CHEMICAL ENGINEERING TRANSACTIONS
VOL. 34, 2013
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet
Guest Editors: Neven Duić, Petar Sabev Varbanov

ISBN 978-88-95608-25-9; **ISSN** 1974-9791
DOI: 10.3303/CET1334011

Terrestrial and Underwater Pollution-source Detection Using Electromagnetic Multisensory Robotic System

Andreja Abina*[,a], Uroš Puc[a,d], Pavel Cevc[b], Anton Jeglič[a,d], Aleksander Zidanšek[a,b,c]

[a]Jozef Stefan International Postgraduate School, Jamova 39, SI-1000 Ljubljana, Slovenia
[b]Department of Condensed Matter Physics, Jozef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia
[c]Faculty of Natural Sciences and Mathematics, University of Maribor, Koroška 160, SI-2000 Maribor, Slovenia
[d]Faculty of Electrical Engineering, University of Ljubljana, Tržaška cesta 25, SI-1000 Ljubljana, Slovenia
Andreja.Abina@mps.si

Terrestrial and underwater pollution sources present a serious problem affecting human health, biodiversity, tourism, fishery, and other environmental issues. There is often little consistent information of wastes available particularly due to lack of efficient technical tools. The main objective of this paper is to study the potential use of high-resolution electromagnetic (EM) sensors to detect waste that can pollute the environment ashore and underwater. Since different environmental conditions demand different sensor types, we propose a multisensory system composed of various non-destructive EM sensors at different frequencies. Low frequency sensors in the kHz region are based on electromagnetic induction (EMI) approach, whereas high frequency sensors in the MHz and GHz regions are based on ground penetrating radar (GPR). We tested components of the designed multisensory system on remotely operated vehicle and found that it has the capacity to discover, map and interpret waste from various materials in different environmental conditions with the option of the objects' size and shape reconstruction as well as waste classification. The results of this study offer new possibilities to improve the understanding of the current status of the terrestrial and underwater waste pollution problem.

1. Introduction

The important issue in environmental science is the detection and identification of terrestrial and underwater pollution sources, and their correlation to various driving forces affecting human health, biodiversity, tourism, fishery, and other environmental processes. There is little and often inconsistent information of waste pollution available particularly due to lack of efficient technical tools. Over the past decade, some advancement have been already proposed and implemented, mainly with sensor networks (Corke et al., 2010) and robotic systems (Daejung et al., 2007). The need of remote sensors on robotic platforms is most interesting to researchers and end-users, especially after serious natural disasters and environmentally harmful accidents. The remote sensing of environmental changes in difficult accessible areas is thus necessary.

There are several sensors available for monitoring physical, biological and chemical environmental variables. The most relevant variables and frequently used technologies are summarized in more detail by Dunbabin and Marques (2012). For terrestrial landfill characterization and illegal waste disposal sites detection often a multidisciplinary approach is applied containing magnetic survey, electromagnetic (EM) techniques, soil sampling, and conventional drilling with subsequent physical and chemical analysis of material. Magnetic and EM surveys are usually employed for a fast and accurate localisation of buried objects in landfills (Boudreault et al., 2010) as well as to detect hidden metallic containers with hazardous content (Marchetti et al., 2002). Moreover, these techniques are ideally suited for non-invasive and non-destructive measuring of environmental changes in terrestrial conditions.

Waste pollution in the ocean, rivers and lakes is a major problem affecting not only the underwater environment but also the rest of the Earth. Among sewage disposal and oil spillages, there are some other causes of water pollution, e.g. dumping litter into rivers, lakes, and oceans such as cardboard, foam, plastic, aluminium, glass, iron, and more. Some of these pollutants are not easily disintegrated and can

Please cite this article as: Abina A., Puc U., Cevc P., Jeglič A., Zidanšek A., 2013, Terrestrial and underwater pollution-source detection using electromagnetic multisensory robotic system, Chemical Engineering Transactions, 34, 61-66 DOI:10.3303/CET1334011

even cause serious threat to humans, plants and animals. However, underwater pollution-source localization and mapping techniques are mainly based on visual and sonar sensors (Beaujean et al., 2011) whereas for monitoring purposes robotic fish concepts (Daejung, 2007) and bio-sensors (Oyekan and Hu, 2010) are used.

In the last decade, there has been extensive research in the field of efficient sensor networks (Corke et al., 2010) and robotics systems (Dunbabin and Marques, 2012) for environmental applications. Although some progress have been done, most of these sensor networks only provide fixed monitoring points without the means to adapt to changes in environment. Even though the robotic systems have increased the data collection efficiency, particularly in hazardous and difficulty accessible environments, the major limitation for the remote sensing technology and subsequent remediation still presents a small concentration of contaminants like heavy metals (Montinaro et al., 2012) in natural environments.

The main aim of this work is to demonstrate the effectiveness of the EM sensors for the localization and detection of buried waste in terrestrial and underwater environments. Since different environmental conditions demand different sensor types, we propose a multisensory system composed of various non-destructive EM sensors operating at different frequencies. Preliminary tests were carried out on selected objects buried in sand and lying at the seabed or lake bottom. The final goal of the research was to validate the reliability of the multisensory survey performed with the robotic platform both underwater and ashore.

2. Methodology and experimental validation

2.1 Terrestrial and underwater site conditions

The terrestrial tests using ground penetrating radar (GPR) were performed in a laboratory on a small cardboard box filled with sand in which the test objects were placed. The radar system antenna with the central frequency of 5 GHz was used. The measurements were performed in a controlled environment. The GPR antenna mounted on a robotic platform was moved over a sand box for five times, each time through another scanline, which were equidistantly separated from each other. We selected two different non-metallic test objects. The first object was a plastic cube which has a similar dielectric constant as hazardous contents in disposed containers. The second object was a glass object. The scenario for electromagnetic induction (EMI) measurements comprised the in-house developed EMI sensor composed of four sensing probes mounted on a wooden pole to reduce destructive interferences from other objects. For the investigation purposes, aluminium and ferrous samples with simple rectangular cross sections were selected.

Underwater measurements were performed at two sites. In order to obtain preliminary results, freshwater experiments were performed at Podpec Lake. The measurements were carried out with a Ramac GPR system from Mala Geoscience, Sweden, using 250 MHz shielded antenna. The antenna was placed in a rubber dinghy on the water surface and the aluminium pipe was selected as a test object. The second site was located at the coastal area of Adriatic Sea near the city of Portoroz. For seawater measurements we used our own developed underwater remotely operated vehicle (ROV) equipped with GPR operating at a frequency of 100 MHz and the EMI sensor consisting of a linear array of eight sensing probes. The current versions of EMI sensor and GPR are capable to measure an object’s EM induction and GPR responses at a distance up to 50 cm and 30 cm from the object.

2.2 Geophysical exploration methods

2.2.1 Electromagnetic induction sensor

EMI sensor typically operates as an active sensor and is widely used to locate buried landmines (Ho et al., 2004) by detecting the metal content in such objects. This sensor usually consists of a pair of concentric, circular coils, one of which is used to transmit EM waveform. The EMI sensor is capable to detect lateral and vertical variations of electrical conductivity. Thus, this method is useful for detection of buried metallic waste particularly due to its electrical conductivity which is greater than that of the surrounding medium. The transmitted field induces a secondary current in any buried or hidden conducting object. A receiving coil senses the secondary field returned from the buried objects (Marchetti et al, 2002). In addition, eddy currents also occur in metallic objects and have an important effect on the induction at the receiver coil. These eddy currents are strongly expressed in case of conductor materials such as aluminium and not as much in case of ferro-magnetic materials such as iron. Partly or wholly metal objects express a distinct combination of electrical conductivity, magnetic permeability, and geometrical shape and size. Thus, this method could be used to identify different metal objects considering the object’s geometry and material composition.

2.2.2 Ground penetrating radar

The GPR sensor uses EM radiation to obtain information about the subsurface structures. Basically, this method operates by transmitting a very short EM pulses into the soil medium using an antenna at selected frequency. The propagation of the radar signals within the medium depends on the EM properties of the material, mainly the dielectric permittivity and electrical conductivity (Gloaguen et al., 2001). If there is a difference in the dielectric permittivity between the adjacent layers or objects in the medium the reflection of incident EM radiation occurs. The travel time of the EM wave travelling from the transmitter to the object in the medium and back to the receiver is known as two way travel time.

The EM propagation in water is rather different from the propagation through the air due to the high permittivity and electrical conductivity of water. Another difference occurs due to the very large attenuation loss of the propagation pulses in water. It depends on the selected frequency and the salinity of water (Al-Shamma'a et al., 2004). However, there are many limiting factors which inhibit the use of the EM waves in underwater environments and originate from the fact that the EM field propagates very differently in freshwater and seawater. Freshwater is known as a low-loss medium whereas seawater is a high-loss medium. The propagation speed c and the absorption coefficient α in freshwater are therefore expressed with equations (Lanbo et al., 2008) given in Table 1, where ε is the dielectric permittivity, μ is the magnetic permeability and σ is the electric conductivity. Since the absorptive loss in freshwater is frequency independent, the EM waves can easily propagate through the freshwater medium. In seawater, the electrical properties significantly differ from those in freshwater. The major difference is related with the electric conductivity, which is about two orders higher than that of freshwater in consequence of greater salt concentration. In seawater, both the propagation speed and the absorptive loss of EM waves are frequency dependent and expressed through equations (Lanbo et al., 2008) given in Table 1.

Table 1: EM propagation properties through freshwater and seawater

	Freshwater	Seawater
conductivity	0.1 - 10 mS/m	4 S/m
attenuation loss at 100 MHz	0.1 dBm^{-1}	100 dBm^{-1}
attenuation loss at 1 GHz	1 dBm^{-1}	1,000 dBm^{-1}
dielectric constant, ε_r	81	81
propagation speed, c	$c \approx \frac{1}{\sqrt{\varepsilon\mu}}$	$c \approx \sqrt{\frac{4\pi f}{\mu\sigma}}$
absorption coefficient, α	$\alpha \approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\varepsilon}}$	$\alpha \approx \sqrt{\pi f \mu\sigma}$

2.2.3 Remotely operated multisensory system

Environmental EU regulations and international initiatives emphasize that the environmental data should be collected, analyzed and managed in a large quantity. For this reason different databases and data managing techniques (Antoljak and Caronna, 2012) have been proposed to overcome the current situation which suffers from the low integrity, uncommon standardisation and insufficient public availability of data. Traditionally, environmental data are obtained manually which is spatially and temporally limited procedure. Marine, terrestrial, and airborne robotic systems are increasingly applied as fundamental data-gathering tools, allowing new approaches and a better understanding of the environmental processes. Although some remote sensors used for detection of waste in environment already exist, there is almost non multisensory system which offers all-in-one solution. Therefore, we integrated the developed EM sensors into an ROV which was equipped with a supplementary optical imaging and navigation system.

Commercially available underwater ROVs did not meet the requirements for EM sensors operation due to their high sensitivity to metallic parts. To satisfy these demands, we constructed a compact ROV with low metal content as shown in Figure 1. The ROV and EM sensors mounted on the hull of the vehicle are controlled via a tethered laptop from the surface. For easily operating of ROV, the streaming video is provided by two small cameras. Current version of ROV is capable to submerse to the maximum depth of 100 m.

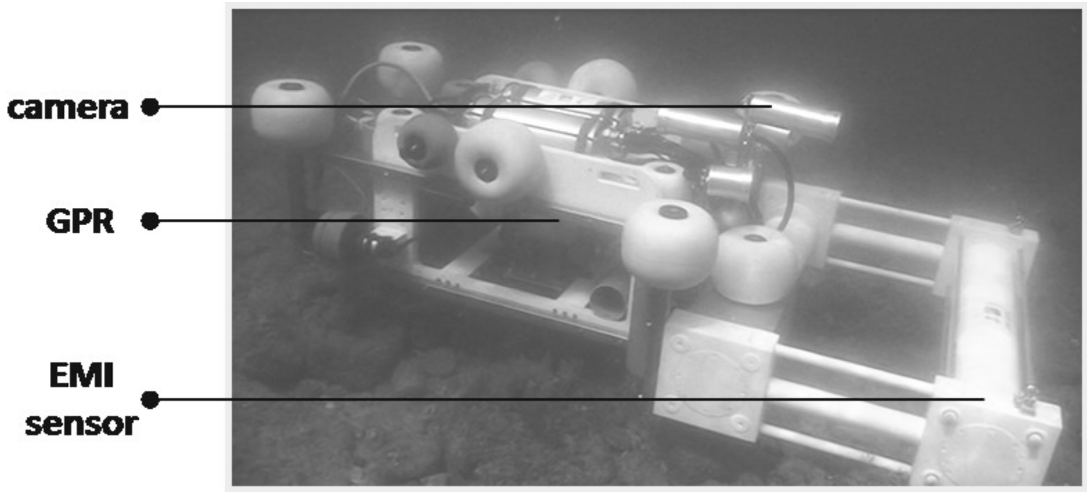


Figure 1: Underwater remotely operated multisensory system design

3. Results and discussion

Different objects underwater and ashore were measured with GPR and EMI sensors. The GPR system for terrestrial purposes was equipped with 5 GHz antenna whereas for salt water inspection we developed a special antenna at the frequency of 100 MHz. Dedicated software was prepared to acquire and process GPR and EMI signals. The raw GPR and EMI signals were recorded in a matrix form. In order to obtain a more realistic rectangular cross section of the detected objects the two-dimensional (2D) interpolation between the EMI matrix elements was applied. Furthermore, the obtained EMI plots were smoothed using cubic interpolation function. Some basic signal processing steps were applied to improve the GPR data such as background removal, static correction and gain function. The final GPR and EMI results were visualized as an intensity plot.
The EMI method is used to characterize whether the material is metallic or not. Apart from this, we also found that different metallic objects give various EMI responses. From results in Table 2 one can notice that the shape, orientation and size of the object could be detected. We placed aluminium objects of different sizes on the seabed and iron objects of the same dimensions on the wooden plate in laboratory. With the imaging method we obtained 2D EMI images which prove that EMI sensor is capable to detect and map an individual object as well as a group of objects with size even below 10 cm in water and terrestrial environment. We selected aluminium and ferrous squares since we wanted to show that EMI sensor can map not only magnetic objects such as iron but also nonmagnetic objects such as aluminium. There is a difference in EMI responses between aluminium and iron objects due to the eddy currents, which are particularly expressed in case of conductor materials such as aluminium and not as much in case of ferromagnetic materials such as iron. This difference can be made more visible with an appropriate visualization function by using various colours for indicating different signal intensities, lower (brighter) in case of iron and higher (darker) in case of aluminium (Figures in Table 2).
EMI sensor allows quick detection of buried metallic waste whereas non-metallic objects (plastic, glass) are completely transparent to detection by EMI. Thus GPR technique is used, which is capable to detect metallic and non-metallic objects. The processed GPR responses from different objects in Table 3 demonstrate that GPR is capable to detect waste of various materials (glass, plastic, metal) buried within sand or lying at the seabed. The greatest distance at which we still recognized the object’s response from the GPR signal underwater was at a distance of 30 cm from the square aluminium object.
The proposed electromagnetic methods are thus able to perform mapping of underwater or subsurface waste objects that can pollute surrounding environment. The implementation of these sensing tools mounted on robotic platforms assures the collection of the large quantity of data which can be included in existing public available databases to support the cooperation between the key stakeholders of various sectors.

Table 2: 2D EMI images for objects of rectangular shape and different material composition

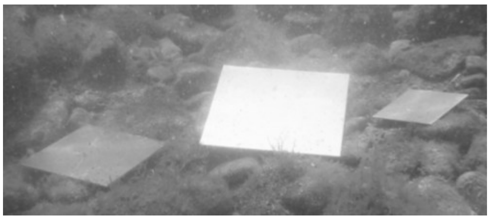
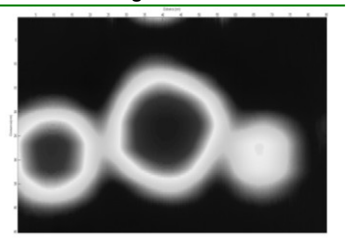
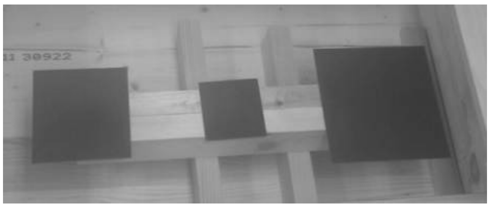
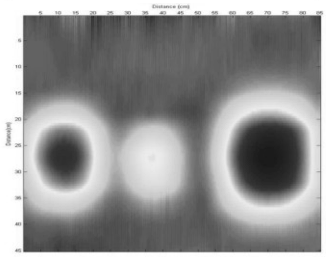
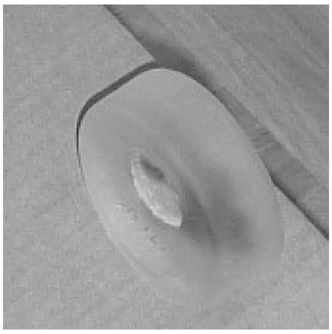
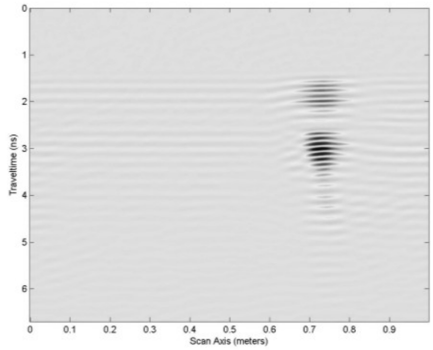
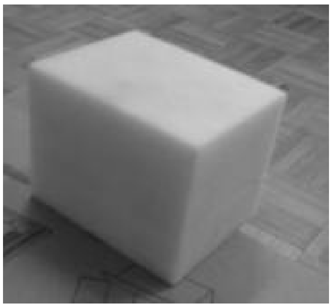
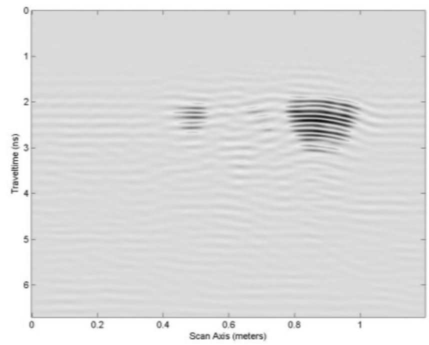
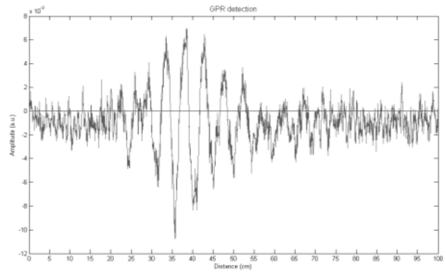
Environment	Material	Submerged object	2D EMI image
Seawater	Aluminium		
Air	Iron		

Table 3: GPR images and signal for three objects composed of various materials

Material	Test object	2D GPR profiles/GPR signal
Glass in sand		
Plastic in sand		
Aluminium in sea		

4. Conclusion

We demonstrated the effectiveness of the multisensory robotic system which can contribute significantly to improved environmental data collection and public decision-making. We tested components of the designed multisensory system and found that it has the capacity to discover, map and interpret waste from various materials in both terrestrial and underwater environmental conditions. It allows the reconstruction of the objects' size and shape in addition to waste material classification. We showed that the used EMI sensor is able to distinguish between different types of metallic materials in underwater environment. Furthermore, the GPR sensor is capable to distinguish even between hidden plastic objects and the surrounding natural environment. The results of this study offer new possibilities to improve the understanding of the current status of the terrestrial and underwater waste pollution problem.

Acknowledgements

The authors would like to thank J. Polanc and V. Eržen for the support at EM sensors development; Slovenian Research Agency grants no P2—0348 and J2—4266 and EC 7th Framework Project UNCOSS for financial support.

References

Al-Shamma'a A. I., Shaw A., Saman S., 2004, Propagation of electromagnetic waves at MHz frequencies through seawater, IEEE Transactions on Antennas and Propagation, 52, 2843-2849.

Antoljak S., Caronna S., 2012, Subsurface Databases in GeoEnvironmental Engineering, Chemical Engineering Transactions, 28, 97-102, DOI: 10.3303/CET1228017.

Beaujean P.-P. J., Brisson L. N., Negahdaripour S., 2011, High-Resolution Imaging Sonar and Video Technologies for Detection and Classification of Underwater Munitions, Marine Technology Society Journal, 45, 62-74.

Boudreault J. P., Dubé J.-S., Chouteau M., Winiarski T., É. Hardy, 2010, Geophysical characterization of contaminated urban fills, Engineering Geology, 116, 196-206.

Corke P., Wark T., Jurdak R., Wen H., Valencia P., Moore D., 2010, Environmental Wireless Sensor Networks, Proceedings of the IEEE, 98, 1903-1917.

Daejung S., Seung You N., Jin Young K., Seong-Joon B., 2007, Fish Robots for Water Pollution Monitoring Using Ubiquitous Sensor Networks with Sonar Localization, International Conference on Convergence Information Technology, 1298-1303.

Dunbabin M., Marques L., 2012, Robots for Environmental Monitoring: Significant Advancements and Applications, IEEE Robotics & Automation Magazine, 19, 24-39.

Gloaguen E., Chouteau M., Marcotte D., Chapuis R., 2001, Estimation of hydraulic conductivity of an unconfined aquifer using cokriging of GPR and hydrostratigraphic data, Journal of Applied Geophysics, 47, 135-152.

Ho K. C., Collins L. M., Huettel L. G., Gader P. D., 2004, Discrimination mode processing for EMI and GPR sensors for hand-held land mine detection, IEEE Transactions on Geoscience and Remote Sensing, 42, 249-263.

Lanbo L., Shengli Z., Jun-Hong C., 2008, Prospects and problems of wireless communication for underwater sensor networks, Wireless Communications and Mobile Computing, 8, 977–994.

Marchetti M., Cafarella L., Di Mauro D., Zirizzotti A., 2002, Ground magnetometric surveys and integrated geophysical methods for solid buried waste detection: a case study, Annals of Geophysics, 45, 563-573.

Montinaro S., Concas A., Pisu M., Cao G., 2012, Remediation of heavy metals contaminated soils by ball milling, Chemical Engineering Transactions, 28, 187-192, DOI: 10.3303/CET1228032.

Oyekan J., Hu H. S., 2010, A Novel Bio-Controller for Localizing Pollution Sources in a Medium Peclet Environment, Journal of Bionic Engineering, 7, 345-353.