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# Combined multiuser acoustic communication and localisation system for µAUVs operating in confined underwater environments

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**Abstract:** This paper describes a communication and localization system for micro-autonomous underwater vehicles (µAUVs) undertaking monitoring and mapping tasks in nuclear storage ponds. A distinctive feature of this underwater environment is the severe multipath propagation and long reverberation times. The paper describes how a common code division multiplexed signal format is used to mitigate the acoustic channel impairments and to achieve both communication and localisation. The system consists of an onshore base-station, equipped with a four-element distributed transceiver antenna, and underwater acoustic modems installed in the µAUVs. The system simultaneously provides localisation of a swarm of µAUVs, with addressed transmission of navigation commands from the base-station to µAUVs, and telemetry data transmission to the base-station from the µAUV.



*Keywords:* communication systems, positioning systems, autonomous vehicles, ultrasonic, signal delay, simulation

## 1. INTRODUCTION

The characterisation of legacy and new-build underwater storage facilities is one of the main challenges facing the nuclear industry (Nawaz et al., 2000). With legacy facilities, the principal problem is identifying the contents, as many of the original records are no longer available (Kendal, 2008). For modern facilities, the challenge is to identify problems early so that in 40 years' time, the legacy problems being faced today are not repeated.

### *1.1 Brief background*

There are currently two methods of characterising underwater storage facilities: human deployed sensors on long poles or large commercial tethered Remotely Operated Vehicles (ROVs) which are controlled from the surface (Watson, 2012). Neither of these solutions provides the temporal or spatial resolution of measurements required to accurately characterise the facilities. To overcome these limitations, a swarm of untethered micro-autonomous underwater vehicles (µAUVs) has been developed at the University of Manchester (York et al., 2012).

The first generation prototype of the Aqua Vehicle Explorer for In-Situ Sensing (AVEXIS) is shown in Fig. 1a (Watson et al., 2012 and Watson, Green, 2012). The second generation prototype is currently under construction, and utilises internal pumps for propulsion to limit the number of external protuberances (Fig. 1b,c). Currently, what both of these prototypes lack is a communications and localisation system which will allow the vehicles to send real-time data back to shore and to accurately localise them to give the required spatial resolution of the measurements.

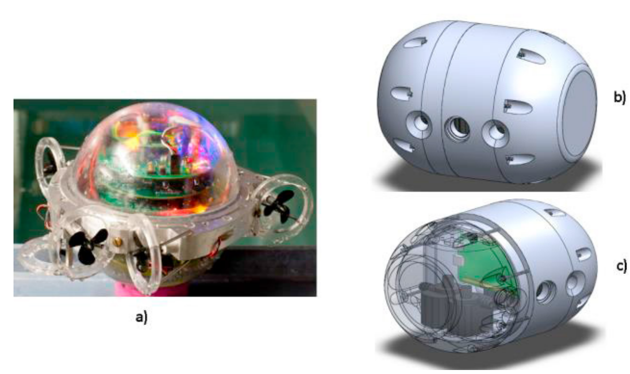


Fig.1 – AVEXIS µAUV prototypes: (a) First Generation (b, c) Second Generation

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*1.2 System Overview*

To address the challenges of limited computing capabilities on the µAUVs, the need for regular localisation estimates for the control system and the enclosed nature of the environment, time difference of arrival (TDOA) was selected as the most suitable method of localisation. This means that the location of any of the µAUVs can be estimated by using a minimum of at least four reference points as depicted in Fig. 2. In this application, the reference points will take the form of base stations located around the edge of the storage facility with the reference transducers mounted on them (Kendal, 2008). The µAUVs (referred to as nodes) will have smaller transducers mounted on them.

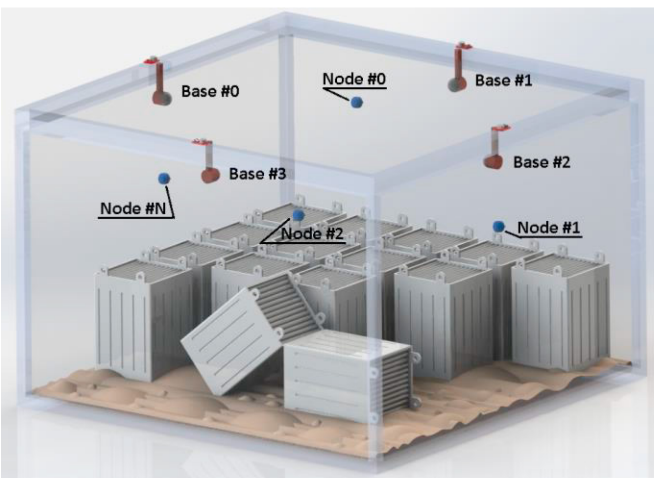



Fig.2 - Deployment of base station transmitters and multiple µAUVs in the tank

*1.3 System requirements*

The main aim of the work presented in this paper is the development of an underwater acoustic wireless communication and positioning system (ACPS) for use by a swarm of µAUVs in an enclosed environment.

The main functions of the ACPS are given below:

- Addressed remote control command transmission from the onshore base-station to a µAUV.

- Addressed telemetry data transmission to the base-station (µAUV's location, environmental parameters, etc.).

- Simultaneous localisation for a swarm of µAUVs.

In the majority of existing communications and localisation systems, the problems of localisation and communication are separated and performed by different subsystems (such as LinkQuest Inc. and IXBLUE). For the given scenario, the method is not feasible for the following reasons:

- Severe multipath caused by the environment. The storage facilities are artificial reservoirs made of concrete, with long reverberation times and severe multipath propagation (Hussain, Trigoni 2010).

- The need for communication to many nodes (> 10) in a shared acoustic frequency band.

- Severe restrictions on the acoustic transducers in terms of physical size and power consumption (Nawaz et al., 2009) on the µAUV's.

- Suitable localisation accuracy (<0.5 m).

There is currently no system available, either commercially or in the research domain, which could be utilised by the µAUVs. Although, Evologics USBL systems provides information about mutual 3D distance between two acoustic nodes while they are communicating to each other, and the system also provides very good accuracy, it is still not suitable to be built into the µAUVs due to power consumption and dimensions.

A new ACPS is under development which uses short fixed-length messages to mitigate the effects of long reverberation times and multipath propagation, and which employs a common signalling waveform to achieve both navigation and communication.

*1.4 Existing Technology*

Typically, underwater localisation tasks can be solved by the following types of systems (Vickery, 1998): USBL (ultra-short baseline), SBL (short baseline) and LBL (long baseline) systems. The majority of existing systems are designed for open sea conditions (Dikarev et al., 2013), and cannot be directly applied in confined spaces, and are poorly suited to µAUVs applications due to weight, dimension and power requirements.

*1.5 Paper structure*

The remainder of the paper is divided into the following sections:

- An overview of the existing hardware including the digital signal processor (DSP) and transducers (Section 2).

- Design of the multiple access system (Section 4).

- A description of the localisation system (Section 5).

- Presentation of preliminary simulation results (Section 6).

- Conclusions and future research (Section 7).

## 2. HARDWARE OVERVIEW

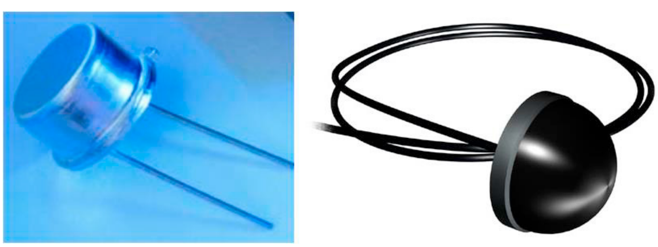
This section provides an overview of the hardware currently being used for the communications system. Taking into account the size and power consumption limitations for the µAUV based system, the starting point for the design of the ACPS is the selection of a suitable DSP.

*2.1 Digital signal processor selection*

The effective approach is to use an inexpensive multi-purpose platform, and the computational unit selected was the STM32F429 processor (ST Microelectronics), which is based on the ARM Cortex-M4 core. It supports floating point operations and is equipped with built-in 12-bit analogue to digital converters (ADCs), digital to analogue converters (DACs). This is a powerful processor which compares favorably with FPGA-based implementations due to the integrated DAC/ADC and the simplicity of development.

*2.2 Transceivers*

Given the size and power constraints of the µAUVs, the current on-board transducers are SensComp 40RT-08 closed face piezoelectric transducers (SensComp,Website) (Fig. 3a). They have a resonant frequency of 40 kHz in air, a small profile and are low cost. For the base station transceivers, Neptune Sonar Ltd. T204s were used (Neptune Sonar Ltd, website) (Fig. 3b). These are specialist underwater transducers which are omni-directional, broadband, and have a resonance frequency of 54 kHz.



a) b)

Fig.3 - SensComp 40RT-08 closed face piezoelectric transducers (a), and Neptune Sonar Ltd. T-204 (b)

3. STRUCTURE OF THE SIGNAL

Having identified the processor that will be used in the µAUVs, the next step was to design the signal format for communication and localisation.

Based on the external conditions for the system (Section 1.3) and the available computational resources, the most appropriate signal format is a wide-band spread spectrum signal created by Binary Phase-Shift Keying (BPSK) modulating pseudo-random bit sequences with good autocorrelation properties (Ferrell, 1990, Hee, 2003). This type of signal is not demanding on the ADC/DAC resolution and is readily modulated and demodulated on the selected type of processor at the sampling rate frequency. In addition, BPSK signals have a high resistance to multipath propagation (Zakharov, Kodanev, 1996).

The particular type of signal is determined by the following parameters:

- The degree of the polynomial of the binary pseudorandom sequence $P_p$, which determines the length of the sequence and hence the signal duration $T_s$. The signal's correlation properties and the maximum delay between the direct and reflected signals, with which the system can still receive the signals, also depends on the length of the pseudorandom sequence.

- Carrier frequency $F_c$, which also determines the duration of chip, as well as the signal and the bandwidth of the spectrum;

The degree of the generating polynomial is chosen based on the following considerations:

- The probability of being able to implement the algorithms on the selected processor. By increasing the degree of the polynomial, the required computational power for real-time processing increases as $N\log N$ as for the Walsh-Hadamard transform (Fino, Algazi, 1976);

- Ensuring the required noise immunity (minimal signal to noise ratio) and resistance to multipath (maximal delay).

Selection of the carrier frequency is performed on the basis of several considerations:

- Ensuring sufficient theoretical accuracy (the smallest propagation time that can be estimated), and this is related to resolution of the signal (chip duration).

- Ensuring that the processor can perform the required computational load. The required sampling frequency, $F_s$, for BPSK must satisfy the condition $F_s \geq 4 \cdot F_c$. Where $F_c$ is the carrier frequency.

- Selection of the length of the chip, $N_c$, is made on the basis of providing sufficient resolution and adequate signal spectral width.

Taking into account the above factors and the experience gained by the authors in (Zakharov, Kodanev, 1996) and (Dikarev et al., 2013), the following signal parameters were proposed: $P_p = 10$, $F_c = 20$ kHz, $N_c = 2$ (chip length, in periods of carrier frequency). The chosen degree of the polynomial and the carrier frequency were found to be the most suitable to implement the communication system on the processor selected in Section 2.1.

The duration of the chip was evaluated as (1):

$$T_C = N_C / F_c \qquad (1)$$

Which in this example was: $T_c = N_c/F_c = 2/20000 = 0.0001$ s., where the symbol rate $F_b$ is equal to the reciprocal of the symbol duration, shown in (2):

$$F_b = 1 / T_c \qquad (2)$$

Which gives $F_b$=1/0.0001 = 10 kHz.

For BPSK signals the main lobe of the spectrum centered about the carrier and its width can be calculated according to (3):

$$B_m = 2 / T_c \qquad (3)$$

That gives $B_m$ = 2/0.0001 = 20 kHz, which must be considered when designing the transceiver circuit. Fig 4 presents the modulated signal spectra for three different chip lengths, $N_c$ =1, 2 and 4. Using signals with $N_c > 2$ leads to an undesirable reduction of the signal resolution and the narrowing of the spectrum. Using a chip length of $N_c < 2$ is not recommended as it leads to an inefficient use of bandwidth and an increase in signal propagation at lower frequencies, which is the region of the acoustic spectrum containing the highest level of noise.

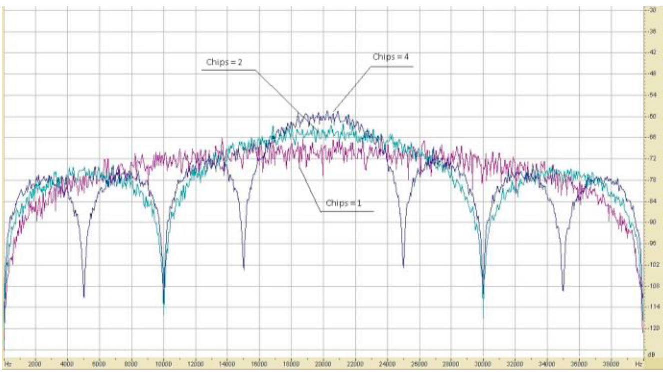



Fig.4– The spectrum of the BPSK signal for $N_c$=1, 2 and 4.

The theoretical signal resolution, $d_s$, for propagation time estimation is equal to twice the duration, $T_c$. Given that the average speed of sound in fresh water at +10°C is $V_s$ = 1450 m/s (Kinsler, 2000), this corresponds to a distance resolution of 0.29 m. The duration of the complete pseudo noise sequence, comprising $2^{Pp}$ chips, is given by:

$$T_s = 2^{P_p} \cdot T_c \tag{4}$$

This leads to $T_s$=$2^{10}$·0.0001 = 0.1024 s, which is very efficient from the point of view of power consumption.

To enable simultaneous data transmission, the signal consists of two orthogonal components: *synchro* and *informational*, each generated from different polynomials as shown in Fig 5.

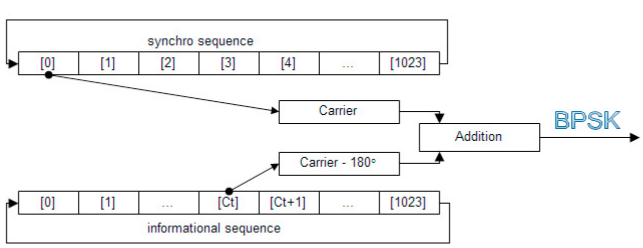



Fig.5– Modulation scheme

Data is encoded by the cyclic shift of the informational component relative to the synchro component (Figure 5 shows a transmitted code offset of $C_t$). It is readily shown that for a chosen sequences length, $2^{Pp}$ possible shifts exist, which provides a transmission capacity of 10 unique bits in every message.

It should be noted, that the selected signal parameters are suitable for the transducers discussed in Section 2.2. Both the base-station and node transducers have resonant frequencies above 30 kHz and the entire main lobe of the spectrum lies below the resonant frequency. This will provide for a more linear frequency response in both transmission and receiving modes.

## 4. SUBSCRIBERS DIVISION SYSTEM

As discussed in Section 1.3, the communications system has to be multi-user, with all of the users operating on the same frequency band. Each message may carry up to 10 bits of information. Based on (Dikarev et al., 2013), a multiple access system can be constructed. The STM32F429 processor has sufficient computational capability to implement in real-time the signal demodulation for one so-called code channel (defined by a pair of polynomials - *synchro* / *information).* For binary pseudonoise sequences of length $2^{10}$, there are only 60 primitive polynomials. Given a desired number of subscribers, and taking into consideration that each code channel requires two polynomials, up to 30 unique code channels can be obtained. In fact, this number could be doubled by the replacement of *synchro* and *informational* sequences with each other. If the assumption is made that each subscriber is only able to receive a single code channel at any given instant, then there remains the problem of identifying the sender. A solution to this problem is provided in (Dikarev et al., 2013), where by dividing the entire range of values into sub ranges, wherein the total number of possible messages $N_m$ in multi-user system can be determined from the relationship (5):

$$N_m = N_b / N_s \tag{5}$$

$N_b = 2^{Pp}$ is the total number of possible code combinations for a given polynomial's degree $P_p$, and $N_s$ is a predetermined number of subscribers. Hence, in the limiting case, when using the maximum number of possible code channels for $P_p$ = 10, the number of different code messages in the system will be $N_{m10} = 2^{10}/30 \approx 34$.

For the transmission of messages from a range of $N_t$ [0 ... $N_{m10}$] in the specified code channel, the sender with address $C_{ct}$ (the number of their adopted code channel) must generate a code from the range of $C_g$ [0 ... $N_b$] according to the following relationship (6):

$$C_g = N_t + N_{m10} \cdot C_t \tag{6}$$

For the sender identification by the received code, the recipient shall use (7):

$$C_{ct} = C_g / N_{m10} \tag{7}$$

The transmitted code can be achieved using (8):

$$N_t = C_g - C_{ct} \cdot N_{m10} \tag{8}$$

This scheme cannot be used explicitly to transmit data, because the transmission of any signal not encoded using the above scheme will lead to incorrect identification of the sender and the transmitted messages. However, as noted above, with few limitations the possible codes range $N_b$ can be expanded by the introduction of so-called "inverted" channels, obtained by means of interchanging *synchro* and *informational* sequences. The addressed transmission of 10-bit values therefore becomes possible. In the present system this capability is used as follows: there is a set of special request codes selected from the range of codes of the subscriber division system. After a transmission of this request, the system enters a special mode where the data transmitted using an inverted code channel is expected. This mode is exited following a predetermined period. The requested party can identify a received code and a requesting subscriber and transmits a value via the inverted channel. This method allows the system to send additional 10-bit values without invalidating the subscribers division system. This may be sufficient to transmit measurement data from the sensors, such as position, temperature etc.

## 5. LOCALISATION SYSTEM WORKING CYCLE

Technically, the localisation system being developed is a short base-line system (Vickery, 1998). Four base station transmitters are located on the walls of the tank as shown in Figure 4. The center of the coordinate system is located in the geometrical center of the surface of the tank. The Z-axis is directed downward (depth). The coordinates of the transmitters are measured in advance and are known by each of the µAUVs. Each transmitter is assigned its own code channel.

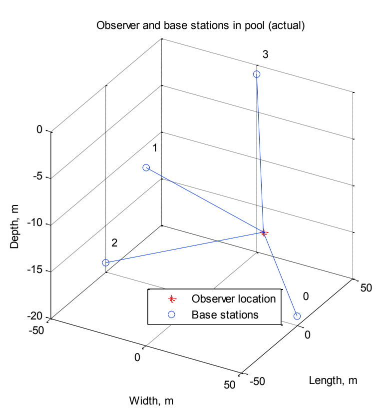



Fig. 6 - The base-station transmitter deployment in a tank

The work of the localisation system is as follows: the base stations emit localisation signals (four signals from the four transmitters) in turn (cyclically) at regular intervals, $T_{bd}$,. Each µAUV to be located initially receives in the first code channel belonging to the first base-station's transmitter. Upon receiving the navigation signal, each µAUV determines the time of arrival (TOA) and switches to receive on the next code channel. Each µAUV has its own clock, which should be precise and stable only during full localisation cycle. Clocks of all µAUV do not have to be synchronized with each other neither to base station's clock. If the µAUV does not receive a message in the desired code channel within a predetermined time period, it switches to receive in the first code channel again and expects to start a new navigation transaction (a full cycle within four base stations). The placing of each transmitter in a different code channel is an important requirement to avoid interference of the navigation signals with each other. This is because of the very long period of sound attenuation in the concrete tank, which can be up to 1-2 seconds (Hussain, Trigoni, 2010).

When the sequence has been successfully completed and an µAUV has recorded all four TOAs, it will be possible for it to determine its own position based on the fact that all the locations of the base-stations and the depth of the µAUV are known (Watson, Green, 2012).

Let the position coordinates of the base-station transmitters be $x_i$, $y_i$, $z_i$, and the position coordinates of the µAUV (to be located) be $x_0$, $y_0$, $z_0$.

From graph theory, for $N$ transmitters, a complete graph can be formed with $N_{TDOA} = N(N\text{-}1) / 2$ pairs of non-recurring (respectively to $N_{TDOA}$) time differences of arrivals. For convenience, we can go directly to the distance differences, $EDD$, at a known speed of sound $V_s$: $EDD_n = TDOA_n \cdot V_s$.

The actual distances $ADD_i$ from the object to observed transmitters can be written as (9):

$$ADD_i = \sqrt{(x_0 - x_i)^2 + (y_0 - y_i)^2 + (z_0 - z_i)^2} \quad (9)$$

Localisation of an object is reduced to the error minimisation problem stated in (10):

$$e = \sum_{i=1}^{N-1} \sum_{j=i}^{N} \left( ADD_i - ADD_j - EDD_{ij} \right)^2 \quad (10)$$

Moreover, the problem of localisation by four TDOAs can be solved directly, as it shown in (Bucher, Misra, 2002).

## 6. SIMULATION RESULTS

As part of this work a Matlab model was created to simulate the operation of a base station and the underwater acoustic modem located on an object (node) to be localised, in the environment depicted in Fig 6. The model's main features are listed below:

- Generation of the localisation signals and the delays corresponding to the specified relative position of the base station transmitters and object.

- Simulation of the effect of multipath propagation (a set of amplitude and delay pairs).

- To perform searches, demodulation of messages and to estimate the signals TOAs with ray selection and accumulation mechanism.

As an example, Figure 5 shows a section of a signal with simulated multipath propagation. The simulation has been run for 1000 different observer positions and different underwater channel impulse responses. The impulse responses, generated randomly, comprise 50 rays with Gaussian amplitude distributions over the range [-1;1] and Rayleigh delay distributions, over the range [0; *Ts*].

From the simulation results, the standard deviation for radial error is 0.38 metres, and this meets the accuracy requirements stated in section 1.3 .

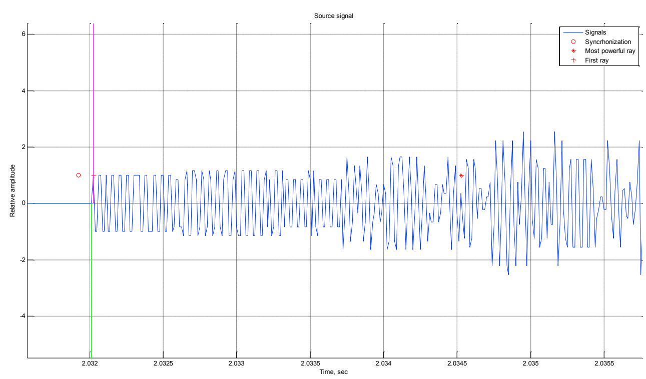



Fig. 5 - Difference in TOA estimation determined from the ray which gives the higher SNR value and the earliest ray (the ray which has a minimal delay) positions. Simulated multipath, 50 random rays (only a part of the signal is shown).

## 7. CONCLUSIONS

A combined multi-user underwater acoustic communication and localisation system for the µAUVs performing tasks of monitoring and mapping in nuclear storage ponds has been designed. The results of the simulation show that the selected design can successfully mitigate the environmental challenges faced in the target application. The system is able to provide the required positioning accuracy of 0.5 m for a swarm of the µAUVs (as well as being designed as a multiple access system), address control commands to the µAUV from the base station and telemetry data from µAUV to the base station. In the future the plan is to field test the system components under conditions close to reality.

The objectives of further research are:

- Increase the volume of data and the transmission speed from the µAUVs to the base-station.

- Implement methods of interaction between the individual µAUVs to most effectively achieve the objectives, described in Section 1.1.

## REFERENCES

Bucher, R., Misra, D., A Synthesizable VHDL Model of the Exact Solution for Three-dimensional Hyperbolic Positioning System, *VLSI Design*, Volume 15/2, 2002, pp. 507-520.

Dikarev, A., Dmitriev, S., Kubkin, V., Kulikov, P., Litvinenko, S., Acoustic communication and positioning system for divers, *1st Underwater Acoustics Conference and Exhibition.* Proceedings., 2013., pp 1363-1367

Ferrell G. Stremler, Introduction to Communication Systems (Third edition) Paperback., Prentice Hall, 1990

Fino, B. J. Algazi, V. R. "Unified Matrix Treatment of the Fast Walsh–Hadamard Transform". *IEEE Transactions on Computers* **25** (11): 1142–1146. 1976

Hee, Jens. "Impulse response measurement using MLS" (PDF). — Paper describing MLS generation. Contains C-code for MLS generation using up to 18-tap-LFSRs and matching Hadamard transform for impulse response extraction. 2003

Hussain, M., Trigoni, N., Distributed Localization in Cluttered Underwater Environments, *The Fifth ACM International Workshop on Underwater Networks* (WUWNet), Sept-Oct 2010, Woods Hole, Massachusetts, USA.

IXBLUE (former IXSEA), Website, www.ixsea.com/en/subsea_positioning/1/gaps.htm

Kendal, P., "The nuclear reactor – A tour of Britain's nuclear power stations", Website, http://www.telegraph.co.uk/earth/energy/nuclearpower/3460214/The-nuclear-reaction-A-tour-of-Britains-nuclear-power-stations.html (2008).

Kinsler L.E., *Fundamentals of acoustics*, 4th Ed., John Wiley and sons Inc., New York, USA, 2000

LinkQuest Inc., Website, http://www.link-quest.com

Nawaz, M. Hussain, S. Watson, N. Trigoni, P.N. Green, An Underwater Robotic Network for Monitoring Nuclear Waste Storage Ponds, In Sensor Systems and Software, Springer 2009. (ISSN 1867-8211 ISBN-10 30642-11527-6, ISBN-13 978-3-642-11527-1).

Neptune Sonar Ltd, Website, http://www.neptune-sonar.co.uk/products-2/communications-transducers/t204/

SensComp,Website, http://www.senscomp.com/pdfs/k-series-40kt08-40kr08.pdf

ST microelectronics, Website, www.st.com/web/en/catalog/mmc/FM141/SC1169/SS1577

Vickery, K., Sonardyne, Inc. "Acoustic positioning systems. A practical overview of current systems", *Dynamic Positioning Conference*, October 13-14, 1998.

Watson, S. A., "Mobile Platforms for Underwater Sensor Networks", PhD Thesis, University of Manchester, UK, 2012.

Watson, S.A., Crutchley, D.J.P., Green, P.N., "The Mechatronic Design of a Micro-Autonomous Underwater Vehicle", *International Journal of Mechatronics and Automation* (IJMA), Vol. 2, pp. 157-168. 2013

Watson, S.A. Green, P.N., "Robust Control of a Micro-Autonomous Underwater Vehicle (mAUV) Using Low-Tolerance Components", *IFAC Workshop on Navigation, Guidance and Control of Underwater Vehicles (NGCUV)*, April 2012.

York, T.A., Green, P.N., Green, P.R., Phasouliotis, A., Qu, Z., Watson, S., Hussain, M., Nawaz, S., Trigoni, N., Stanley, S., "Acoustic Sensor Networks for Decommissioning", *Measurement and Control*, Vol. 45/2, pp 48-54, March 2012.

Zakharov, Yu. V., Kodanev, V. P., Immunity of adaptive methods for receiving of acoustical prseudorandom signals under ocean surface and bottom reflections, *Acoustical Physics*, 42(2), pp.212-219, 1996