

Transmission of classified and varying quality underwater maps over constrained networks

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Abstract – Autonomous underwater mapping operations are limited by onboard energy constraints in AUVs. The ENDURUNS project proposes to use fuel cells technologies to provide extended duration of AUV mapping operations. This type of mission generates large quantities of multi-beam sonar data available onboard at remote maritime locations. Satellite links can provide connectivity from remote control centers to these unmanned assets, but have limited bandwidth to transfer unprocessed data. This paper describes onboard semantic classification of raw sensor data using deep learning for a compressed representation of data for operators to analyze and selectively demand higher resolution data for specific areas of interest from large data sets. This is aimed at providing access to downstream end users and stakeholders with the required data within the constraints of communication technologies with minimal operational delay.

I. INTRODUCTION

The ENDURUNS project (Development and demonstration of a long-endurance sea surveying autonomous unmanned vehicle with gliding capability powered by hydrogen fuel cell) is aimed towards the design and development of an AUV (Autonomous Underwater Vehicle) capable of extended duration underwater sensing and mapping operations. A hybrid AUV-glider design powered by hydrogen fuel cells is provisioned to support long duration operations. A surface based USV (Unmanned Surface Vehicle) will be used as a docking, recharging and communications relay station to the RMCC (Remote Monitoring and Control Centre) that is located onshore. The RMCC is connected to the USV via a satellite link enabling it to be based at any location and send or receive commands and data respectively.

Long duration operations (in the order of days) result in the collection of large data sets from sonar and imaging sensors on board the AUV. The exploitation value lies in

providing access to important datasets to RMCC operators, scientists and relevant stakeholders in an acceptable time frame. Transmitting this raw data to the RMCC over a constrained satellite link is not practical in terms of time, cost and energy requirements [1].

This paper focuses on pre-processing the raw data acquired by the AUV over long duration missions, semantically classifying the data sets and optimizing their size. The proposed paradigm is supported by a set of tools for RMCC operators to define map data requests from the offshore AUV-USV based on semantics, areas of interest and quality parameters. This methodology is aimed at providing access to these data sets to consumers over a constrained satellite link due to the remote deployment locations of the ENDURUNS unmanned systems.

II. THE ENDURUNS APPROACH

AUVs are equipped with a wide range of sensors and acquisition devices, in particular there is great interest in sonar and bathymetric images which come from multi-beams echo-sounders (MBES): the former encode information about the reflectivity index of the seabed while the latter about its morphology. Using these sources provides a rich understanding of both the geometrical and the environmental characteristics of the seabed, for example type of sediments and possible presence of living organisms or sunken relics.

A wide scale mapping mission can produce huge amounts of data in a very short amount of time, which makes for a big challenge for autonomous vehicles. Currently almost all data processing tasks are handled offline by human operators, while our project aims to be fully automatic. To implement these tasks onboard we employ a modern embedded computer (NVIDIA Jetson TX2) equipped both with a 4-core ARM Cortex CPU and a 256-core GPU (massive parallel unit), ensuring sufficient computing power to perform MBES data processing and analysis, with a very small weight (85 grams) and a reduced energy consumption (7.5 W).

The RMCC provides an operator with the tools to plan,

execute, monitor and replay missions. The operator marks a zone of interest on an interactive map for which a scan pattern is generated. During execution, telemetry is provided as it becomes available, indicating freshness. After AUV-USV data transfer, a preliminary compressed map (low-resolution or classified areas) is sent to the RMCC.

The user can request a higher detail image of a subsection to be transmitted by the USV. This on-demand level of detail choice conserves bandwidth, while still providing baseline information at all times. Using a progressive image transfer, the user need not wait for the transmission to be completed to get an impression of the mission environment. Based on new information, the operator can subsequently refine the mission for the AUV to perform a closer rescan the area. The complete uncompressed map becomes available after AUV and/or USV retrieval.

The AUV-USV connection via acoustic signals is bandwidth-limited in the range of kbps, with long connection gaps (up to several minutes) [2]. Data is not available in real-time. An L-band satellite link (357 kbps) connects the USV to the RMCC to relay the AUV data and receive commands. With possible disruptions, limited speed and costly data volume on the satellite link, data transfer optimization is a key issue. The involved bandwidth values are reported graphically in Fig.1.

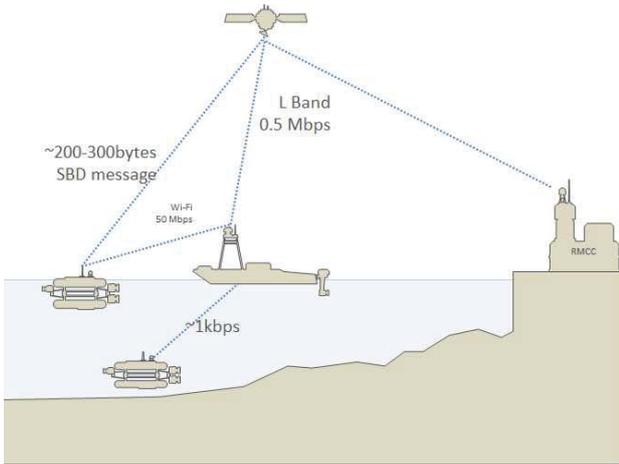


Fig. 1. Communication between ENDURUNS components.

III. MBES DATA PROCESSING

Full resolution images provided by a MBES must be processed on board before transmission because of bandwidth constraints: a multi-resolution spatial model should handle the internal database of the AUV, accordingly filtered, stitched, compressed and incrementally added as the acquisition progresses.

Then image textures should be classified on the full scale dataset and tagged according to relevance and possible interesting features: this may be achievable

through texture analysis or through modern deep learning techniques. Semantic classification of seabed structures enables the possibility of tagging relevant data when sending compressed streams to the RMCC. This simplifies the task of analyzing huge datasets and focusing in more detail only on the most interesting areas while skipping flat regions, thus making the whole mission faster and more responsive on a large scale.

A. Texture classification

Backscattering strength (BS), which is the intensity backscattered by the seafloor, is the basic information used for seafloor classification as the BS varies according to the seafloor nature. The texture classification methods for MBES systems exploit swath images generated by the snippet approach [3].

In this method, the single swath image is reconstructed by the concatenation of each smaller time-series piece extracted from each beam around the seabed detection sample. Using all the samples, a bathymetry profile is first constructed on across track direction. This profile is sampled at a predefined spatial across-track resolution. For each across-track sample, the beam angle is known, and the assigned BS value for this sample can be extracted from the corresponding beam and time. Then, the single swath pixel scans are stacked and mosaicked in order to produce the final image of the seafloor, after removal of the angular dependency of BS values.

Texture-based classification techniques rely on the extraction and characterization of the information of each seafloor type, assuming the existence of homogeneous zones (groups of pixels sharing the same seafloor type). Computer vision traditionally offers many sets of feature vectors (e.g. HOG) which are suitable even for acoustic images [4].

Given a suitable choice for the feature vector and for the subsequent classification algorithm (e.g. Naive Bayes, Random Forests, XGBoost or another machine learning method), the image can be divided in blocks and each block can be classified in a predefined set of classes. Whichever the selected feature-classifier combination, it is needed to define a training set made by supervised data in order to train each combination in advance. Many results of several machine learning approaches for seafloor classification with MBES images are reported in [5].

A more modern and effective approach involves direct processing of image data without an explicit feature extraction step, using a deep learning model (the Convolutional Neural Network architecture, CNN [6]). The processing board hosted by the ENDURUNS underwater vehicle (NVIDIA Jetson TX2) already supports natively a wide set of highly optimized computing modules to develop image processing and classification algorithms, including the ones based on CNN and other deep learning architectures.

So, it is possible to select the most suitable approach based on expected performances and computational requirements. As a result of the classification step, transmission of MBES data can be conditioned by the occurrence of a given class subset.

B. MBES data compression

Another critical point in optimizing data transmission of MBES data is image compression. A MBES generates large amounts of data and the procedures of handling such large data can be very costly and time-consuming, since high-bandwidth transmission channels are not available and the backup of very large databases is often inconvenient.

The amount of generated data strongly depends on the mission requirements and is larger when, in addition to measuring bathymetry and seafloor reflectivity of each beam, an MBES records also water column reflectivity measurements. This can be useful to address questions in fisheries (i.e. fish school detection), marine mammal and zooplankton research as well as in studies of seeps and hydrothermal vents. A complete review of MBES operating modes can be found in [7]. Moreover, in shallow water applications higher repetition rates are typically needed. All these aspects may lead to a final throughput higher than 1 MB/sec (or about several GB/hour).

Data compression provides a potential solution to the problem of data handling, however, commonly used lossless data compression techniques yield only modest compression rates (about 25% [8]) and lossy methods must be used to achieve higher compression rates.

Image compression of the MBES data is often applied to the results of the data analysis carried after the final image mosaicking step, but traditional lossy techniques like JPEG are proved to be not well suited for acoustic data and more advanced schemes like JPEG2000 are preferable. Using JPEG2000, lossy compression rates higher than 20:1 can be easily achieved with a minimal signal distortion [8].

A recent work demonstrated that a high compression degree can be obtained working on the ping time-series stacked as if they were rows of a two-dimensional array (waterfall image) [9]. This is an optimized representation of the MBES backscatter data, obtained by consolidating the individual beam time-series into a single signal. The waterfall image is then compressed using standard image compression algorithms.

Results indicate compression ratios of up to 100:1 may yield to final mosaic images from compressed data that are virtually indistinguishable from the original (PSNR about 35 dB). This approach allows online compression of raw data and nearly lossless image reconstruction when needed and it is well suited for the ENDURUNS project aims.

IV. RMCC OPERATION

The RMCC will provide a visualization tool that will merge and display all information received over time from the autonomous system. Data will be displayed using a visual map, text, tables and charts. The tool will allow an operator to select type of semantics to be displayed, select and zoom on areas of the map and choose external geographic data overlays. On each filtering and area selection a datasheet will be available to be processed or plotted. The operator will be able to request from the AUV/USV sets of data regarding specific areas or command the device to further investigate a designated zone. A diagram of the action cycle of the remote controlled seabed mapping mission is reported in Fig.2.

As mission duration will span multiple days, the RMCC provides mostly monitoring functions, in contrast to direct control. Current telemetry on system health (battery, motors, buoyancy, etc) are displayed in relation to all-time historical values over the course of the mission.

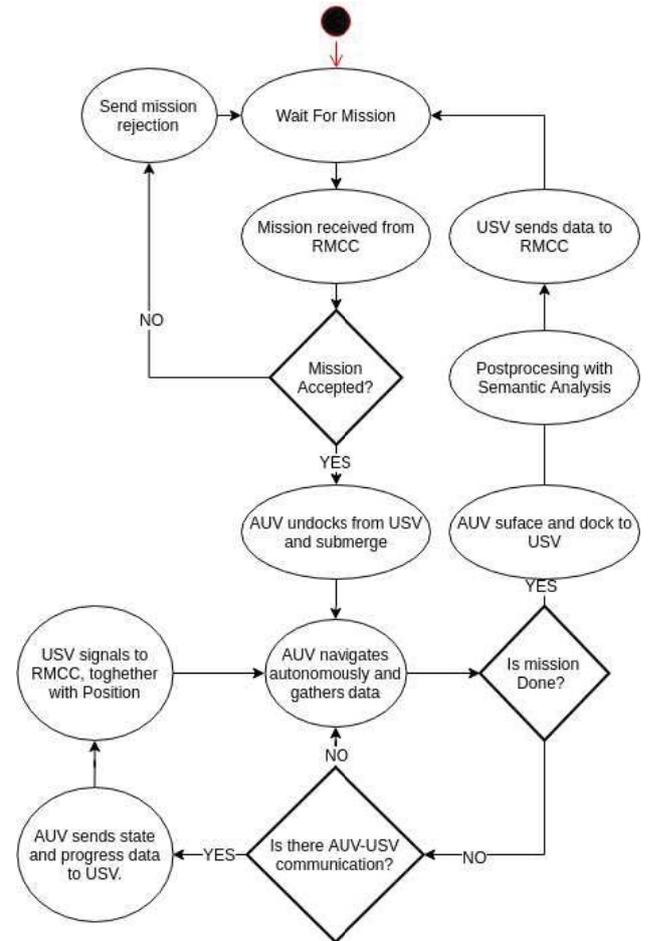


Fig. 2. Action diagram for the remote controlled and monitored seabed mapping mission.

This allows operators to assess the nominal bounds for these values. In case of system failure or non-nominal operations, an active alert is sent out to operators.

The AUV and USV undertake steps autonomously to ensure safety, if no mitigation steps are commenced from the RMCC. Actions will include resurfacing and auto-piloting to a designated recovery point, as well as signaling nearby vessels of their status. This limits the risk of losing either vessel if the satellite hardware fails.

V. COMMUNICATION LIMITATIONS

The main driver behind the data compression and communication architecture, is the bandwidth. Both the AUV-USV and USV-RMCC connection have their own limitations, stemming from the choice of hardware. This in turn is influenced by the monetary budget as well as design constraints. The chosen hardware needs to be affordable, yet small in form factor, withstand submersion and be highly power-efficient.

It is obvious that, due to the aquatic environment the AUV resides in, any regular electro-magnetic communication is not an option. This includes RF (radio-frequency), Wi-Fi and light signals, due to high absorption. The only viable option of acoustic modem (which also incorporates relative location functionality) however suffers from low bandwidth.

Furthermore, due to the non-homogeneous density of water (because of e.g. a temperature or salinity gradient), acoustic signals can get dispersed easily. Even with all these caveats, an acoustic modem is the only option for the AUV-USV connection.

A satellite link between the USV and RMCC is an obvious choice, as 4G (and other mobile connections) are not available on the high-seas, away from shore (see [10],[11] as references for maritime LTE coverage). Here the choice for an L-band antenna is three-fold. For starters, L-band is the most stable connection, whereas e.g. K and Ku-band antennas can lose connection during overcast weather or fast motion [12]. Secondly, the envisaged model (Thales VesseLINK, Fig. 3) is a phased array antenna.

These antennas do not have any moving parts, but instead use electronic beam-steering to optimize gain in a certain direction. Moving parts are more susceptible to damage, require maintenance and would be more difficult to proof them for submersion. Lastly, the L-band antenna is reasonably priced, small and light.

It is therefore the perfect choice given the tight constraints of the ENDURUNS project. The only downside to the L-band antenna is again the limited bandwidth (as opposed to K and Ku-band antennas), reaching speeds of several hundreds of kbps.



Fig. 3. Thales VesseLINK L-band antenna

Because the system is power-constrained, continuously powering a 30-100 W antenna is not ideal. The USV could use a low-power satellite antenna and modem combo to ping the RMCC command queue at certain intervals and determine if powering up the main antenna would be needed.

This can be used to concentrate transmissions to timeframes where energy is abundantly available, or in general make information transmission more efficient. A draw-back would be the additional time spent connecting to the satellite constellation. A similar low-power antenna can be added to the AUV.

When resurfaced and unable to connect to the USV during non-nominal operations, the AUV can signal its status to the RMCC independently.

VI. CONCLUSIONS

The ENDURUNS project lasts 4 years and now it is still ongoing. Its conclusion is expected in 2022, with the execution of two seafloor survey missions in the South Adriatic Sea (Bari/Monopoli canyons, Italy) and in the Baltic Sea (Klaipeda port, Lithuania). ENDURUNS is managed by ALTUS LSA (Greece) and the Consortium includes 18 partners from 10 different countries (official site www.enduruns.eu).

The context of ENDURUNS project provides a major opportunity in seafloor exploration due to the highly extended autonomy for an AUV with a supporting USV. The challenges that come with autonomous long-term missions in remote offshore environments are monitoring, adaptation and control.

The core of the proposed approach for the transmission of MBES data and underwater images in ENDURUNS is a learning-based algorithm that extracts the key features of a mapped seabed region and builds a map containing the semantic classification of features. Intensive data processing in completely performed onboard without human intervention.

The extracted data is small, thus transmittable via existing satellite technology to a remote control center, allowing the remote operator to analyze, request higher quality of data for selected areas and adjust the next tasks for planning the further exploration without having to

wait for long durations until the unmanned systems are physically recovered to access the data.

Our approach is aimed at making long term offshore missions highly efficient in terms of relevant data identification, onsite adaptation to findings and speed of exploration.

VII. ACKNOWLEDGEMENTS

The ENDURUNS project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 Research and Innovation Programme (Research Grant Agreement H2020-MG-2018-2019-2020 n.824348).

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