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Range Extension for Electromagnetic Detection of Subsea Power and Telecommunication Cables.

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Abstract—

Subsea cables protection afforded by burying a cable [beneath the sea bed] also means that the available methods for their survey are drastically reduced. From the existing methods only electromagnetics (EM) detection can penetrate the sea bed and provide an effective means for cable localization. However EM waves attenuate faster in conductive media such as sea water. EM localisation is considered a short range detection mechanism requiring the use of autonomous or remotely operated underwater platforms. In this paper the authors investigate the range of EM detection and test detection distances exceeding one hundred metres. The EM signal was detected at distances around 140 m in sea water during the trials conducted in a 'real' environment at Hooe Lake in Plymouth.

Keywords—subsea cables, underwater electromagnetics, surveying.

I. INTRODUCTION

Submarine cables play an important role in social and economic life. Connections made between continents, islands, and offshore installations require constant attention, periodic maintenance and repairs. The most vulnerable are located in shallow water and are often protected by burying them up to several metres beneath the sea bed. Despite this, they are subject to being displaced by the dynamic marine environment.

Buried cables are difficult to localise and survey. From all the possible techniques only electromagnetic field (EMF) methods can penetrate the sea bed without loss of resolution and provide a reliable means of localising thin cables [1, 2].

This paper considers extensions of EM cable's detection. The main contribution of the paper is to demonstrate that the low power EM signals can be detected at distances well exceeding 100 m through the sea water. All experiments were conducted in salt water at the tidal lake connected to Plymouth Sound.

The paper is organized as follows. After a short presentation of theoretical aspects, it discusses hardware design and improvements. The subsequent section considers new algorithms for cable detection. It also tests validity of using fast attenuation rates in all cable tracking situations. The final section of the paper presents results of the experiments showing that the submarine cable can be detected from a distance of 140 metres.

II. ELECTROMAGNETIC FIELD IN CABLE DETECTION

The primary aspect of buried cable detection is the response of the sensing element to the fields being sensed surrounding the utility. Magnetic (MF) and electric (EF) fields around a submarine cable originate from the electric currents and charges which either exist in the cable or are induced in the surrounding waters. These fields are described by Maxwell's equations [3].

For the purpose of submarine cable surveys, the frequency of the electric current within the cable is often in the range of 25 kHz to 1 kHz. The use of these low frequencies (LF) is mainly determined by the relation between frequency and attenuation of the EMF in sea water.

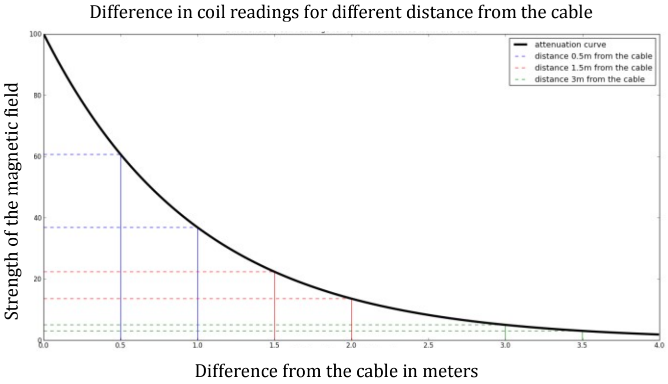
In the LF range the methods of quasi-static fields can be used to describe the dominating component of the EMF. The quasi-static method first derives a static MF, which is posteriorly described as oscillating in amplitude at the frequency of the sinusoidal source current. The spatial distribution of the field maintains the same shape but its amplitude varies in time with the source.

The EMF has three components attenuating at different rates, function of the distance (r) to the EMF source. These are identified as the "static" $(1/r^3)$ term, "induction" $(1/r^2)$ term and "radiation" $(1/r)$ term. In the quasi-static method, most commonly used in cable tracking, only the first two terms are grouped together and considered [3]. These two components with dominating static term play a major part in magnetic detection and are considered to be near-field methods [4].

Many existing tools rely on near-field analysis. The attenuation of the EM signal is modeled as an exponentially decaying curve with an attenuation of $(1/r^3)$. The signal is sampled at two points in space and the ratio between the readings is compared with the decay rate. This approach to estimation is shown in Figure 1.

The problem with this method is that it works only in small vicinity of the cable. In many cases the error in estimation is claimed to be - 5% of the distance. For short distances this is reasonable, but exceeds expectations for distances greater than 10 metres.

Figure 1 Traditional approach of distance estimation based on attenuation curve



The experimental results presented in this paper show that the $1/r^3$ attenuation component of the EMF is not the only one which can be detected. After the near field attenuates other components start to play a dominating role, allowing detection of the signal at much further ranges.

III. NEW APPROACHES TO CABLE TRACKING

Localisation algorithms require the EMF to be sampled as high precision, low noise data. Sample points need to be collected in the field along with the position of each sample. Commercial tools rarely provide the possibility to incorporate custom algorithms. To overcome this limitation, a new, fully digitised design with recording and storage capabilities was proposed. The prototype was later commercialised as SCT MC01 and SCT SC01 [5].

The subsection A focuses on important aspects of data acquisition. Following part B considers sensor design. It tests validity of using highly tunned and expensive ferromagnetic coils against well designed air coils. Finally subsection C presents results of recent experiments and work undertaken to model the distribution of the signals emitted by submarine cables.

A. Hardware For Data Acquisition

New sensing methods rely on high resolution, low noise acquisition systems with digital signal processing connected to sensors with linear characteristics. New acquisition tools were proposed to incorporate these features.

The central part of the system is an Analogue to Digital Converter (ADC) ADS1282 [6] with 32-bit resolution. High resolution allowed for numerical precision of $5/2^{32}$ where 5 is a reference voltage of 5 V and 2^{32} is the number of “zero-one” possibilities at this range. It means that the ADC can differentiate with a step of 1.2 nV.

The ADC used allows sampling at a speed of 4 kHz. The sampling rate is important in analysing different frequencies. An increase in sampling speed may give better processing capacity associated with a large number of elements. However, the high sampling rate carries also unwanted effects. Approximately one bit of resolution is lost for every doubling in rate [7].

For the purpose of cable tracking the acquisition tools were designed to sample the signal in the range from 25 Hz to 1 kHz. From practical considerations, this range covers all requirements. 25 Hz and 40 Hz are often used as a tone frequency in the cable station. Most of existing submarine cable systems are able to induce the tone with cable station’s Power Feed Equipment (PFE). Other often used frequencies are 512 Hz and 640 Hz. [8] [9]

Sensitive equipment with directional sensors are able to detect frequencies in passive mode. For inactive cables can be detected with resonating oscillations from the power grid at 50/60 Hz or resonance from radio frequencies are detectable.

B. Sensors

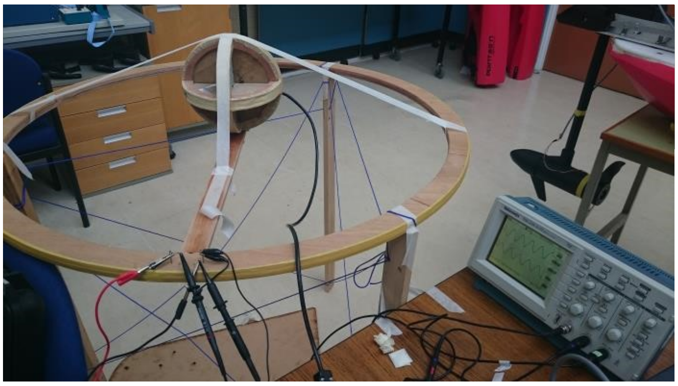
A second very important element for detection range extension is sensor design. It often requires resolving conflicting interests.

The coil size and number of turns play a key role in the coil’s sensitivity. For this reason, air searching coils become very large and difficult to use. The miniaturisation problem is often overcome by incorporating a ferromagnetic material as the coil’s core. The core concentrates the magnetic flux inside the coil. The relative permeability μ_r/μ_0 of modern ferromagnetic materials often exceeds the ratio of 10^5 and largely increases the coil’s sensitivity.

Although the sensitivity of the coil can be increased, a ferromagnetic core does not always provide the best characteristics [10]. Ferromagnetic coils lose linearity. Even the best materials introduce nonlinear factors into the transfer function which depend on temperature, frequency, flux density, etc. Ferromagnets increase the magnetic noise known as the Barkhausen noise, hence decrease the resolution of the sensor. Altering the distribution of investigated MF results in difficulties of describing underlying phenomena.

For the range extension three air flat coils (shown in Figure 2) with a diameter of 30 cm and 1000 turns were proposed.

Figure 2 Testing of three axis Helix Air coil later used during experiments



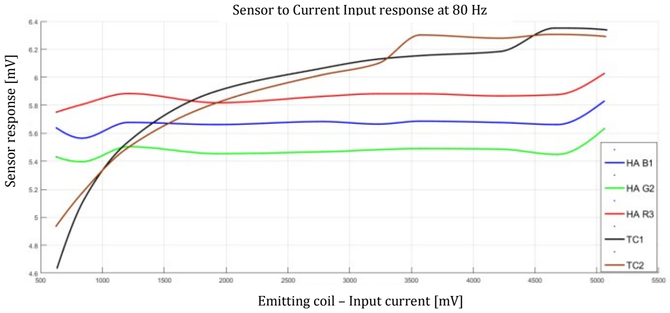
The choise of the helix air (HA) coil against high sensitive, tuned ferromagnetic core coil (TC) was tested in a laboratory. The experimental setup included a drive coil. It was a 1-metre radius coil with 100 turns coiled on a circular, half centimetre high wooden frame. The function generator induced a sinusoidal AC current with a given frequency. The current was measured with a multimeter. The magnetic flux ϕ in the middle of the drive coil was calculated as $\phi = \mu_0 I * n/l$ where $\mu_0 = 0.00000125663706$ [H/m], where I stands for measured current, $n = 100$ is the number of turns and $l = 0.005$ [m] is the length of the coil.

HA and TC coils were placed in the middle of the drive coil and the peak-to-peak voltage output of the sensor was recorded.

Figure 3 shows the output of three overlapping HA coils set into a three-axis sensor. Diameters of HA differ by 5 mm and 10 mm. These differences explain why all three readings show output on different levels.

For comparison outputs from two separate TC coils were measured. Both TC coils were manufactured by the same company and should give identical results. It can be noted that TC coils reacted to the signal exceeding the level necessary for the core's magnetisation.

Figure 3 Comparison of Air and Core coil response for different signal strength



The outcome of the experiment shows important nonlinear characteristics of the TC sensors, nonlinearities in response to a weak MF. The output of the TC coil is similar to that of the air coil. Nonlinearities in the response can result in unpredictable consequences.

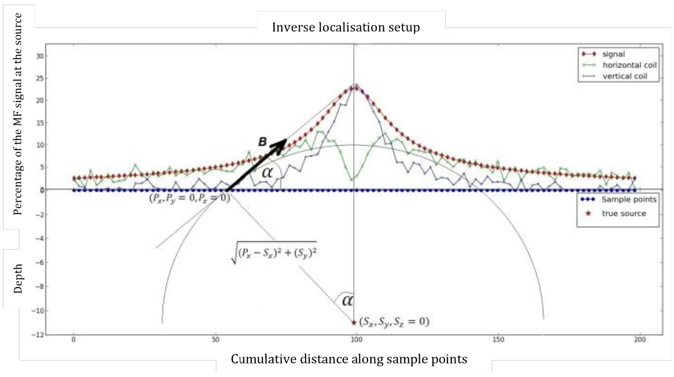
The depth measurement algorithm used by available cable tracking tools relies on extrapolation of the response-distance function. The profile is produced during the on-land calibration process and is built only upon a small range of MF differences. Changing the MF characteristics, applying calibration data to a diver's search, a weaker MF or different temperature can result in increased error.

From all the tested sensors, the air coil shows the most linear response with the output, at least as good as the expensive proprietary coils. The linear characteristic is important for application of the algorithms described in later section.

C. Modelling

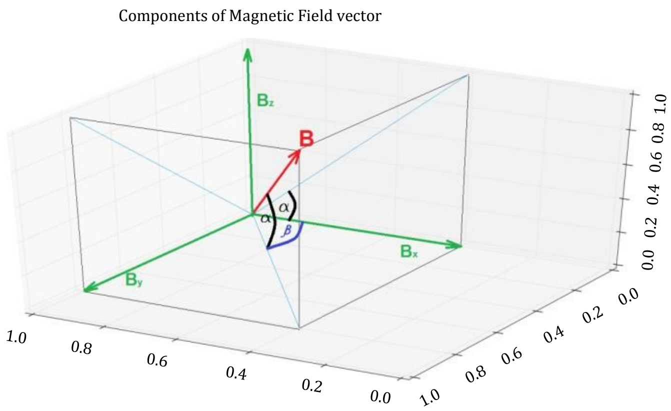
Triangulation algorithms used in commercial cable tracking gives distance estimation based on readings' amplitudes. In an ideal situation without noise and nonlinearities in the readings the setup shown in Figure 4 could give satisfactory readings.

Figure 4 Simplified 2-dimensional model of traditional estimation



For distances larger than a few metres, the noise incorporated into the readings results in large estimation errors. To avoid this problem sensors are built into 3-dimentional setups sampling each component of the MF vector as shown in Figure 5.

Figure 5 Three axis coils setup



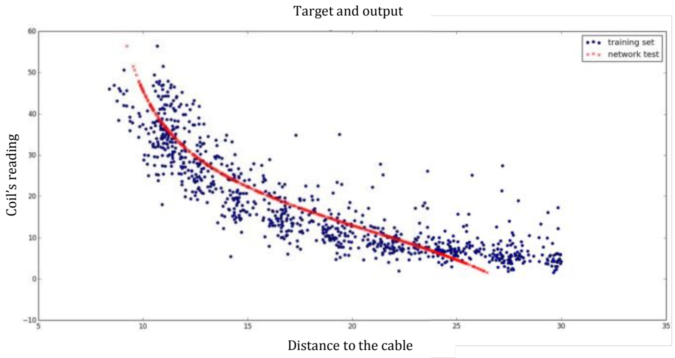
A Triangulation algorithm can be improved by black-box modelling such as Neural Networks (NN) ability to detect the angle of the incoming signal [11]. The advantage of using an NN approach is that they learn to link features of the signal with the distance to the array. The procedure eliminates requirements of prior knowledge about parameters of the signal [12].

NN training datasets were obtained from samples taken at a distance between 7 m and 50 m to the cable. Different NN models were tested showing different performances. The best results were obtained with a feed-forward back propagation model with horizontal coil readings as the input and the distance to the cable as the output. The NN was trained with real survey data of a submarine cable with a 40 Hz tone.

First, the training set was used to build an NN model and to calculate the parameters. From the available survey data, only those samples within 30 metres of the source were considered. This made a set of 2046 data points. One-quarter of the points (510) were chosen randomly and used to train the NN model. From the rest of the data points, 100 points were chosen to test and validate the fit.

Results of the modelling are shown in Figure 6. The validation test is shown as red cross marker and training data points are shown as blue dots. The vertical axis of the plot shows the coil readings. The horizontal axis shows the distance between the cable and the sample point.

Figure 6 Neural Network's Horizontal coil's output modelling



It can be seen that the model of magnetic readings at larger distances corresponds to the cubic decay curve of MF attenuation. As was expected the amplitude of MF attenuates quickly but it can differentiate the readings in a range of up to 25 m. After the range of 20 m, the curve of the readings changes its properties exhibiting a different behaviour.

The NN modelling can better estimate attenuation curves but is impractical in real world solutions. It requires well-formed samples for model building. In the survey situation, it is often impossible to have a section of cable which would be well presented for building the model. In addition the NN model is only valid localy and not guaranteed in different cable secions. To avoid this problem a model-less solution such as batch particle filters can be adapted [13].

IV. DETECTION RANGE TESTING

The modelling of the cable's sensing shows that the utility can be detected from a distance of more than 20 m. It also shows that the attenuation curve behaves different after the first section. The hypothesis that the MF signal attenuation follows near field and far field distribution is tested in this section.

A. *Experiment data*

The practical range of cable tracking was tested during experiments conducted in February 2017 on Hooe Lake in Plymouth. For the experimental purpose, a 200 m cable was laid on the seabed. One end of the cable was connected to a tone generator SCT TG01 [5] the second end was submerged in the sea water. The tone was induced in such a way that the returning path for the current was through the water.

Different tone frequencies were tested but the current was kept at 0.2 A with the voltage drop between the two ends of the testing cable within 2.5 V.

Figure 7 shows the experimental setup and survey platform's path for differenced frequencies.

Figure 7 Experimental setup with testing cable and samples collected for different frequencies

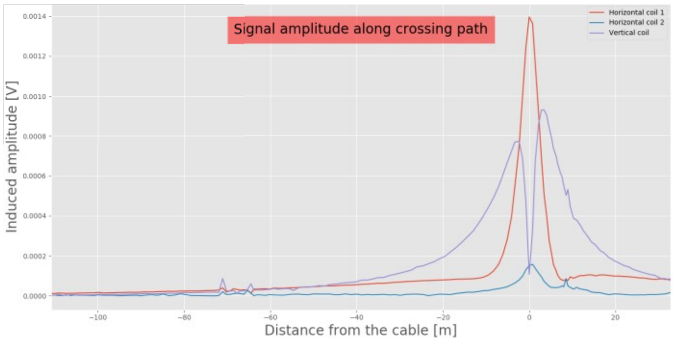
The setup, water's depth and dimensions of the lake allowed performing the survey from as far as 140 m away from the cable. The signal was detected at all of these distances.

The readings were taken with the commercialised version of survey equipment SCT MC01 [5]. The acquisition unit was connected to three axis searching coils. The readings of the coils were plotted in real time and recorded for post-processing.

For this particular survey the HA coils described previously was used. The axis of horizontal coil 1 was set up in the direction perpendicular to the cable line. This direction gives the strongest reading above the cable. The axis of horizontal coil 2 was in the same line as the cable line, giving no reading above the cable. The vertical coil's axis gives high readings at the side of the cable with null reading at the crossing point.

Figure 8 shows readings of the coil generated whilst crossing the cable with a 223 Hz tone.

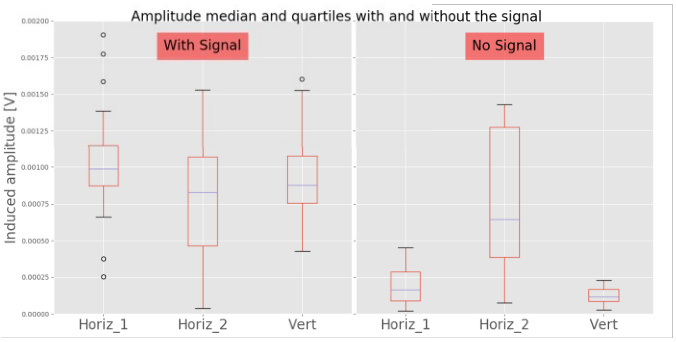
Figure 8 Example of readings during cable crossing. (Crossing path for frequency 223 Hz)



The amplitudes show a clear pattern for the signal behaviour. The signal is strongest above the cable and attenuates fast in the first ten metres on either side of the utility. After the fast attenuation in the near-field area, the signal gradually attenuates in the further range. The difference between Horizontal coil 1 and 2 are still visible after 80 m of distance confirming positive detection. The water depth across the lake was only 1.5 metres and can be neglected.

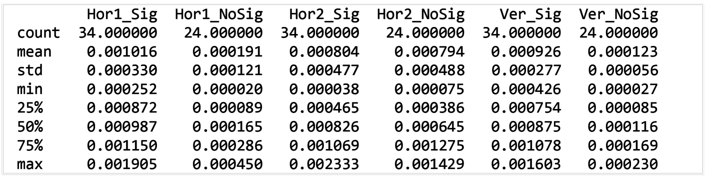
To further test the distance, two sets of readings were taken between 126 and 132 metres from the cable. The platform was moving in the survey direction perpendicular to the cable. For the first set of readings, the 0.2 A, 479 Hz tone was introduced to the cable. The second set of readings was taken without any tone in the cable, hence no signal to read. Figure 9 shows summary statistics. The positive readings were taken beyond the 140 metres, although the tidal nature of the lake did not allow to repeat readings which are not reported.

Figure 9 Comparison of output for Horizontal coils 1 and 2 and Vertical coil in case of signal's presence and absence taken at the distance between 126 and 132 metres from the cable



The readings in the two sets suggest the signal was observed at the tested distances. Table 1 summaries the readings for all coils.

Table 1 Values of outputs for Horizontal coils1 and 2 and Vertical coil in case of signal's presence and absence



```
       Hor1_Sig  Hor1_NoSig   Hor2_Sig  Hor2_NoSig    Ver_Sig  Ver_NoSig
count  34.000000   24.000000  34.000000   24.000000  34.000000  24.000000
mean    0.001016    0.000191   0.000804    0.000794   0.000926   0.000123
std     0.000330    0.000121   0.000477    0.000488   0.000277   0.000056
min     0.000252    0.000020   0.000038    0.000075   0.000426   0.000027
25%     0.000872    0.000089   0.000465    0.000386   0.000754   0.000085
50%     0.000987    0.000165   0.000826    0.000645   0.000875   0.000116
75%     0.001150    0.000286   0.001069    0.001275   0.001078   0.000169
max     0.001905    0.000450   0.002333    0.001429   0.001603   0.000230
```

The significance of the difference between the readings was tested with Mann-Whitney statistic. Table 2 summaries obtained values.

Table 2 Values of statistics for Mann-Whitney test

```
Mann Whitney Test outputs
Horizontal coil 1: z-stat = 6.27, p-val = 3.6635726197589435e-10
Horizontal coil 2: z-stat =-0.19, p-val = 0.8497380288082937
Vertical coil    : z-stat = 6.44, p-val = 1.183830057882682e-10
```

The difference of Horizontal coil 1 readings taken with and without signal are significantly different. The same applies to the readings of Vertical coil. There is no significant difference between the readings of Horizontal coil 2 which was situated in the null direction.

Experiments show that a weak signal from the cable can be read at a distance as far as 140 metres. Careful consideration about the equipment, algorithms and survey configuration can allow surveying subsea cables in shallow waters.

V. CONCLUSION

Detecting submarine power and telecommunication cables is an important but difficult task. Existing tools and algorithms allow surveying those utilities only from short distances, often engaging divers or remotely operated vehicles.

Careful consideration about survey hardware and algorithms used allows extending cable detection ranges to tens or even hundreds of metres.

In this range of detection signal attenuation needs to be considered as heterogeneous following near field and far field distributions.

allow surveying subsea cables in shallow waters.

VI. FUTURE DIRECTIONS

Presented methods are designed to track EM signal from the tone induced to the submarine cables. In most situations, tone injection provides a stable signal with well-determined frequency. The method, however, can detect EMF from other sources such as power cables or submarine joints. Initial experiments in power cables detection show that although the EMF can be detected, its characteristic is not stable, showing fluctuance in amplitude across the range of frequencies. More experiments with live power cables and around submarine connections are planned to validate the presented approach.

The method shows positive results in the 130 metres range. Shallow water survey is often designed to be carried by a small barge or survey boat. Deeper waters require the use of underwater vehicles and provide different challenges. The authors have done some work in the integration of EMF detection with a survey by autonomous platform. The extension of this work can give application of EMF detection in deeper waters

VII. REFERENCES

[1] T. Szyrowski, S. K. Sharma, R. Sutton and G. A. Kennedy, "Developments in subsea power and telecommunication cables detection : Part 1 – Visual and hydroacoustic tracking," *Underwater Technology,* vol. 31, no. 3, pp. 123-132, 2013a.

[2] T. Szyrowski, S. K. Sharma, R. Sutton and G. A. Kennedy, "Developments in subsea power and telecommunication cables detection : Part 2 – Electromagnetic detection," *Underwater Technology,* vol. 31, no. 3, pp. 133-143, 2013b.

[3] R. Olsen and P. Wong, "Characteristics of low frequency electric and magnetic fields in the vicinity of electric power lines," *IEEE Transactions on Power Delivery,* vol. 7, no. 4, pp. 2046-2055, 1992.

[4] J. Zhou and J. Chen, "Maximum distance estimation of far-field model for underwater magnetic field communication," in *017 IEEE 7th Annual Computing and Communication Workshop and Conference (CCWC)*, Las

Vegas, NV, 2017.

[5] SCT subsea cable tracking ltd, June 2017. [Online]. Available: http://www.subseacable.co.uk.

[6] Texas Instruments, "High-Resolution Analog-to-Digital Converter High Resolution : Flexible Digital Filter : Analog Supply :," *Specification,* 2007.

[7] R. H. Walden, "Analog-to-digital converter survey and analysis," *IEEE Journal on Selected Areas in Communications,* vol. 17, no. 4, pp. 539-550, 1999.

[8] "Electroding Generator Model 5915," Tinsley Instrumentation Ltd., 2015. [Online]. Available: http://tinsley.co.uk/wp/?page_id=1805. [Accessed 12 October 2018].

[9] "Cable and Pipe Locator Range," Radiodetection Ltd, 2018. [Online]. Available: https://www.radiodetection.com/en-gb/products/precision-cable-locator-range. [Accessed 12 Octobe 2018].

[10] S. Tumanski, "Induction coil sensors—a review," *Measurement Science and Technology,* vol. 18, no. 3, pp. R31-R46, 2007.

[11] Y. Geng and J. Jung, "Sound-Source Localization System for Robotics and Industrial Automatic Control Systems Based on Neural Network," Goyang-si, Korea (South), 2008.

[12] B. Colnet and J. Di Martino, "Source localisation with recurrent neural networks," Atlanta, Georgia, USA, 1996.

[13] T. Szyrowski, S. K. Sharma, R. Sutton and G. A. Kennedy, "Subsea cable tracking in an uncertain environment using particle filters.," *Journal of Marine Engineering & Technology,* vol. 14, no. 1, pp. 19-31, 2015.