Reducing Theft of Oysters Through the Use of RFID Technology

FRG 2016-02

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Final Report

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Introduction

Purpose of study
Poaching (theft) of oyster from the oyster beds is a huge problem. Purpose of this study is to assess a means of reducing poaching. The means to be studied is the use of RFID (Radio Frequency Identification) tags to mark oysters that would be placed on the beds so that when oysters from those beds are brought to the seafood processor, their origin can be identified. A detailed discussion of RFID appears in a later section of this study.

RFID tags are to be put in dummy oysters, which should be hard to detect from real oysters. The shells must have a suitable media to hold the shell together and give it about the same density as a live oyster. Further, as detailed later, the media should be an electrically insulating material so that it does not absorb electromagnetic radiation.

It is beyond the scope of this study to address how this technology will be implemented in the field.

Procedure of study.
The two main issues to be studied are :
  how to prepare dummy oysters
  what RFID technology to use.

Both issues are equally important because overall success is dependent on success in both. It is easier to experiment with making dummy oysters than to study the various RFID options therefore the study started by studying methods to prepare dummy oysters.

Preparing dummy oysters.

As mentioned earlier, whatever material is used inside the dummy oysters should disguise the dummy oyster and also be an insulation material, or more specifically a low loss dielectric. Silicone caulk was selected for reasons described later.

The next step was to prepare dummy oysters. I found that shell pairs taken at random from a shucking line has more than ½ rejects due to broken beaks and other signs of damage that would make them apparent as not real oysters. I checked that I had a pair of shell that fit together without gaps at the edges and without broken beaks. I then scrubbed the interior of the matching halves free of all organic material, reasoning that it would be undesirable to have decaying material inside the dummy oyster, which among other undesirable things might produce gases inside the dummy. I next attempted to prepare the dummy by putting caulk in the shell. I immediately discovered that it is absolutely necessary for the shell to be completely dry for the caulk to stick. The photos below show the sequence I used.


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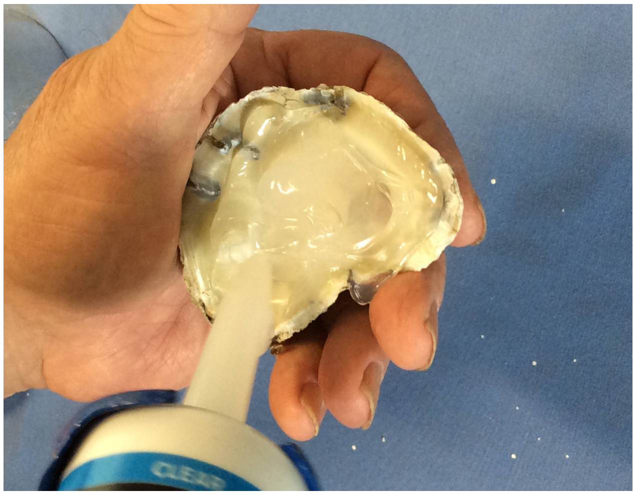
DAP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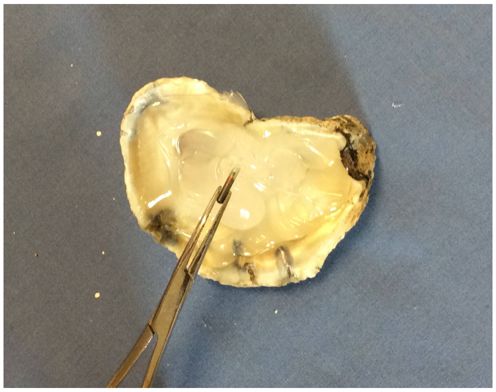
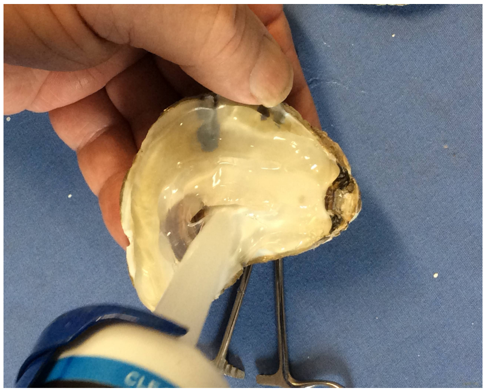
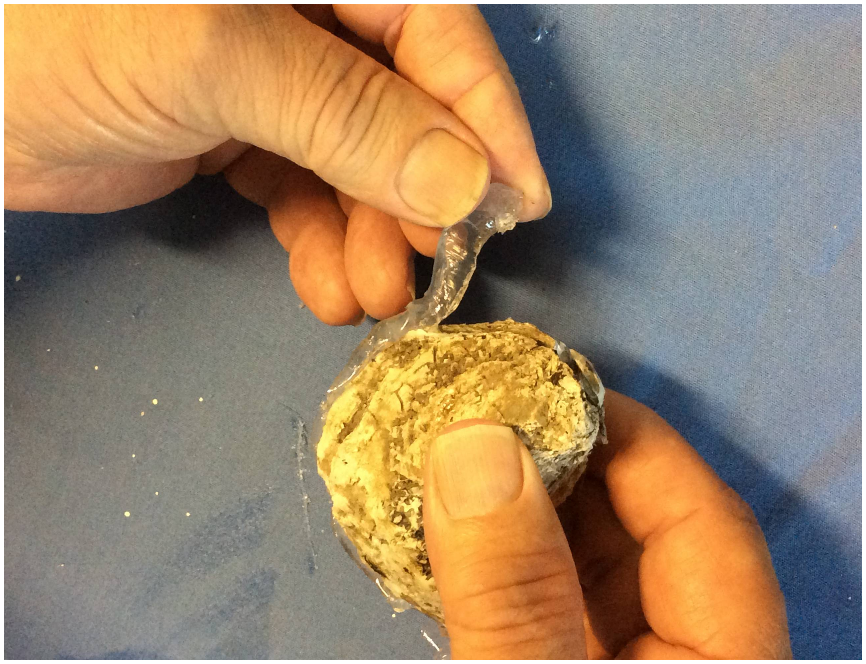






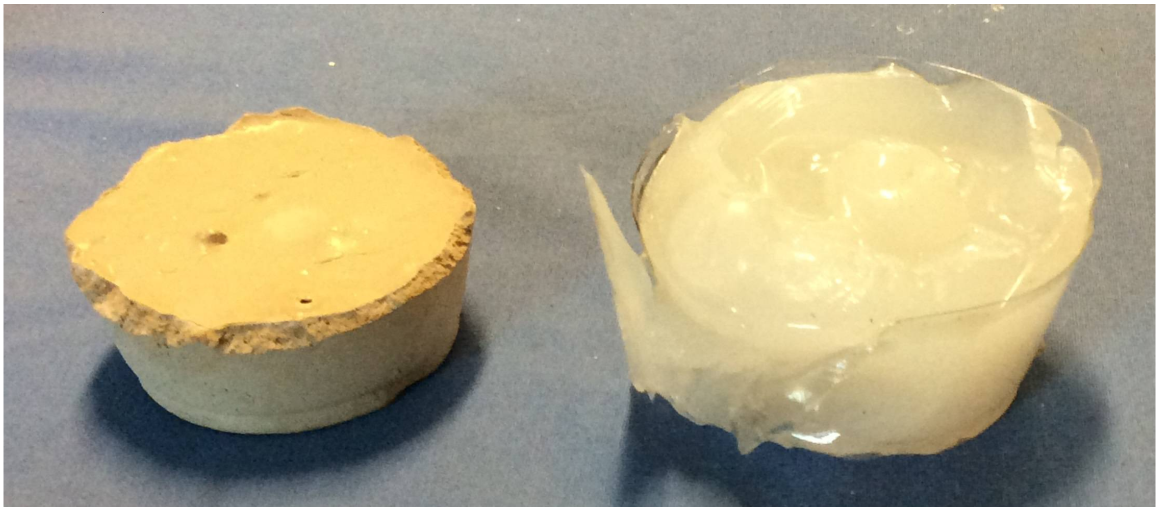
The photos above are in the same order as this description. The caulk was applied near the edge of the shell where the adhesive properties were to be relied on to hold the shell halves together. Next an amount of caulk was deposited in the center of the shell to fill it up approximately half way. An RFID tag was place on the caulk and more caulk was applied on top of that to completely fill the shell. The reasoning of putting the tag in the center of the shell was to have the tag separated from a conductive table or conveyor belt regardless of the orientation of the dummy oyster. Next the matching halves of the shell were pressed together and clamped as shown. Excess caulk was squeezed out of the shell as shown. No attempt was made to remove the excess at this time because previous experience had taught me that an effort to do so would smear the caulk on adjacent surfaces.. Having experienced the time it takes for silicone caulk to cure, I waited a couple of days before I proceeded to the next step. The caulk that had squeezed out of the shell was attached by a very thin section where the two halves of the bivalve were pressed together. The excess caulk was very easily removed as shown. Incidentally, silicone caulk cures most quickly in a humid environment.

The next step was to see if the dummy oysters could pass the culling process at an oyster packer's plant. Tommy Kellum of Kellum Seafood did this part of the study. In order that the test be a blind test, he put the dummy oysters in with oysters to be processed. They went through his plant undetected. They were so effective in deception that he shipped them out and had to alert the customer about the experiment and that he had unintentionally sold them two fake oysters.

Selecting the best RFID technology.

Selecting materials to prepare the dummy oysters.

Before going into the the various choices among RFID products available, I shall explain why silicon caulk was selected for use in preparing the dummy oysters. The material needed should be transparent to radio waves, that is not absorb radio energy. Thus the material had to be an electrical insulator. However a material can be an insulator but at the same time absorb electromagnetic radiation. An example of such a material is some ‘stoneware pottery’ therefore we tested substances by placing them in a microwave oven to see if they are heated by the microwaves. This is not meant to be a quantitative test, but rather a simple comparison between materials. Two materials come to mind: concrete and. silicon caulk. Two materials were tested as shown in the photo below.



One material was a cementitious material, actually tile grout because that is what I had on hand, and the other was 100% silicone caulk. Both materials were allowed to cure for several days before testing. The cementitious material was assumed to be cured in that time where as the silicone caulk was tested by cutting into it. Each were placed in a microwave oven for 30 seconds. The cementitious material became very hot whereas the silicone caulk showed no signs of heating, thus the caulk was selected.

The silicone caulk also proved to have a specific gravity of greater than one, which I deemed a favorable because we definitely did not want a materiel that floats.

Background and selection of RFID type.

RFID (radio frequency identification) tags are tags to be put on or in a product that can be read by a reader that communicates with the tag via radio. The tags can be classified by their various characteristics as follows:

Active or passive. Passive tags receive their energy from the signal transmitted from a tag reader. Active tags have their own source of energy, typically a battery. For our purpose passive is the best choice.

Read only or read/write. These terms are similar to the same terms used to describe memory in computer. Read/write RFID tags may be written to by a tag reader. Read only tags can only be read. Read only tags typically have only a serial number written to them.

Our choice is read only because the serial number on the tag can be refereed to a database for associated data.

A further classification is half-duplex or full-duplex. Duplex means signal goes in both directions. With half duplex energy from the reader goes to the tag and this energy is stored in the tag. Immediately upon completion of a query from the reader the tag sends signal back to the reader. With full duplex the tag is sending information back to the reader as the reader is sending signal to the tag. The tag is actually loading the antenna of the reader according the information to be conveyed to the reader. Half-duplex uses two frequencies to 1's and 0's (frequency shift keying) to communicate back to the reader. Half-duplex gives longer read ranges than full-duplex because the reader is not receiving and sending signal at the same time.

RFID tags are available in various sizes. Other things being equal, the larger the tag the greater the distance from which it can be read. A large antenna within the tag is capable of capturing more energy from the reader than a smaller antenna, just as radio or TV with a large antenna can receive more stations than with a small antenna. The size of the tag we can use is limited to the size of the oyster shell in which we put the tag. For our purposes the tag should be less than about 30 mm x 40 mm x 7 mm.

Operating environment. The environment in which we wish to use a RFID tag is marine environment but not under seawater. We want to be able to read a tag that is within a pile of oysters that contain a lot of water but the tag will not be under water. Physical degradation of the tag due to the environment is not an issue. Tags are available packaged to avoid such damage. The end of this report includes references covering the difficulty of reading tags under water.

Operating frequency of the RFID tags. The selection of the operating frequency of the tags is another question to be answered. Three main frequency ranges are of interest to us:
120–150 kHz Known as Low Frequency (LF)
13.56 MHz Known as High Frequency (HF)
433 MHz and 865-868 MHz Known as Ultra High Frequency (UHF)
There are additional frequencies available in the microwave region but they require active tags.

Examining each of the available frequency ranges.
120–150 kHz Known as Low Frequency (LF)

In the low frequency range say 150 kHz has a wave length of roughly 2 Km, therefore the tag will be in the near field of the reader. What this means is that the tag is so close to the reader it is not acting as a radio receiver, it is sensing the magnetic field of the reader. Typically the strength of radio waves decreases as the square of the distance from the source, however if we are much closer to the source than one wavelength we are sensing just the magnetic field and the field decreases roughly proportional to the cube of the distance from the source. Look at the situation another way, think of the reader as being the primary of a transformer and the tag as being the secondary of the same transformer. With transformer coupling, a load on the secondary results in a load on the primary. The tag reader senses the load presented by a RFID tag and is thus able to read the data stored on the tag. In this same frequency range tags can act in half duplex mode wherein after the tag is queried it becomes a transmitter and sends a signal to the reader.

So why do we need to know all this about magnetic fields from between a reader and the tag it is reading? We know a magnetic field can penetrate water. Also a changing magnetic field can penetrate water but a changing magnetic field induces an electric current in the water. If the magnetic field is changing slowly it does not induce much current, if it is changing fast it induces more current. This is the reason microwave ovens work at their microwave frequencies whereas a 150 kHz source would heat water only a minuscule amount. This means not much energy is lost to the water when low frequencies are used.

In conclusion, the LF tags will work under water but only at a very short distance. The larger the reader antenna and the tag antenna the greater the distance that can be read with low frequency tag systems. Also half-duplex read/write cycles give greater range.

13.56 MHz known as High Frequency (HF)

At this frequency the read range might be as much as ten time the range at the low frequency, however the loss of signal from the reader due to currents being induced in water is also greater because the magnetic field is oscillating faster. Within our environment we don't know whether the possible greater reading distance is offset by the presence of water in the oysters. I have not found anything in the literature that address our situation.

433 MHz and 865-868 MHz Known as Ultra High Frequency (UHF)

At this frequency we are working with wavelengths on the order of a half-meter and thus we are no longer working in the near field. Signal attenuation in water will be very great, however this frequency could possibly work if we are trying to read an RFID tag on top of a pile of oysters and not inside the pile.

Final selection of the technology to use.

I selected low frequency half-duplex system. I also chose as large a tag as I could reasonably fit in the dummy oyster and opted for a reader with a large antenna.

Internet research

My internet search lead me to the attached article titled "RFID Under Water: Technical Issues and Applications". This article further led to The Virginia Aquarium and Marine Science Museum. I contacted the Museum and they were very helpful by telling me Oregon RFID had helped them with their exhibit shown in the article. I have found Oregon RFID very helpful and very knowledgeable about the application of RFID underwater. I highly recommend them as a source of further information. All other RFID sites responded to my rather detailed inquiry with a form email from a sales person asking "How can we help you?" None appeared to have read my inquiry.

Oregon RFID sent me a tag they recommended. It is a low frequency half-duplex tag in a cylindrical form about 3.65 mm in diameter and 23 mm long. Using the reader VIMS provided I found I could read the tag at a distance of about 7 cm when the axis of the tag is parallel to the face of the reader, i.e., orientation of the axis of the tag antenna is perpendicular to the axis of the antenna of the tag reader. However, when the axes of the two antennas are in alignment the reading distance was about 30 cm. Oyster shells tend to lay flat on a surface which lead me to measuring the space between the two shell halves of an oyster. I selected a 3+ inch shell from my collection and measured the clearance inside the shell. To do this I rolled modeling clay into a ball a little larger than the amount of space I anticipated inside the shell. I then placed the ball inside the shell and closed the halves. After opening the shell I was able to measure that the maximum space was about 7 mm. Thus It would not be possible to orient the tag in a vertical position inside the shell.

Testing of my selection of RFID technology

Equipment used:
A hand held reader provided by VIMS.
A back pack reader with a 10" loop antenna provided by Oregon RFID
See appendix for more detail on the readers.

Assumptions: In each test the dummy laid flat on the surface of the test environment. The RFID tag had been inserted in the dummy oyster parallel to to the approximate plan of the shell. The reader was held with its antenna parallel to the test surface. With this orientation of reader and tag the antenna loops are perpendicular. Thus it is assumed that the test configuration is the worst case scenario in so far as read distance is concerned. All read distances should be taken as approximate because a very slight change of orientation of the read antenna could result in a rather large change in read distance. In practice the spacial relation between the antenna and the tag will most likely vary. Hand held readers are typically waved over the subject and oysters moving on a conveyor have a changing relation to a fixed antenna above the conveyor. Therefore it is reasonable to assume the reading distance that would be achieved with a system to monitor for RFID tags would be at least as great as the distances achieved with the tests.

The Photos following are the various test conditions. Each of four test environments was tested both with and without oysters piled on the tagged oyster and each of these conditions was tested with the VIMS supplied reader referred to as the hand reader, and the Oregon supplied reader referred to as the large reader.


1
4 FOOT PANEL STICK

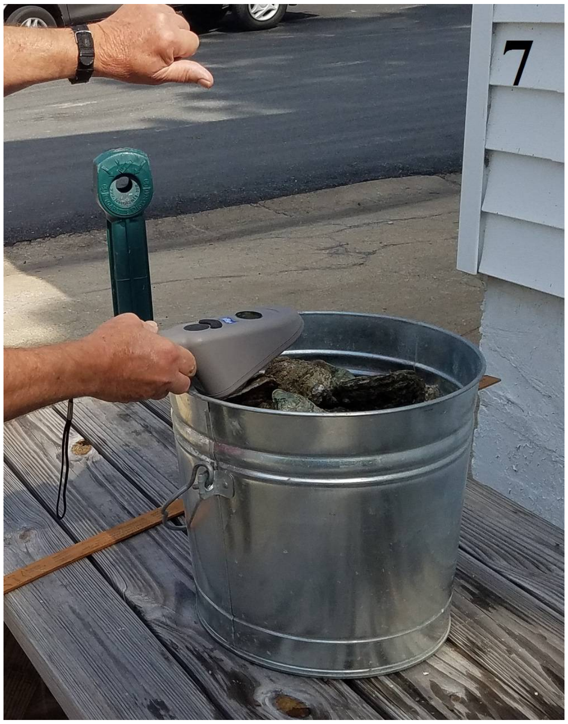

2
MORE FOR LESS AT MOORE'S


3


4
MORE FOR
MOORE'S


5


6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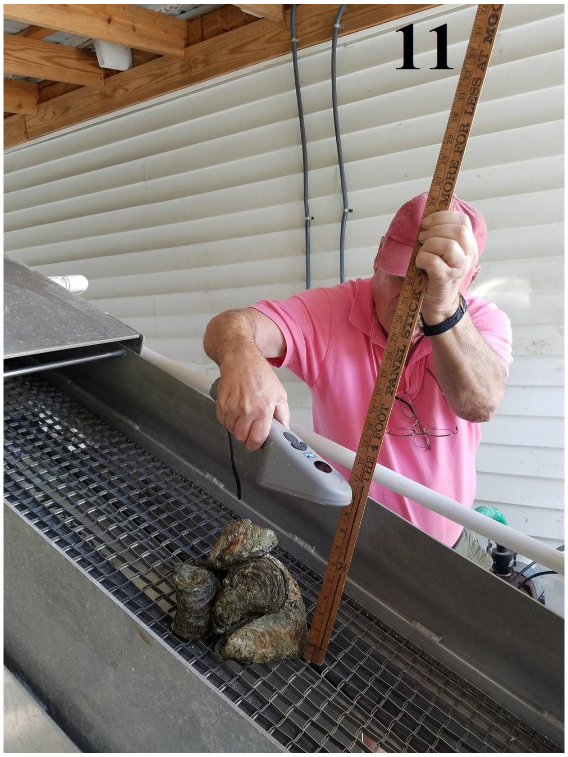
THE 4 FOOT PANEL STICK YOU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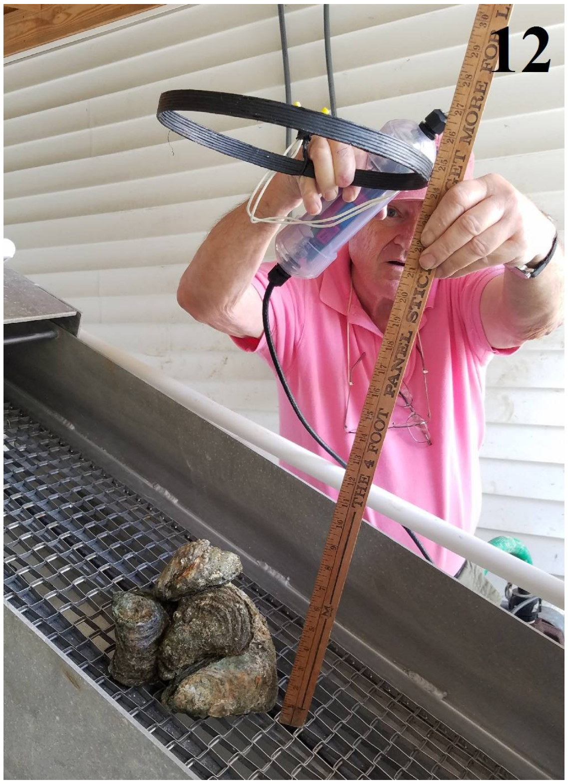
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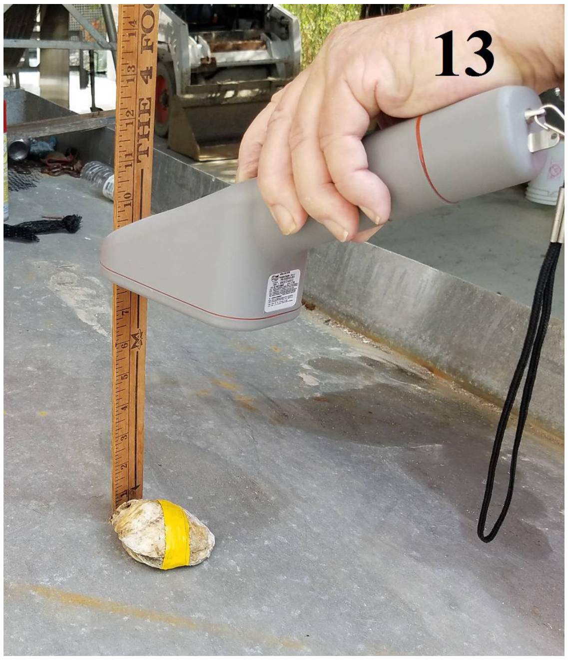

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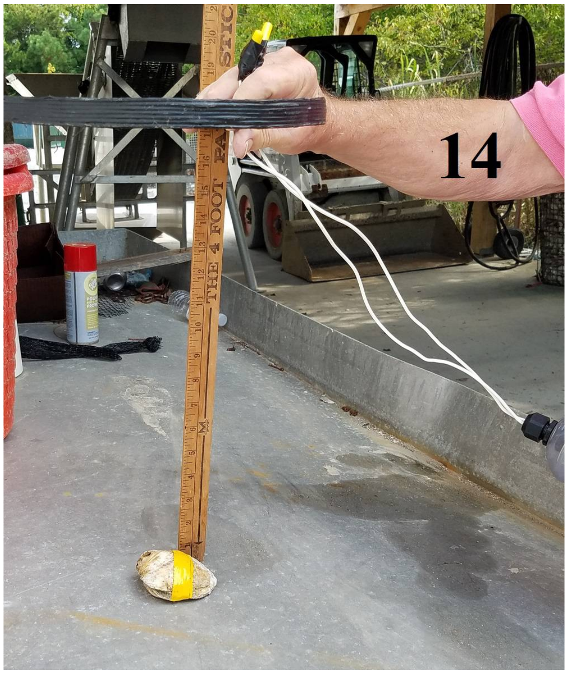

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15

16

Each page of photos above are of a different test environment, Photos 1-4 show tests being done on a wood table which is an insulating material. Photos 5-8 show test being done in a galvanized steel bucket. Photos 9-12 show tests being done on a conveyor that has a stainless steel belt and aluminum sides. And finally photos 13-16 show tests being done on an aluminum table which is a very good conductor.

The test results are shown below. There appear to be inconsistencies in the results. This is most likely due to the reader angular orientation to the tag. The behavior of the reader is very much like the old radio direction finders used before GPS. The operator tuned for a null signal by rotating an antenna. A null was achieved when the orientation of the loop antenna was perpendicular to a radio transmitting station. Our loop antenna is perpendicular to the antenna of the tag, thus a slight change in orientation takes the reader off the null and thus re read distance is greater.

Test environment: wood table:

	Hand reader	large reader
Dummy oyster alone	Photo 1 read distance- 8”	Photo 2 read distance- 13”
dummy with oysters on top	Photo 3 read distance- no read	Photo 4 read distance- 17”

Test environment: w steel bucket

	Hand reader	large reader
Dummy oyster alone	Photo 5 read distance- 5”	Photo 6 read distance- 15”
dummy with oysters on top	Photo 7 read distance- no read	Photo 8 read distance- no read

Test environment: w conveyor

	Hand reader	large reader
Dummy oyster alone	Photo 9 read distance- 6”	Photo 10 read distance- 24”
dummy with oysters on top	Photo 11 read distance- 9”	Photo 12 read distance- 24”

Test environment: waluminum table

	Hand reader	large reader
Dummy oyster alone	Photo 13 read distance- 8”	Photo 14 read distance- 17”
dummy with oysters on top	Photo 15 read distance- 8”	Photo 16 read distance- 12”

Conclusions

In a nutshell, I conclude the RFID technology I tested would be satisfactory to be used to track oysters from the oyster bottom to the point they are shipped or shucked. The technology would not provide a reliable means of detecting tagged oyster from a distance of greater than about one meter.

Appendix

Oregon RFID contact information:
Warren Leach
Oregon RFID, Inc.
2421 SE 11th Ave
Portland, Oregon 97214
(503) 788-4380 ext 602
http://www.oregonrfid.com
Tag provided by Oregon is described as follows:
23mm HDX+ PIT Tag, $1.80
Read-only tags with a 64 bit unique ID. ISO 11784/11785 compatible. The diameter is 3.65 mm and weighs 0.6g. Pressure tested to 1000 psi, equivalent to a depth in water of 500 meters.

VIMS reader specification:
ISO 11784; ISO 11785 HDX and FDX-B and Fecava FDX-A
Oregon RFID reader is a 'backpack' reader with a 10” loop antenna comprised of seven turns of wire. The information sent with it did not contain more detailed specification. It has the ability to send its readings wirelessly to other devices.

Silicone calk used in our experiments: DAP 100% silicone 9.8 fl. oz. Tube. UPC #70798 08641.

Attachment:Paper “RFID Under Water Technical Issues and Applications”

Chapter 18

RFID Under Water: Technical Issues and Applications

Giuliano Benelli and Alessandro Pozzebon

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/53934

1. Introduction

While RFID technology is nowadays very common in many commercial and industrial sectors, from items tracking to personal identification, few studies have dealt with the chance to use RFID systems in marine or fluvial environments for underwater monitoring operations. While the technical limitations for these scenarios can be in some cases insurmountable, ad-hoc studies have proven that in some cases RFID technology can work even under water.

RFID, like all radio technologies, in unsuitable to work in presence of water. Still water is not a natural conductor, but the presence of dissolved salts or other materials turns it into a partial conductor. Electromagnetic waves cannot travel through electrical conductors: this means that in most cases radio waves cannot be used to communicate under water. Anyway, studies have proven that the chance to transmit radio signals under water mainly depends on two factors: the conductivity of water and the frequency of the radio wave. While the conductivity of water is a factor that cannot be modified to increase the possibility to use radio waves under water, the only factor that can be modified to increase the performances is obviously the radio frequency.

This factor has already been employed when using the electromagnetic fields for the common radio transmissions: Very Low Frequency radio waves (VLF – 3-30kHz) have proven to be able to penetrate sea water to a depth up to 20 meters, while Extremely Low Frequency radio waves (ELF - 3-300Hz) can travel in sea water up to hundreds of meters. Anyway, these frequency bands present severe technical limitations. First of all, their extremely long wavelengths require antennas of very big dimensions: frequencies lower than 100Hz have wavelengths of thousands of kms, forcing to use antennas covering wide areas. Secondly, due to their narrow bandwidth, these frequencies can be used to transmit only text signals al slow data rates.

Some of these considerations can be applied also to RFID systems. First of all the use of active technologies is discouraged by many factors: at lower frequencies only passive systems can be found; moreover, the use of active systems is also impeded by the required dimensions of the antennas. Due to these limitations, only two RFID technologies can be employed for underwater applications: the High Frequency systems, operating at 13.56MHz and the Low Frequency systems, operating in the 125-134kHz band. The first solution (13.56MHz) still presents some severe limitations due to the reduction of the reading range: with common desktop antennas the reduction in the range is up to 80%, forcing to bring the transponder practically in contact with reader antenna. For the second solution (125-134kHz) the reduction is lower (around 30%) and the reading at a distance is still achievable. Laboratory tests proved that, with long-range antennas, a 50cm reading range is still achievable.

Both these two solutions can be anyway employed to set up RFID systems working in under water environments. Some solutions can already be found in some parts of the world [1]. USS Navy is testing the use of RFID technology for their applications based on the use of Unmanned Underwater Vehicles. Other applications foresee the use of RFID for the monitoring of underwater pipelines, with RFID transponders employed as markers to guarantee the integrity of the pipes. RFID has also been employed in aquariums to identify fishes, in the same way as Low Frequency RFID capsules are employed in cattle breeding. Finally RFID has been employed as a way to track the movement of pebbles on beaches, in order to analyse the impact of coastal erosion during sea storms.

The chapter will be subdivided in four main sections.

In the first section, the transmission of radio signals in water will be analysed. Details will be given on how the presence of water affects the electromagnetic fields, and examples of applications working in the VLF and ELF bands will be provided.

The second section will focus only on RFID. Technical data will be provided concerning the signal attenuation due to the presence of water. Some results will be given to prove the agreement of experimental data with the theoretical analysis.

In the third section the state of the art concerning under water RFID applications already existing all around the world will be provided. The few already tested applications will be described in detail.

Finally, in the fourth section some future applications based on this technology will be proposed.

2. Underwater radio signals

2.1. Water electric and magnetic properties

Water molecule is composed by two oxygen atoms and one hydrogen atom bonded together by a covalent bond. Oxygen has a negative charge, while the two hydrogen atoms have a positive charge: this means that the vertex of the molecule has a partial negative charge, while the two ends have a partial positive charge. A molecule with such a charge equilibrium is called electric dipole, and is characterized by its dipolar momentum μ, defined as the product between the absolute value of one of the two charges and the distance between them. This value indicates the tendency of a dipole to orientate under the effect of a uniform electric field.

While still water has a very low electrical conductivity, this value increases in presence of ionized molecules, in proportion to their concentration. When a salt is melt in still water, the single molecules are equally perfused in the whole liquid so that each single volume portion of the solution dissociates, creating many positive and negative ions that remain in the solution together with all the other molecules that aren't dissociated. This phenomenon is called electrolytic dissociation, and the so created solutions are called electrolytic solutions. These solutions can be crossed by an electrical current, in contraposition with still water that acts as a pure insulator.

2.2. Marine water

The chemical composition of marine water is influenced by several biological, chemical and physical factors: one simple example is the presence of rivers that add every day new chemical materials to the water. On the other side, other materials are removed by the action of organisms and due to erosion. Anyway, the most part of the salts dissolved in marine water remains almost constant due this continuous interchange phenomenon. The most important factors that influence the chemical composition of the marine water are the following:

- The draining of materials deriving from human activities;
- The interaction between the sea surface and the atmosphere;
- The processes between the ions in solution;
- The biochemical processes.

The elements that can be found is marine water are around 70, but only 6 of them represent the 99% of the total. These predominant salts are:

- Chloride (Cl): 55.04 wt%
- Sodium (Na): 30.61 wt%
- Sulphate (SO42-): 7.68 wt%
- Magnesium (Mg): 3.69 wt%
- Calcium (Ca): 1.16 wt%
- Potassium (K): 1.10 wt%

The symbol (wt%) stands for the mass fraction, and represents the concentration of a solution or the entity of the presence of an element in a solution. The quantity of these ions is proportional to the salinity of water, a parameter describing the concentration of dissolved salts in water. Due to the evaporation, this value is lower at the poles (around 3.1%) and higher at the tropics (around 3.8%), with the highest value for an open sea reached by the Red Sea (4%, with a peak of 4.1% in the Northern parts). Moreover, salinity is lower close to the coasts due to the inflow of fresh water by the rivers. Salinity affects the conductivity of water: while this parameter also depends from the water temperature and pressure, it ranges from around 2 S/m to around 6 S/m. Anyway, in most cases it can be considered constant, with a value of 4 S/m. Water is then a conductor.

Once the value of water conductivity is known, it can be used to calculate the values of the penetration depth and of the attenuation.

The penetration depth δ is the distance where the electrical and magnetic fields are reduced of a *1/e* factor, and it can be calculated using the following formula:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \; m$$

where f is the frequency of the electromagnetic wave, μ is the absolute magnetic permeability of the conductor and σ is the conductivity. While water is a diamagnetic material, their absolute magnetic permeability can be considered the same as the vacuum magnetic permeability, i.e. $\mu_0 = 4\pi * 10$ H/m. This means that, with the conductivity considered constant, the penetration depth only depends on the frequency: the higher is the frequency, the lower is the penetration depth.

The attenuation α can be calculated using the following formula [2]:

$$\alpha = 0.0173\sqrt{f\sigma} \; dB / m$$

where f is the frequency of the electromagnetic wave and σ is the water conductivity that, as said before, can be considered constant. Attenuation is then in inverse proportion with the frequency and then obviously also with the penetration depth.

2.3. Fresh water

Around 97% of the water of the world is found in seas and oceans, while two thirds of the remaining 3% of fresh water is retained as ice in glaciers and at the poles. This means that the most part of studies that can be found concerning the chance to communicate under water using the electromagnetic fields focuses on the marine environment.

Anyway, similar considerations as the ones made for salt water apply to fresh water. The biggest difference derives from the different values of salinity that are detected in fresh water. While the salinity of salt water is around 3.5% (See section 2.2), in fresh water this value decreases down to 0.05%. Anyway, unlike marine water, a general analysis concerning the quantity and typology of salts that can be found in fresh water is impossible to carry out due to the single peculiarities of rivers, lakes, and the chemical and geological composition of the territories that they pass through and where they are located.

A different value in salinity also means a different value in conductivity. In particular, conductivity of fresh water ranges from 30 to 2000μS/cm: these are nevertheless extreme values; river water conductivity usually ranges from 50 to 1500$\mu S/cm$, while rivers supporting a good wildlife usually range from 150 to $500 \mu S/cm$. This value is notably lower than the average one for marine water. The main consequence of this fact is that for fresh water the penetration depth is higher and the attenuation is lower.

2.4. Underwater radio communication

Some easy calculations prove that the electromagnetic fields can be used to transmit radio signals under water (Especially under the sea) only when their frequency is very low. As an example we can calculate the penetration depth for an electromagnetic wave traveling through salt water at frequency of 10kHz, using the average values for μ and σ:

$$\delta_{10kHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 10^4 \bullet 4\pi \bullet 10^{-7} \bullet 4}} \approx 2.5m$$

This value allows a short range communication, while long range communication requires even lower frequencies.

Looking at fresh water the situations is a little bit better. The previous calculation can be made, using a very low conductivity value of 30 μS/cm (3mS/m):

$$\delta_{10kHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 10^4 \bullet 4\pi \bullet 10^{-7} \bullet 3 \bullet 10^{-3}}} = 92m$$

Anyway, while this value is higher, long range communication is not allowed when the operative frequency is higher than some kHz.

As a consequence of the previous analysis, the only bands that have been used for underwater radio communication have been the ELF (Extremely Low Frequency) band, ranging form 3 to 300 Hz, with the sub-band ranging from 30 to 300 Hz called SLF (Super Low Frequency) band, and the VLF (Very Low Frequency band).

The ELF band was used for the communication with submarines both by the US and the Russian Navies. The US system, called Seafarer, operated at the frequency of 78Hz, while the Russian one, called ZEVS, operated at the frequency of 82Hz. These systems had a penetration depth in the order of 10km, allowing thus a communication from a fixed station on the sea surface with a submarine traveling close to the ocean floor. Anyway, the realization of a communication channel at these frequencies presents several technical limitations that are extremely difficult to be overcome. One of the biggest problems to be solved is the size of the antenna: its dimension has in fact to be a substantial fraction of the wavelength, but at these frequencies the dimension of the wavelength is in the order of the thousands of kilometres. The solutions found by the US and Russian Navies were complex and expensive, making prohibitive their use for civil applications.

The VLF band ranges from 3kHz to 30kHz: this means that the penetration depth of electromagnetic waves at these frequencies is in the order of ten meters. This value allows a communication with submarines positioned few meters below the sea surface. The limitations on the antenna dimensions, deriving from the big wavelength, have to be taken in account also in this case. Moreover, due to the limited bandwidth, this communication channel cannot be used to transmit audio signals, but only text messages.

3. Underwater RFID

RFID, being a radio technology, suffers from the same limitations of the standard communication channels. This means that the higher is the frequency, the lower are the chances to have a reliable communication {3-7}.

RFID systems are usually subdivided in the following bands:

- Low Frequency (LF) – 120-150kHz;
- High Frequency (HF) – 13.56MHz;
- Ultra High Frequency (UHF) – 433MHz, 868-928MHz;
- Microwave – 2.45-5.8GHz.

3.1. Salt water

As underlined in section 2, significant differences occur according as the RFID system has to be used in salt or fresh water. Starting from salt water, some calculations show that only LF RFID can be used for systems requiring a long reading distance (over 50cm). In particular at a frequency of 125kHz, the average value (Using the salinity value of 4S/m) for the penetration depth is:

$$\delta_{125kHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 1.25 \bullet 10^5 \bullet 4\pi \bullet 10^{-7} \bullet 4}} \approx 71cm$$

This value is just lower than the maximum achievable reading range for a Low Frequency system, which is usually lower than 1m. This means that Low Frequency RFID can be theoretically used for the underwater identification of items.

Moving at higher frequencies, the use of these systems for long range identification becomes virtually impossible. The calculation for the penetration depth provides an extremely low value. Starting from the High Frequency band, where all RFID systems work at the standard frequency of 13.56MHz, with the same conditions as in the previous case, the obtained value for the penetration depth is:

$$\delta_{13.56kHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 13.56 \bullet 10^6 \bullet 4\pi \bullet 10^{-7} \bullet 4}} \approx 68mm$$

This result proves that High Frequency RFID can be used under water only for short range solutions. In particular, due to the fact that the effectiveness of every RFID system is notably influenced by the performances of the hardware devices employed, it’s possible to affirm that the chance to use High Frequency systems is limited to the applications where the tag is in close contact with the reader.

The UHF band is currently employed in many different systems and probably represents the best solution for many applications due to its good performances in terms of reading range, costs and bitrate. Anyway, its frequency is too high to allow its use also for underwater contactless applications. The calculation of the penetration depth, using an average frequency value of 800MHz (varying this value from 433MHz to 930MHz the order of magnitude remains quite constant), provides the following result:

$$\delta_{800MHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 800 \bullet 10^{6} \bullet 4\pi \bullet 10^{-7} \bullet 4}} \approx 9mm$$

This value is obviously too short to use this technical solution for other than contact applications. Only bringing a transponder in contact with the antenna of the reader, the reading becomes possible. While this fact strongly limits the possible uses of these systems, in some cases UHF systems can still become a good choice.

Finally, the Microwave band is obviously the one that provides the worst results. The value of the penetration depth is provided only for completeness, even if currently no application can be found worldwide using this technical solution:

$$\delta_{2.45GHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 2.45 \bullet 10^{9} \bullet 4\pi \bullet 10^{-7} \bullet 4}} \approx 5mm$$

Before moving to the next section a clarification has to be made. In the previous analysis no differentiation has been done on the powering method of the transponders. In fact, while active transponders usually provide higher reading ranges, they are generally used only at higher frequencies (UHF and Microwave bands): anyway, at these frequencies the penetration depth is so short that even with the most powerful active transponder no improvement in the performances of the systems would be noticeable. Moreover, even at lower frequencies, the value of the penetration depth is anyhow lower than the reading range achievable using passive transponders: therefore, a study for the use of active transponders also at these frequencies would be useless and wouldn’t provide any improvement.

3.2. Fresh water

The analysis for fresh water is similar to the one carried out for salt water. The main difference derives from the fact that, while the range of the conductivity values of salt water is very short, it becomes wider in the case of fresh water. As anticipated is section 2.3, fresh water conductivity roughly varies from 30 $\mu S/cm$ to 2000 $\mu S/cm$. While both these values are notably lower than the conductivity of salt water, the differences between the obtained values for penetration depth are less distant. In order to provide an accurate set of data, the penetration depth value will be calculated both for the best (30 $\mu S/cm$) and the worst (2000 $\mu S/cm$) case.

As in the case of salt water, the analysis will begin from the Low Frequency band. In this case, at the frequency of 125kHz, with a conductivity value of 30 $\mu S/cm$ (3 mS/m), the value of penetration depth is:

$$\delta_{125kHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 1.25 \bullet 10^{5} \bullet 4\pi \bullet 10^{-7} \bullet 3 \bullet 10^{-3}}} = 26m$$

With a conductivity value of 2000 $\mu S/cm$ (0.2 S/m) the penetration depth becomes:

$$\delta_{125kHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 1.25 \bullet 10^{5} \bullet 4\pi \bullet 10^{-7} \bullet 0.2}} = 3.2m$$

Both these values are high enough to allow a reliable long range RFID communication channel.

Moving on to higher frequencies, the second evaluation is made for the High Frequency band. The calculation is made using the standard frequency of 13.56MHz. The penetration depth value with a conductivity of 30 $\mu S/cm$ (3 mS/m) is:

$$\delta_{13.56MHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 13.56 \bullet 10^{6} \bullet 4\pi \bullet 10^{-7} \bullet 3 \bullet 10^{-3}}} = 2.5m$$

With a conductivity value of 2000 $\mu S/cm$ (0.2 S/m) the penetration depth drops to:

$$\delta_{13.56MHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 13.56 \bullet 10^{6} \bullet 4\pi \bullet 10^{-7} \bullet 0.2}} \; 30cm$$

While at lower conductivity values the realization of an efficient long range RFID system could still be possible, when the water conductivity grows the penetration depth drops down to values that make this solution difficult to be implemented or even totally impossible. Anyway, the chance to use HF RFID in particular environments like rivers or lakes has to be carefully evaluated case-by-case. An additional remark has to be made: in terms of performances, LF and HF systems are similar. This means that, if the system doesn't present specific requirements, the use of LF technology is however strongly suggested.

At higher frequencies the value of penetration depth drops down to values that allow the use of these systems only for contact or short range applications. At 800MHz the penetration depth with a conductivity value respectively of 30 $\mu S/cm$ (3 mS/m) and 2000 $\mu S/cm$ (0.2 S/m) is:

$$\delta_{800MHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 800 \bullet 10^{6} \bullet 4\pi \bullet 10^{-7} \bullet 3 \bullet 10^{-3}}} \approx 32.5cm$$

and

$$\delta_{800MHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 800 \bullet 10^{6} \bullet 4\pi \bullet 10^{-7} \bullet 0.2}} \approx 4cm$$

For Microwaves, these values drop down to:

$$\delta_{2.45GHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 2.45 \bullet 10^{9} \bullet 4\pi \bullet 10^{-7} \bullet 3 \bullet 10^{-3}}} \approx 18.6cm$$

$$\delta_{2.45GHz} = \frac{1}{\sqrt{\pi f \mu \sigma}} = \frac{1}{\sqrt{\pi \bullet 2.45 \bullet 10^{9} \bullet 4\pi \bullet 10^{-7} \bullet 0.2}} \approx 2.3cm$$

A remark is necessary: the values obtained for the penetration depth are ideal values and represent mainly an upper bound. This means that in most cases the effective system will present real reading ranges notably lower and in some cases it won't work at all.

	Low Frequency **125kHz**	**High Frequency** **13.56MHz**	**Ultra High Frequency** **800MHz**	**Microwaves** **2.45GHz**
Salt Water $4S/m$	$71cm$	$68mm$	$9mm$	$5mm$
Fresh Water $30\mu S/cm$	$26m$	$2.5m$	$32.5cm$	$18.6cm$
Fresh Water $2000\mu S/cm$	$3.2m$	$30cm$	$4cm$	$2.3cm$

Table 1. The penetration depths for the considered frequencies for both salt and fresh water

In conclusion, while theoretical data suggest that several solutions are possible when RFID is required for under water applications, it's possible to affirm that to obtain reliable results the operative frequency as to be the lowest possible. In particular:

- For salt water long range reading is obtainable only using Low Frequency systems;
- In salt water, short range or contact reading could be possible also at higher frequencies. Anyway, also in these cases a reliable reading level could be very difficult to be achieved at frequencies higher than 13.56MHz;
- For fresh water long range reading could be obtained not only with Low Frequency systems, but also with the use of High Frequency devices operating at 13.56MHz. Anyway, also in this case the use of Low Frequency is strongly recommended due to their higher reliability;
- When short range or contact reading is required in fresh water, quite all the frequencies could be efficient, even if there is a lack of studies proving the effectiveness of UHF frequencies.

4. RFID applications under water

RFID is currently one of the most widespread technologies for the automatic identification of items. There are countless fields where RFID is used for access control, items tracking, people and animal identification and many other different applications. Anyway, few applications exist where RFID is used under water.

The question of the transponders waterproofing is crucial for many applications and several devices providing a high protection level against the contact with water have been realized. Plastic tags are inherently waterproof devices, while items like wristbands have been customized to be worn also under water. Anyway, all these devices have been designed only to resist against water intrusion, and not to be read directly under water. Moreover, no reader has been realized to be used under water. Readers providing a high protection level against water can be easily found: anyway, they are designed only to be positioned on the outside, for example on building walls for access control, and then to resist against bad weather.

A step ahead is the development of transponders realized ad-hoc to be positioned on bottles or other items containing liquids. In this case the solution mainly deals with the introduction of a dielectric layer that simply separates the transponder and the liquid allowing thus its reading.

Anyway, the number of applications where the data exchange happens totally underwater is nowadays very little: the most part of these applications deals with animal tracking and environmental monitoring, mainly in marine environment.

4.1. Animal tracking

The chance to track animals, crucial for industrial stock-breeding activities, using RFID technology has probably raised for the first time the question whether is possible or not to read RFID tags immersed in water. The body of most part of living beings is mainly composed by water: as an example, around 65% of human body is composed by water. The necessity to guarantee the integrity of the tracking device (In this case the transponder) has encouraged its positioning in a place where it cannot be removed, i.e. inside the body of the animal to be tracked. While the body of the animal is mainly composed by water, to read the transponder from the outside it's necessary to find a technological solution avoiding the insulating effect of the water layer.

The use of RFID for animal tracking is nowadays very common, and has also led to the realization of two ad-hoc standards, the ISO 11784 and ISO 11785 standards, that regulate the use of RFID devices, in particular implantable transponders, for the identification of animals. Standard RFID systems for animal tracking operate at the frequency of 134.2kHz (Low Frequency band). The transponders used for this purpose are generally glass cylinder tags that are modified to be applied under the skin of the animal, to be clasped to the ear of the animal or to be ingested by the animal.

Even if these applications deal with the interaction with water, they are not properly under water systems. Anyway, RFID technology has been employed also to track animals under water. In particular, Low Frequency RFID technology has been used to identify fishes in the aquariums [8]. At the Underwater World Singapore Oceanarium, at Underwater World Pattaya, Thailand and at Virginia Aquarium & Marine Science Center, Low Frequency cylinder glass tags have been applied under the skin of a number of fishes.

The tagged fishes are identified when they come close to a long range antenna positioned on the glass of the tank where the fishes are kept. When the fish passes in front of the antenna, the identification code stored inside the transponder is read and the fish is identified. Once the fish has been identified the visitors of the aquarium can receive an interactive set of information concerning the animal. In particular, an ad-hoc software provides on a screen a picture of the fish and a description: these data are kept on the screen until a new fish passes close to the antenna.

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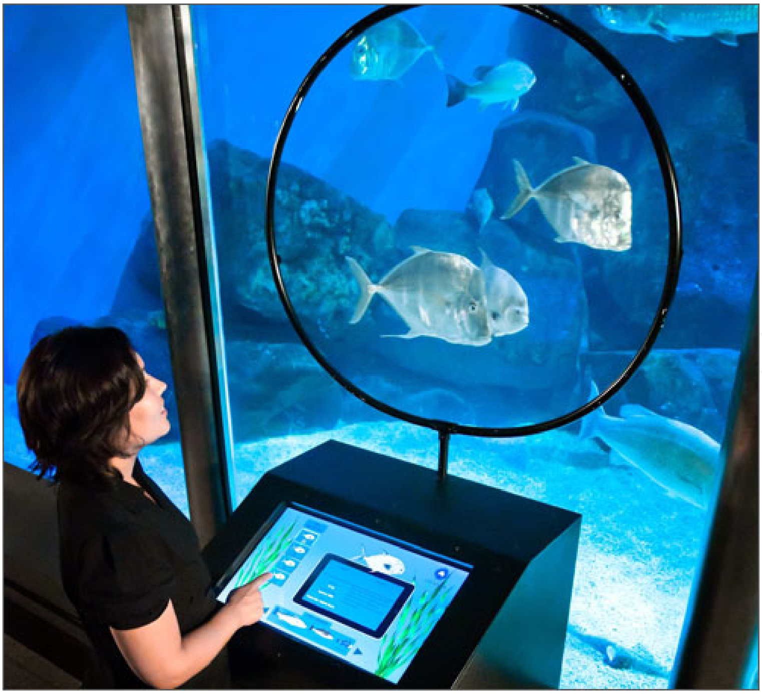

Figure 1. The Virginia Aquarium and Marine Science antenna identifying fishes.

4.2. Pipeline monitoring

Another interesting application that foresees the use of RFID technology under water focuses on the monitoring of pipelines used to carry oil [9]. This solution has been currently only tested, while no information has been retrieved on possible effective applications nowadays working. In this kind of applications Low Frequency RFID tags were applied directly on the pipeline, keeping a fixed distance between one tag and the other.

The tags operated the frequency of 125kHz and they were customized to fit exactly on the pipe: in particular, standard Phillips Semiconductor Hitag transponders were introduced inside a protecting case, shaped on the curvature of the pipe.

Enertag, which tested the system, also developed an ad-hoc underwater reader: this was a handheld waterproof device connected with a cable to a PC positioned on a boat on the sea surface.

This system was employed to monitor the conditions of the pipeline. In practice, the transponders acted as milestones, used to identify the exact portion of pipeline. This was combined with the data concerning repairs that the pipeline had undergone, and suggesting which portion of the pipeline required assistance.

Figure 2. The Enertag system for the pipeline monitoring

4.3. Underwater navigation

US Navy analysed a possible use of RFID technology as a support for the navigation of autonomous underwater vehicles [10]. In this application tags are positioned directly on the sea bottom, and they contain information related to their position inside the area where the vehicle is moving.

The reader is embedded directly inside the vehicle: every time that a transponder comes inside the interrogating range of the reader, the information stored inside it is read and then used by the vehicle to manage its movements.

While no data has been found about an effective application of this solution, the possible uses of such a kind of system are many. Even if this solution has been proposed by the US Navy, it could be employed also in many civil applications, from the environmental monitoring to the harbour management.

4.4. Environmental monitoring

RFID technology has been used for the monitoring of coastal dynamics. The University of Siena and the University of Pisa, in Italy, have realized the so-called "Smart Pebble" system, where Low Frequency transponders are used to trace the movements of a set of pebbles along a pre-defined span of time, in order to study the dynamics of the shoreline [11].

In this system different typologies of 125kHz transponders have been employed in the last 4 years, from plastic disc tags to cylinder glass tags. These tags were inserted inside real pebbles picked up directly on the beaches where the system had to be employed: in order to allow the housing of the transponder, the pebbles were drilled. The transponder was then glued on the bottom of the small hole realized in the pebble and then it was covered with the small rocky cap extracted during the drilling operation.

Once a large set of pebbles was realized, it was positioned on the beach to be studied, following a grid pattern covering both the emerged and the submerged portion of the beach. Through an ad-hoc waterproof reader realized modifying a common reader used for access control, the pebbles were then localized after a pre-defined span of time. The starting and final positions were recorded using a GPS total station: with these data the path followed by the pebble swarm was traced, allowing geologists to easily understand the dynamics of the shoreline and the erosive effects of the meteorological events.

This application proved to be very interesting because its biggest requirement was to achieve the largest reading range possible. This constraint forced to test different hardware solutions in order to obtain the best performances especially for salt water, which was the environment where the system had to be employed. A few tests were made with HF (13.56MHz) devices but the results achieved discouraged from using this solution. In particular, the reading range obtained with a common desktop reader under salt water was lower than 3cm. This result is in accordance with the theoretical data and excludes the use of this technology for long range under sea applications.

The following experimentations were carried out on LF 125kHz systems: the theoretical analysis on this technology foresaw the chance to use them for long range applications also under sea. The tests were carried out using a long range reader usually employed for access control. Several kinds of transponders were used for the tests, from plastic discs to glass tags. The tests tried to simulate as much as possible the real environmental conditions: to achieve this result a model of the sea bottom was realized using a plastic tube. The results of the laboratory tests are shown in Table 2 and demonstrate that, using Low Frequency, long range reading is possible also under sea. Note that the experimentation was carried out in two times, and the results are then divided in two sub-sets: the first three results provide an average value from the best and worst coupling value, while the second three provide these two values separately [12]. The results are in accordance with the theoretical analysis: the achieved reading range is lower than the penetration depth, that acts then as an upper bound.

Tag Typology	Ideal Reading Range	Real Conditions
Nylon disc	55cm	41cm
ABS Plastic disc	63cm	51cm
PVC disc	49cm	36cm
Transparent disc	50cm	28-47cm
Long Glass tag (34mm)	65cm	48-63cm
Short Glass tag (14mm)	42cm	30-41cm

Table 2. Reading ranges of different Low Frequency transponders under water

The first experimentations on the Smart Pebble system were carried out in 2009 and this solution has been since then employed in several on-site applications on different beaches in Italy. The effective use of the system has roughly confirmed the results recorded in the laboratory tests: during the localization process, the transponders embedded inside the pebbles were localized even from distances higher than 50cm.

Figure 3. A Smart Pebble. On its surface is possible to notice the hole housing the transponder

Figure 4. A moment of the localization operations

While this application is interesting because sea is probably the most complex environment for the underwater use RFID, this technology has also been employed several times for the study of sediment transportation in rivers [13-14].

All these solutions are based on the use of Low Frequency technology. 125kHz or 134.2kHz transponders are introduced inside pebbles that act as tracers in the same way as the marine application.

Anyway, differences occur in the way transponders are detected. In some applications, a reader carried by hand is employed: this means that in most cases the reader is kept outside water and used as a sort of metal detector along portions of the river where the depth is very low. Other interesting solutions are based on the deployment of an array of antennas directly on the river bed. In this case, the tagged pebbles are detected only when they pass over one of the antennas.

5. Future applications

The systems described in the previous sections represent a good starting point for the development of many other possible applications, in the same applicative fields but also in totally new ones.

Starting from the animal tracking application, the extension of this solution to other scenarios is limited mainly by the reading range, which forces the fish to come close to the reader antenna to be identified. Anyway, the chance to track animals also under water suggests a possible use of RFID technology also in the sector of fish breeding. In this case, the use of such a solution could be used to trace the production process and to guarantee the quality of the final product. On the opposite side, the use of RFID technology to trace the movements of wild fishes is notably more difficult. The RFID reading range makes the possibility to trace fishes in the sea (or even in a lake) virtually impossible because the chances that a fish will come close to some antenna positioned elsewhere are close to zero. On the other hand RFID could be used to monitor the movements of fishes along a river. In this case, antenna arrays could be structured as a sort of RFID barrier in locations where the river depth is low enough to allow the detection of every transponder passing over it. In this case, such a system could be for example useful to study the migration processes of fishes like salmons.

The technique set up for the pipeline monitoring could be easily extended to other typologies of industrial monitoring. In particular, it could be applied to monitor the state of harbour infrastructures, ship hulls, oil platforms and all the other offshore industrial plants. In all these scenarios, RFID could be useful to keep trace of the maintenance interventions performed in specific locations. The operators could use RFID transponders as a sort of electronic note where the state of the site could be read and then updated every time that any sort of intervention is performed.

The underwater navigation application could be a good starting point to develop applications where RFID is used to manage the movements of boats inside the harbours. In this case, RFID transponders could be used as a sort of electronic trail, with a reader positioned directly on the boat analysing the information stored on them and using it to move inside the harbour. On the other side, it could be possible to deploy transponders directly on the boat, and to use them as a sort of electronic license plate. This could allow the boat to be automatically identified by a reader positioned on the pier without the direct intervention of a harbour operator.

The field of environmental monitoring probably opens the way to the widest range of possible applications. Together with the geological applications concerning the sediments tracking, RFID could also be useful for the monitoring of biological activities both is rivers and in the sea. The application concerning the tracking of pebbles has in fact suggested a possible extension for this technique. The pebbles recovered at the end of the experimentation presented a lot of organic sediments left on them: this fact suggests then their possible use also as probes to analyse the impact of pollution on the biological activity of the portion of littoral under study. This technique could also be extended to be employed in other scenarios where sediments tracking is required: a similar system could be for example deployed in the city of Venice to monitor the condition of the canals. In general, such a solution could be used in those water environments where the dynamics are slow enough to keep the tracers in an area small enough be manually scanned using a reader. In this sense, such a system could be used for example to analyse in detail the dynamics of a glacier.

Together with these possible applications, deriving from the existing systems, other possible solutions could be studied every time that an under water monitoring or tracking system is required.

6. Conclusions

In this chapter the chance to use RFID technology for systems operating under water has been analysed.

The composition of salt and fresh water has been described, together with the influence that the salinity has on the conductivity of water and then on key parameters like water attenuation and penetration depth. The value of this second parameter has been calculated for the standard RFID systems: the results show that only at Low Frequencies it's possible to develop solutions where a long reading range is required, both for salt and fresh water. Anyway, moving at higher frequencies, while for fresh water the chances to set up efficient solutions are still high, especially for short range applications, for salt water RFID becomes virtually unusable.

However, the chance to use the lower frequency bands has led to the development of some applications that use RFID technology for specific purposes, both in marine and in fresh water environments. These applications range from animal tracking solutions to environmental monitoring systems, and represent a good starting point for a wider diffusion of this technology even in a sector traditionally precluded to technologies relying on electromagnetic fields for their functioning.

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