIN proposes a network from heterogeneous sensors over data processing and holding entities to a situational awareness picture emphasises abnormal behaviour in a maritime environment. It provides a multi-layer architecture with (partially novel) sensors, a powerful middle layer performing deep learning analysis and data fusion and a decision supporting human machine interface. Its components are divided into independent micro-services that communicate in a secure manner.

The chosen IoT based infrastructure comes with all the advantages and disadvantages that are common in these web-based architectures [19, 26]. However, the advantages of simple interoperability not only between the modules built for this network but also to other public APIs and thus the extensibility of the architecture are considered worth the issues that come with the reliance on IP based structures.

X. Acknowledgement

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