Towards unmanned vehicle detection using distributed acoustic sensing

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***Abstract*—Within the last decade, technological advancement and research breakthroughs have enabled the exploitation of existing underwater fiber optic cables for monitoring their environment. Those cables are critical parts of the maritime infrastructure and are, thus, targets for sabotage. Passing unmanned vehicles perturb the water column and generate acoustic emissions with distinct signatures at specific frequencies that can be sensed by the cables. In this study, we deployed a fiber optic cable on the bed of a lake and along its shore and detected a remotely operated vehicle and a drone using distributed acoustic sensing. We simulated attacks, analyzed acoustic signatures, and applied a spectral source detection algorithm to the data. Our results show evidence for detecting unmanned vehicles close to a fiber optic cable, both underwater and in air. Thus, this study provides a compliment to existing studies for further automatic vehicle detection and with that a tool to support the protection of maritime infrastructure.**

***Index Terms*—Maritime infrastructure, distributed acoustic sensing (DAS), fiber optic cables, remotely operated vehicle (ROV), drones, detection algorithms**

I. Introduction

Subsea power and telecommunication cables are critical maritime infrastructure and form an essential backbone of modern society. They support energy supply, global communication, and economic stability, and their disruption can lead to significant operational and societal consequences. Besides their economic relevance, subsea cables have become strategic assets of growing importance for national security and geopolitical stability [1], [2].

At the same time, the threat landscape affecting such cables has become more complex. Recent incidents and intelligence assessments have highlighted the relevance of sabotage, hybrid threats, and other deliberate activities targeting underwater infrastructure [2], [3]. This development increases the need for monitoring approaches that are capable of identifying localized and potentially covert activities in the vicinity of subsea cables. Conventional monitoring technologies, including hydrophones, sonar, radar, and satellite-based systems, provide valuable information but are often limited in their ability to deliver continuous and spatially resolved coverage over extended cable routes. Distributed acoustic sensing (DAS) offers a different approach by turning optical fibers into distributed acoustic sensors. Based on coherent Rayleigh backscattering, acoustic or mechanical disturbances along the fiber induce measurable changes in the backscattered light, allowing events to be detected and localized along the sensing path [4], [5].

This study investigates the use of DAS for detecting underwater and air-based vehicle activities near fiber optic cables. The focus lies on controlled experiments with a remotely operated vehicles (ROV) and a drone to assess how their presence can be identified both through cable-near disturbances and through characteristic vehicle-related acoustic emissions.

II. Methods

Our detection concept is based on two analysis paths. The first path addresses activities at or near the cable and, therefore, focuses on localised disturbances caused by interaction with the cable or by operations in its immediate vicinity. The second path addresses acoustic emissions generated by the vehicles themselves. This includes characteristic signals from propulsion or related vehicle dynamics that can be distinguished from background noise. To investigate these effects under controlled conditions, an ROV and a drone were used as test platforms. Their controlled operation allows relevant parameters such as speed and proximity to the cable to be varied in a repeatable way.

A. Distributed acoustic sensing (DAS)

DAS transforms optical fibers into distributed acoustic sensors and thereby enables spatially resolved monitoring along an extended sensing path [4], [5]. A DAS interrogator sends pulses of laser light at a wavelength of 1 550 nm down a fiber. As the light travels, tiny natural imperfections in the silica scatter a small amount of the light back towards the interrogator, based on coherent Rayleigh backscattering.

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Mechanical or acoustic disturbances acting on the fiber induce measurable changes in the optical phase of the backscattered light [4], [6], [7], which can be evaluated to detect and localize events along the fiber. In subsea applications, this provides continuous monitoring capability over long distances and makes the approach attractive for cable-related security and monitoring tasks.
In contrast to point sensors, the sensing information is obtained continuously along the fiber path. This allows localized activities in the vicinity of subsea cables to be detected with spatial resolution referenced to the sensing path. For the present study, this characteristic is particularly relevant because underwater vehicle activities may generate both localized disturbances near the cable and acoustic signatures that can be observed over a certain cable section.

B. Study site and equipment

On October 28, 2025, we deployed a 1 232 m singlemode optical fiber cable (BRUclean 250, G.652D, Solifos AG, Windisch, CH) on the bed and along the shore of lake Neuenwalde in Northern Germany supported by a rubber boat (Figure 1a, b, latitude: 53.660574°, longitude: 8.66887°). At the western shore, we placed a DAS interrogator (N5225B, AP Sensing GmbH, Böblingen, Germany), connected it to the cable, and recorded data along the entire cable for approximately 50 minutes from 13:20 (UTC) to 14:08 (UTC). For data collection, we used a sampling frequency of 1 000 Hz, a gauge length of 10 m, a pulse width of 5 m, and a channel spacing for the cable (steps of spatial sampling) of 1.25 m. The first 30 m of the cable were placed on land and subsequently transitioned into the lake. Between 30 m and 150 m, we simulated cable attacks using a blueROV2 (c, BlueRobotics, St. Torrance, CA, USA) with eight type T200 thrusters each with three blades. This operation was limited to the cable length of the ROV of 120 m. The water depth within this area was between 0.6 m and 8.7 m. At the northern shore, the cable continued onto the shore for another 525 m. Approximately 475 m of the cable were coiled together and the remaining 232 m were arranged as three lines. Approximately 20 m were buried 15 cm into the ground. This area was used for drone detection along the cable using a DJI Matrice 400 (d, DJI, Shenzhen, China) with four 2510F type propellers each with two blades.

C. Data processing

The DAS system records differential optical phase. We applied a cumulative sum for each channel to the differential phase. We then scaled the cumulative sum by a factor of $\pi \cdot 2^{-15}$ to convert the units to radians. Additionally, we converted the differential phase into strain by removing the mean phase from the timeseries to unwrap the phase, converting into units of radians, and applying a photo-elastic scaling factor for fused silica [6], [8], [9]. As a result, the phase change is proportional to the strain and a constant.
We converted both the cumulative sum of the phase and the strain from the time domain to the frequency domain using the Welch's method for spectral density estimation which allows us to estimate the power of a signal at different frequencies. We set the number of samples per segments to 1 000 and used a window size of 30 s.
We extracted a 21 s and a 16 s audio track of blueROV2 operations in the water from youtube videos [10], [11]. We recorded two short videos of the propeller movement of our DJI drone in our lab and extracted audio tracks. From the audio tracks, we computed the one-dimensional n-point discrete Fourier Transform of the audio tracks by means of the Fast Fourier Transform (FFT) algorithm. Audio signals emitted by vehicles can be characterized by narrow stationary frequency signatures, as the propellers and cavitation produce sounds that usually remain stable along the duration of a single recording [12] and, thus, are used for comparison with the DAS data.

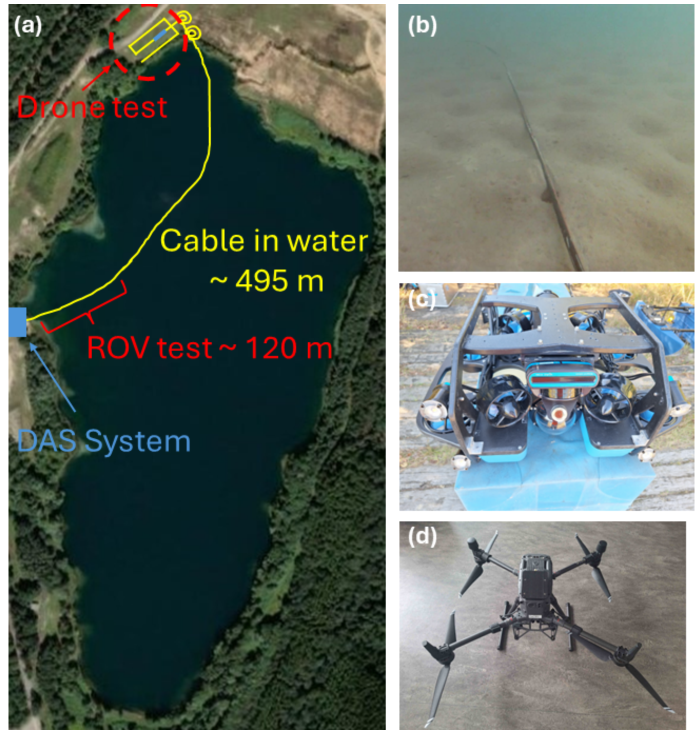

Fig. 1. (a) Study side. The three yellow lines in the top indicate the drone operation area including an approximately 20 m stripe (blue) where the cable was buried 15 cm into the ground. (b) Cable placed on the lake bed. (c) BlueROV2 (BlueRobotics, St. Torrance, CA, USA). (d) Drone DJI Matrice 400 (DJI, Shenzhen, China).

D. Detection algorithm

We used a spectral source detection algorithm to automatically detect ROV and drone activities. The algorithm sweeps between 10 Hz and 120 Hz and acts on peaks that are significantly above the background noise, here, above 20 dB. Both, the frequency band and the detection threshold can be set as needed. The algorithm performs a frequency analyses for each cable channel. Based on previous analysis, we assume that ROVs have typical propulsion frequencies at approximately 30 Hz or harmonics. Within the algorithm, one can add a frequency range that should not be considered, such as frequency peaks evolving from the DAS system itself, e.g. electrical and vibration.

III. Results

Our results are presented to investigate two detection factors: activities at or near the cable and vehicle-related acoustic emissions. Localized activities at or near the cable produced distinct responses in the DAS data. Figure 2 shows the time-space signature of the ROV operation near the cable as the cumulative sum of the phase in radians, band-pass filtered in the frequency band 20-200 Hz. We operated the ROV in the water along and above the cable between 30 m and 150 m (area marked by vertical black dashed lines in Figure 2. Occasionally (within the areas marked by the black dashed rectangle) we operated the ROV in such that it was hitting the cable, simulating an attack. Those hits are displayed as short periods of elevated magnitudes stretching approximately 30 m along the cable. This means that the fiber senses this hit not only at the exact position where it happened but along a wider range. Thus, targeted attacks can, in this case, be localized to an accuracy of 30 m.

ROV-related acoustic emissions were also detectable in the

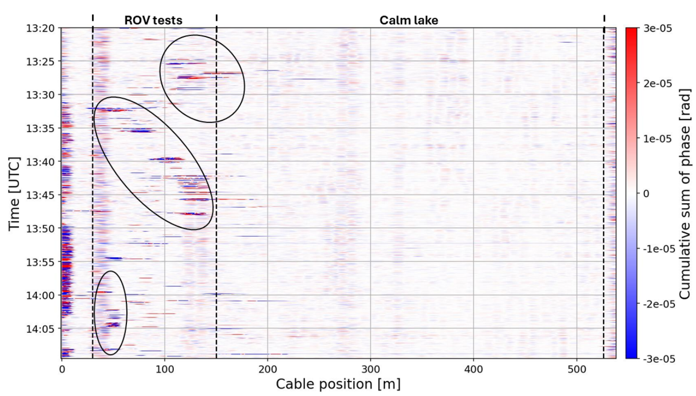

Fig. 2. DAS cumulative sum of phase, band-pass filtered in the frequency band 20-200 Hz for the cable segments from 0 m to 550 m and for the time period from 13:20 (UTC) to 14:08 (UTC) when the ROV was operated. 0 m: Cable connected to DAS interrogator. 30 m: Cable transitions into the lake. 30 m to 150 m: ROV operations. 525 m: Cable transitions ashore.

DAS data as the spectral signature illustrated in Figure 3a. Several clear peaks at specific frequencies are visible, e.g., at 57 Hz and 172 Hz. The thruster rotational speed of the ROV at 12 V is 3 075 rpm and at 16 V 3 600 rpm. Expressed in frequency, this is 51 Hz and 60 Hz and referred to as shaft frequency. As the thruster has three blades, the blade-pass frequency is three-times the shaft frequency, resulting in a range of 153-180 Hz. The frequency peaks detected in the DAS data are within this range. Applying the spectral source detection algorithm yielded 20 alarms between 40 m and 60 m of the cable, in the vicinity of the shore, during the time when the ROV was operated at those cable segments. Alarms were triggered due to peaks above 31-38 dB at 56-57 Hz. Those peaks coincide with the peaks in the DAS data (Figure 3a).

The frequency peaks detected in the DAS data and by the

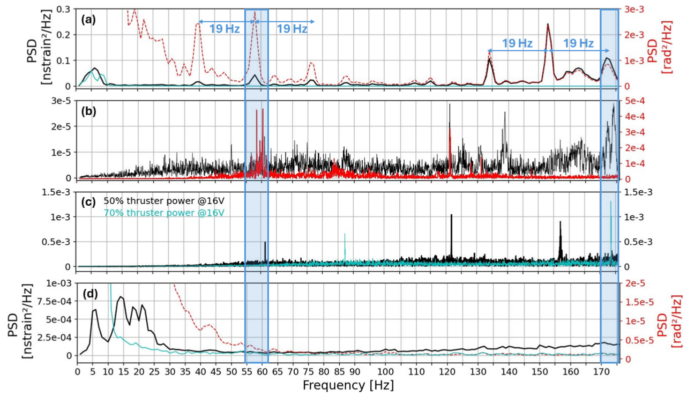

Fig. 3. Frequency analysis. (a) Power density spectra based on DAS data for ROV operation close to western shore of strain (black), cumulative sum of phase (dashed red), and background noise from mid lake (cyan). (b) FFTs based on audio tracks from youtube videos [10], [11] and (c) from recordings of single and detached ROV thrusters in the lab. (d) Power density spectra based on DAS data collected in the same location as in (a) but for a time where the cable was undisturbed.

algorithm are supported by the frequency analysis of the two individual audio tracks recording the operation of blueROV2s from BlueRobotics [10], [11] (Figure 3b). Both, the peaks at 56-57 Hz and at 172-174 Hz are visible in the FFT of the audio tracks, corresponding to the shaft and blade-pass activity, respectively.

The analysis of audio tracks from recordings of a single and detached ROV thruster (Figure 3c) reveal clear frequency peaks. Some of those peaks are comparable to the peaks revealed in the DAS and the video-based data.

Figure 3d displays the power density spectrum of the DAS data at the same location where the ROV was operated but during a time when no ROV operations were conducted. The power density spectrum has no prominent frequency peaks and the signals are two orders of magnitude lower than when the ROV was present (Figure 3a).

The two frequency peaks at 57 Hz and 153 Hz observed in the DAS data (Figure 3a) potentially correspond to the Doppler-shifted carrier frequencies associated with the forward and backward motion of the ROV relative to the cable. The Doppler-shifts arise from the time-varying distance between the ROV and the cable, resulting in frequency modulation of the emitted or scattered acoustic emissions. The peaks exhibit symmetric sideband structures spaced at regular intervals usually equal to the blade-pass frequency, here 19 Hz, which contradicts the interpretation of the DAS data above regarding blade-pass frequency. The sidebands are characteristic of periodic amplitude modulation (envelope) induced by time-varying acoustic scattering due to the rotating blades. In underwater environments, acoustic waves reflect off the water surface, lake bed, and internal waveguide boundaries, arriving at the cable with varying delays and phases. These delayed replicas interfere with the direct path signal, causing spectral broadening, fading, and spurious sideband-like features. However, the proximity of the ROV to the cable and the regular spacing and symmetry of the observed sidebands are inconsistent with random multipath effects and instead support the rotating thrusters as a deterministic, periodic modulation source. In a follow-up study, we plan to conduct a systematic DEMON (Detection of Envelope Modulation On Noise, [13]) analysis of the data to interpret those spectral features in more detail.

Figure 4a shows the time-space signature of the drone as strain along the cable segments 1 000 m to 1 232 m. For example, we operated the drone at 13:27 (UTC) from 1 230 m backwards to 1 160 m at the height of approximately 1 m directly above the cable. Along this trajectory the strain is elevated, likely caused by the air that the drone pushed towards the cable. We operated the drone again at 13:28:30 (UTC) from 1 010 m forwards to 1 175 m. Along this trajectory the strain is also elevated besides along the area where the cable was buried (between black dashed lines) where the signal is significantly damped and the strain is close to zero.

Drone-related acoustic emissions were also detectable in the DAS data as the spectral signature illustrated in Figure 4b. Several peaks at specific frequencies are visible, e.g., at 35 Hz, 71 Hz, and 140 Hz. Those peaks appear in the frequency analysis of two audio tracks from phone videos recording the propellor movement of the drone in our lab, although shifted by 3-5 Hz (Figure 4c). This could be explained by different operational speed of the propellors but needs to be investigated in detail further.

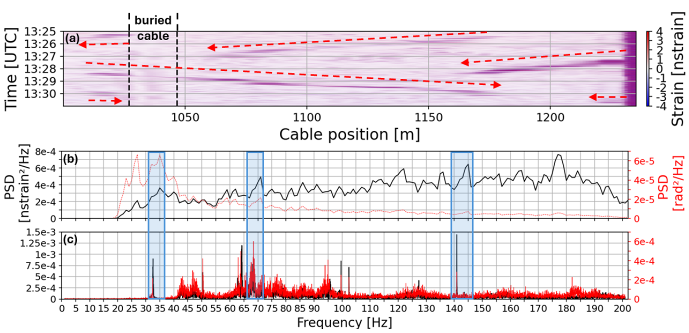

Fig. 4. (a) DAS strain for the cable segments from 1 000 m to 1 232 m where the drone was operated. (b) Frequency analysis. (b) Power density spectra based on DAS data from study site of strain (black) and cumulative sum of the phase (dashed red), both band-pass filtered in the frequency range 20-200 Hz. (c) FFT based on audio tracks from phone videos of drone propeller movement as recorded in a lab.

The spectral source detection algorithm triggered 117 alarms between 1 024 m and 1 230 m of the cable during the time when the drone was operated along those cable segments. Alarms were triggered due to peaks above 31-42 dB at 21-27 Hz which are displayed in figure 4b.

IV. Summary and Outlook

We investigated the use of DAS for detecting underwater vehicle activities near a cable deployed in a lake and for detecting a drone operated along a land-based part of the cable. The results show that ROVs and drones can be detected and that activities at or near the cable produce clear and relevant signatures in the DAS data. The use of DAS data is supported by independent analyses of audio tracks from ROV and drone operations. These findings confirm that the approach is suitable for identifying underwater activities that are relevant for the protection of critical underwater infrastructure.

At the same time, as the background noise from mid lake did not reveal characteristic ROV signatures, the results indicate that activities at greater distance from the cable are more difficult to detect and, therefore, involve higher uncertainty in the context of monitoring and alarm generation. This limitation is important for the interpretation of detection results and for the design of reliable detection systems.

Overall, the presented study demonstrates that DAS provides a promising tool for the detection of underwater vehicle activities and cable-near operations. Further studies should focus on the analyses of similar ROV operations in different environmental settings, for varying operational scenarios, such as ROVs crossing cables perpendicularly, and investigating the effect of variations in cable types and deployments such as burial depths of the cables. The overcharging goal focuses on improving detection robustness for more distant activities and refining automated detection methods, for example, through advanced signal analysis or artificial intelligence based approaches.

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