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CAMELOT - localization beacon system

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CAMELOT - Localization Beacon System

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Abstract*—C2 Advanced Multi-Domain Environment And Live Observation Technologies (CAMELOT) is a H2020 project intended to develop and demonstrate different advanced command and control service modules for multiple platform domains customizable to the user needs. Currently, there is no widespread standard for multi-service, multi-domain command and control (C2) systems. The CAMELOT architecture and modules will help build critical support in both the industrial and the practitioner communities leading to the adoption of these technologies. The underwater domain is a special case in command and control as communication and localization have to be implemented in a completely different way. The underwater domain is reached using one or many, mobile or stationary surface assets that act as gateways. The same assets provide underwater assets with positional updates. The localization beacon system (LBS) is a novel localization system being developed in the scope of the CAMELOT project. LBS provides assets with position data in a unidirectional way. The beacon is composed of a circular transducer array which signals vary in properties from one another thus allowing assets to hear a composite signal that varies depending on the bearing from the beacon. As the beacon can be mobile a parallel acoustic modem message is sent informing assets of the beacon pose and other relevant data. To keep the method unidirectional synchronized clocks are used for ranging thus allowing any listener to calculate its position using only a receiving hydrophone. As the underwater robotic world is growing and more and more multi-platform solutions are being proposed for various maritime missions and tasks, this LBS brings an advantage in comparison to classic underwater positioning systems as it provides a constant position update rate invariant to the number of assets. Assets are "linked" using an acoustic modem network allowing them to exchange data and inform the C2 station of their status. The JANUS acoustic modem standard is used to render the system in the spirit of the CAMELOT project. This paper presents the LBS concept using simulated signals and provides analysis of the expected accuracy for the later experiments.

CAMELOT project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 740736.

Keywords—multi-domain, command, control, localization

I. INTRODUCTION

CAMELOT H2020 project purpose is to develop and demonstrate different advanced command and control service modules for multiple platform domains customizable to the user needs. Non-existence of a widespread multi-domain mission station data model and services is a growing problem for end users as the current situation forces them to depend on a single manufacturer or use completely separate non-compatible systems in parallel which increases equipment cost, adds overhead in manpower and can ultimately diminish operator focus. Since there is several contemporary attempts to standardize different levels of multi-domain robot command and control, the CAMELOT project selected the emerging STANAG MCDS 4817 as the basis for the CAMELOT data model whilst several multi-domain service modules will be developed in the framework of the CAMELOT C2 network to complete the project. In the multi-domain C2 system the underwater domain poses a special case as the currently achievable communication bandwidth cannot support the payload of such a data model and resulting data overhead. This problem is solved using surface assets as gateways between the underwater acoustic communication and aerial RF communication. Like for communication, acoustics is used in underwater localization. Today, there is a wide variety of acoustic localization systems and products that even fuse communication with localization but most of them rely on an interrogator node that interrogates each participant at a time, or multiple beacons are used where deployment/recovery logistics and deployment precision becomes problematic. As underwater vehicles and sensors become more affordable and even expendable, more and more multi-platform solutions are being proposed for various maritime missions and tasks. Each new asset in the localization system reduces the position update rate for every other asset (usually in the order of 1s). Therefore, an unidirectional localization system is an efficient solution to that problem when multiple vehicles are used. Adding a JANUS standard [4] acoustic modem parallel to that system will enable the robots to inform the C2 station of their position in low update rate whilst maintaining a high position update rate from the LBS.

II. LOCALIZATION BEACON SYSTEM

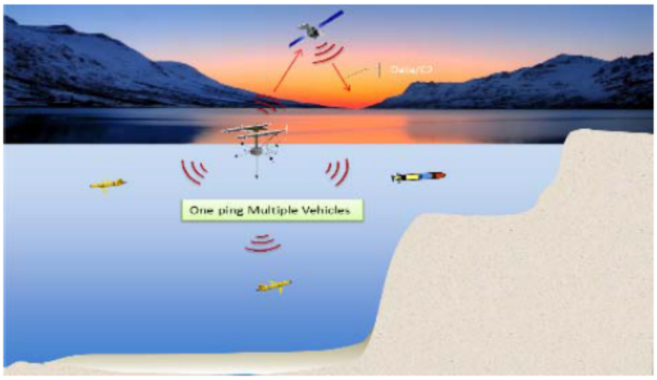


Fig. 1. LBS operation depiction in CAMELOT framework

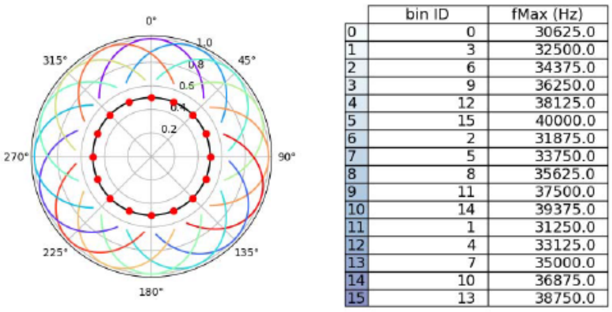
Unidirectional localization is not new as a concept. There have been multiple concepts developed on this topic (one pinger navigation, etc.). Some of them would be based on ranging only, some of them on triangulation or multilateration methods using multiple beacons. The proposed LBS is inspired by the work of Benjamin

Dzikowicz's research [1] where a spiral wavefront beacon was developed to provide the listener with bearing to beacon information using the phase difference between a spiral wavefront signal and a referent circular wavefront signal. That research was inspired by the Very High Frequency (VHF) Omni-Directional Range (VOR) system used to navigate aircraft to airports mainly before the Global Positioning System (GPS) era. In recent years, even some patents were released on this subject (for example: [2]Benjamin Dzikowicz, "Underwater acoustic beacon and method of operating same for navigation", U.S. Patent 7,406,001 B1 (US7406001B1), issued Jul 29, 2008., [3]David Alan Brown, Boris Aronov, Corey Lionel Bachand, "Acoustic transducers for underwater navigation and communication", U.S. Patent 8,638,640 B2 (US8638640B2), issued Jan 28, 2014.) detailing beacons using the spiral wavefront as a localization method. The CAMELOT LBS aims to improve on mentioned research using an array of directional transducers that generate composite signal with bearing dependent signal components in frequency and phase. The resulting signal is no longer using a spiral wavefront but it should gain in robustness to signal multi-path whilst introducing some other improvements which will be explained in the following sections.

The complete LBS (Fig. 1) will include a bearing dependent signal and a JANUS standard modem broadcasting the beacon attitude. The LBS signal and JANUS broadcast transmission will be triggered by a GPS xPPS ($x \leqslant 1$) signal (xPPS – Pulse Per Second with a pulse on ever x second. $x \leqslant 1$ means the pulse is generated once every 2 or more seconds). As range is calculated by counting the time from the last xPPS, receiving assets will have previously synchronized atomic clocks in order to minimize range error during mission execution. The clock can be synchronized with the GPS PPS signal when the underwater asset is surfaced.

III. BEACON SPECIFICATION

Chosen beacon design is 16 directional conical beam transducers in a circle. Signal firing is not separated in time as all transducers emit the signal on xPPS. According to available off-the-shelf transducers the beacon frequency band is: 30kHz to 40kHz. The beacon frequency band is divided in 16 frequency bins resulting in frequency bin width of 625Hz. Each transducer if of around 80 degrees horizontal beam width (-3dB). The transducers have a reasonably flat Transmit Voltage Response (TVR) (±3dB) in the band 25~45kHz. Using this information, the beacon frequency band in this simulation is 30~40kHz..



	bin ID	fMax (Hz)
0	0	30625.0
1	3	32500.0
2	6	34375.0
3	9	36250.0
4	12	38125.0
5	15	40000.0
6	2	31875.0
7	5	33750.0
8	8	35625.0
9	11	37500.0
10	14	39375.0
11	1	31250.0
12	4	33125.0
13	7	35000.0
14	10	36875.0
15	13	38750.0

Fig. 2. Beacon specification

Each transducer is assigned a frequency bin 625Hz wide. To contribute to robustness to multi-path the frequency bins are assigned using an algorithm that maximizes transducer frequency bin separation between best "visible" transducers from any location (Fig. 2). Each transducer transmits a hyperbolic up-chirp of 100ms ranging from f_L to f_H in the allocated frequency bin. The signal transmission is synchronous for all transducer triggered by the xPPS signal.

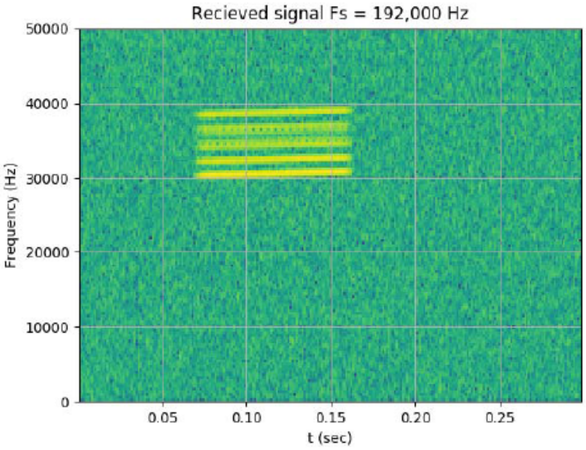


Fig. 3. Example received signal spectrogram

IV. RECEIVER – DOPPLER SHIFT ESTIMATION

Underwater signals undergo many changes in the acoustic channel of which the first to measure is the Doppler shift. As the beacon is composed by 16 different sound sources, a receiver should always hear at least 5 of them in a direct travel line. Note that the receiver positions outside the vertical beam width coverage (example: under the beacon) are not covered in this article. Hyperbolic chirps are used because they don't get deformed by Doppler shift. The following equations are related to hyperbolic up-chirps.

$$f(t) = \frac{f_L f_H T}{f_H T - F_{bin} t} \qquad (1)$$

Equation (1) shows the frequency-time relation in a hyperbolic chirp where f_L = low frequency (Hz), f_H = high frequency (Hz), T = chirp duration (s), F_{bin} = frequency bin width (Hz). In order to measure the Doppler effect we use the theoretical time offset in matching the original hyperbolic chirp with a Doppler shifted one. Equation (2) shows the relation between the offset in time τ due to Doppler shift κ [5].

$$\tau = \frac{f_H T(\kappa - 1)}{\kappa F_{bin}} \qquad (2)$$

A general equation for each transducer signal reception moment in relation to the last xPPS is (3), where t_R is the moment of received signal start, R is range (m), c is the speed of sound (m/s) and τ_{CC} is the offset in time due to beacon curvature:

$$t_R = \frac{R}{c} + \tau + \tau_{CC} \qquad (3)$$

By subtracting the same equation (3) for two transducers A and B (t_{RA} - t_{RB}) in the same beacon we get:

$$\kappa = \frac{\frac{T}{F_{bin}}(f_{HA} - f_{HB})}{\frac{T}{F_{bin}}(f_{HA} - f_{HB}) - (\tau_A - \tau_B)} \tag{4}$$

Equation (4) assumes all frequency bins are of equal width F_{bin} and $\tau_{CC}=0$. Using the equation (4) and correcting the $\tau_A - \tau_B$ by minimum curvature offset τ_{CC} we can calculate a vector of κ factors for each possible "visible" transducer pair. In a simple way we can find the transducer with the minimum t_R (the closest one) and compare the surrounding 4 transducers to that one. To cope with signal match error due to various factors we use the κ vector median value as our final κ measurement. Using a sampling rate of 192 kS/s and given beacon parameters in this article, the worst resolution for rRate is 0.13m/s and the best one is 0.03 m/s (assuming c = 1500 m/s). To cover a larger doppler factor interval we use a larger hyperbolic match filter that comprises Doppler shifts ranging from κ_{MIN} to κ_{MAX} (example: 0.99 to 1.01 → range-rate -15 to 15 m/s using c = 1500 m/s). The following set of equations determine the parameters of the match filter (MF) hyperbolic chirp:

$$t_{MIN} = \frac{f_H T}{\kappa_{MIN} F_{bin}}(\kappa_{MIN} - 1) \tag{5}$$

$$t_{MAX} = \frac{T}{\kappa_{MAX} F_{bin}}(\kappa_{MAX} f_H - f_L) \tag{6}$$

$$\begin{aligned} f_{HMF} &= \kappa_{MAX} f_H \\ f_{LMF} &= \kappa_{MIN} f_L \\ T_{MF} &= t_{MAX} - t_{MIN} \end{aligned} \tag{7}$$

Equations (5) and (6) calculate the beginning (t_{MIN}) and end (t_{MAX}) time when the original transducer hyperbolic chirp will get to f_{LMF} and f_{HMF} defined in equation set (7). Using this MF the equation (3) is expanded with a known MF induced offset τ_{MF} (8) for each frequency bin and used in the κ calculus (4).

$$t_R = \frac{R}{c} + \tau + \tau_{CC} + \tau_{MF} \tag{8}$$

Measuring the Doppler shift is important not only for the later bearing match filter scanning but also for reducing range error as τ introduces a range error in order of meters for range-rates in order of meters per second. To have a better Doppler shift estimate, κ is first calculated using the wide MF (κ_0). To have a more accurate estimate of the doppler shift, we then Doppler shift the original transducer signals by κ_0 and use them as match filters in the same way. Using the equation (4) we now get $\kappa_k = \kappa_{k-1} + \kappa_{offset} - 1$. The same process can be repeated multiple times to calculate a vector of Doppler shifts κ_{est} estimates. For the moment the median value of the κ_{est} vector.

V. RECEIVER – BEARING SCAN

Beacon size and transducer relative offsets will, in signal samples be, in the same order as the signal match position error. To circumnavigate that fact bearing will be found by scanning the perimeter by compiling the theoretical signal for each bearing step. Having a range estimate $R = t_R \cdot c/Fs$ (Fs = sampling rate) and measured Doppler shift κ, correctly shifted ideal transducer signals can be multiplexed to form a match filter. To reduce computation time, a coarse scan is performed (for example ±15 degrees, 1 degree step). The bearing with maximum correlation value is selected as the most correct result. Next a fine bearing scan is used around the coarse bearing scan result (for example ±5 degrees, 0.1 degree step). Again the maximum correlation value bearing is considered to be the final bearing result.

The following figures (Fig. 4, Fig. 5, Fig. 6, Fig. 7) show the Doppler, range and bearing measurement/estimation process. Signal parameters: range = 100m, bearing = 0 deg, range-rate = 5 m/s, c = 1500 m/s, SNR = 10 dB. The signal used contains 4 multipath signals: 1) range = 101m, bearing = 2 deg, range-rate = 5 m/s, 2) range = 101m, bearing = -2 deg, range-rate = 5 m/s, 3) range = 110m, bearing = 10 deg, range-rate = 1 m/s, 5) range = 120m, bearing = 150 deg, range-rate = 4 m/s.

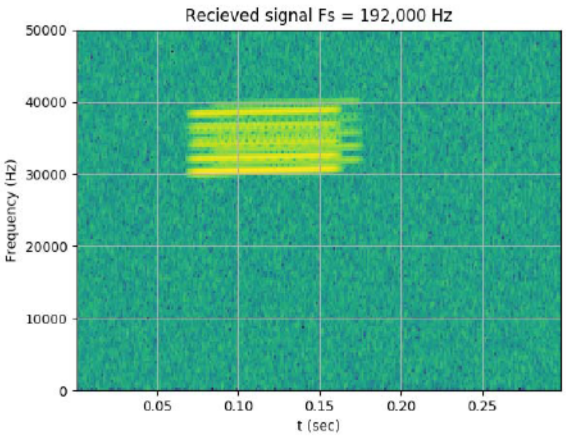


Fig. 4. Received signal spectrogram

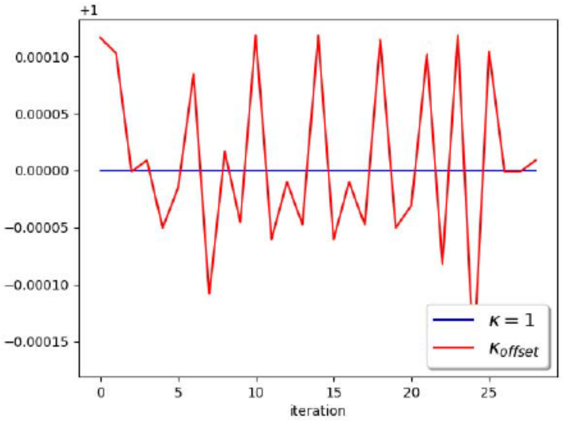


Fig. 5. Doppler shift offset in relation to range-rate = 0

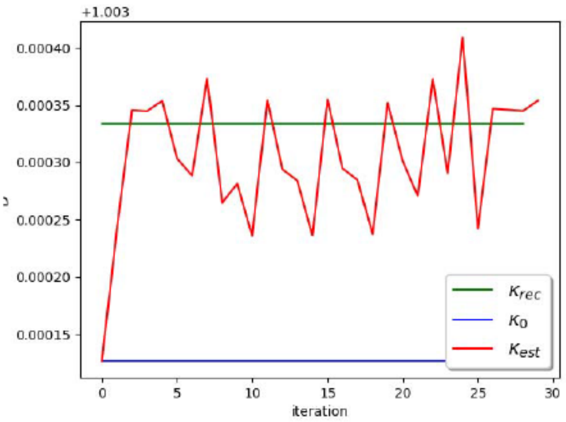


Fig. 6. Doppler shift estimate vector

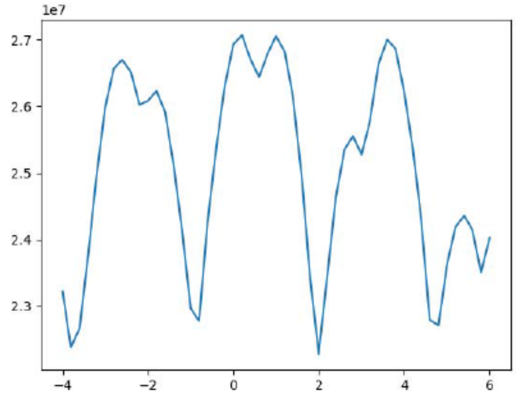


Fig. 7. Bearing fine scan correlation curve (x-axis is bearing, y-axis non-normalized is maximum correlation value)

The result in shown figures is: R = 100.1484375m, bearing = 0.2 deg, κ_{median} = 1.0032981700055483 where the ideal Doppler shift is κ_{rec} = 1.0033333333333334.

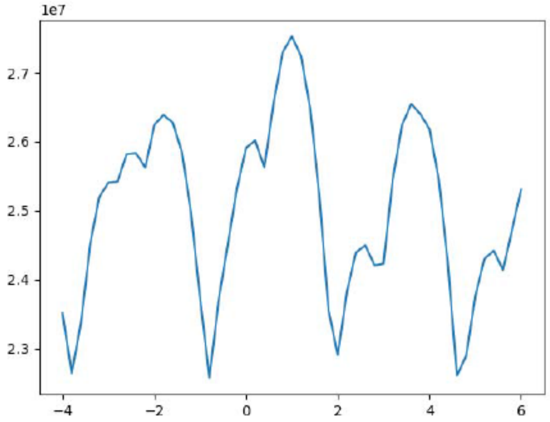


Fig. 8. Bearing fine scan correlation curve (x-axis is bearing, y-axis non-normalized is maximum correlation value)

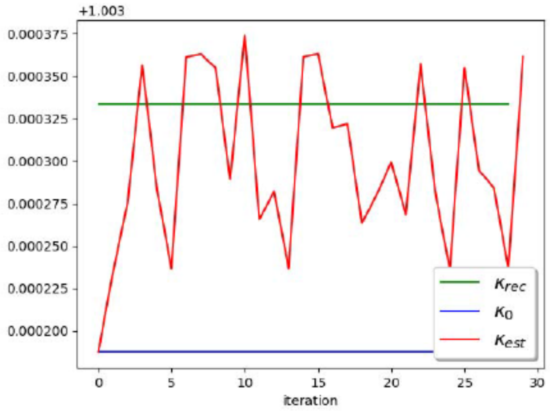


Fig. 9. Doppler shift estimate vector

The explained process is the current method used in this simulation. It is highly sensitive to Doppler shift estimate accuracy and therefore is going to be upgraded in near future field measurements. This method requires the accuracy in estimating the Doppler shift of 10^{-4} to give a bearing result inside ±1 degrees. Figures (Fig. 8, Fig. 9) show the same situation (different random noise SNR = 10 dB) when the Doppler shift is not estimated accurately enough, resulting in: κ_{median} = 1.0032867019650036, bearing = 1.000 deg, R = 99.351 m.

VI. CONCLUSION

CAMELOT project goal is a standardized scalable mission control framework. The concept of a unidirectional localization system like the LBS provides mission scalability while maintaining a constant localization update rate regardless of the amount of underwater assets. In contemporary underwater missions it is no longer necessary for the operator to have the same asset location update rate as the asset itself. Providing the operator with information through an underwater acoustic network is sufficient as in an autonomous mission the operator really needs information about assets mission results, alerts, detections etc. Although achieving satisfactory robustness to multi-path is challenging this system has the potential to bring swarm-like underwater autonomous missions a step closer to reality while allowing stealthiness, lower energy consumption and in the end lower cost robots to be used.

REFERENCES

[1] B. R. Dzikowicz, B. T. Hefner and R. A. Leasko, "Underwater Acoustic Navigation Using a Beacon With a Spiral Wave Front," in IEEE Journal of Oceanic Engineering, vol. 40, no. 1, pp. 177-186, Jan. 2015. doi: 10.1109/JOE.2013.2293962

[2] Benjamin Dzikowicz, “Underwater acoustic beacon and method of operating same for navigation”, U.S. Patent 7,406,001 B1 (US7406001B1), issued Jul 29, 2008.

[3] David Alan Brown, Boris Aronov, Corey Lionel Bachand, “Acoustic transducers for underwater navigation and communication”, U.S. Patent 8,638,640 B2 (US8638640B2), issued Jan 28, 2014.

[4] J. Potter, J. Alves, D. Green, G. Zappa, I. Nissen and K. McCoy, “The JANUS underwater communications standard,” 2014 Underwater Communications and Networking (UComms), Sestri Levante, 2014, pp. 1-4. doi: 10.1109/UComms.2014.7017134

[5] Huang S, Fang S, Han N., “An Improved Velocity Estimation Method for Wideband Multi-Highlight Target Echoes in Active Sonar Systems,” Sensors (Basel). 2018;18(9):2794. Published 2018 Aug 24. doi:10.3390/s18092794

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