Survey and Preliminary Results on the Design of a Visual Light Communication System for Radioactive and Underwater Scenarios

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Abstract: The use of radio-frequency communication systems is very well known and also it is broadly used in the design of mobile robotics. In fact, it can be very well applied in rescue robotic systems, such as the ones that present smoke and fire. In radioactivity scenarios the robot might get problems to communicate, in the presence for example of magnets. Also, in underwater fields radio-frequency solutions need to improve the communication distance, while sonar systems present variable delays and limited bandwidth, which are difficulties to provide remote visual feedback to the operator. This paper states that field robotic systems, such as the ones in radioactivity and underwater scenarios, need to complement the current communication systems with multi-modal solutions, in order to enhance operation safety and reliability, while better adapting to the mission unexpected situations. For this, Visual Light Communication solutions have been studied in detail and a preliminary prototype, which is presented in this paper, has been designed. This prototype would need further work to be applied successfully in real radioactive and underwater scenarios, as stated in the conclusions.

1 INTRODUCTION

The TWINBOT project is a spanish research performed in collaboration between the Girona University, University of Balearic Island, and Jaume I University of Castellon. The main focus of the project is to go beyond the state of the art of mobile underwater cooperative robots for manipulation, in order to be able to solve robotic interventions which require more than one robot at a time (e.g. transporting and assembling big objects).

In order to be able to perform such a cooperative interventions, it is necessary to work in order to improve the way the robots communicate as a team, and also to the surface. One of the communication improvements to be faced is the use of wireless underwater links. Previous experiences in this subject (Centelles et al., 2020) demonstrated that radio frequency modems can help to create a wireless communication between the robots at a few meters, with constant time-delay, and sonar system for linking to the surface. These experiments demonstrated that it is possible to send image feedback over these links by using very specific communication protocols (Rubino et al., 2017), and using a supervised control technique.

Sonar and radio-frequency channels offer limited bandwidth (around 1-60 kbps), while being able to transmit under low visibility conditions. Also, in order to be able to transmit more information at short distances, under good visibility conditions, the use of Visual Light Communications has been studied and experimented.

This paper is organized as follows. First of all a survey on Visual Light Communication Systems for underwater applications is presented. Secondly, the design of a preliminar VLC prototype is presented, which has as objective the demonstration of the concept by using a low power laser, for safety reasons. Third, the experiments with the VLC system are described, presenting the low level protocol and the results of sending a dataset of 100 underwater images. Finally, next steps on the design of the underwater VLC system are presented.

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2 STATE OF THE ART

Emerging underwater communication technology developed for commercial sea resource exploration, military warship-to-submarine communication, and satellite-to-submarine communication is a challenging field of research. In fact, with the rapid advancement of technologies, different ways to communicate in an underwater environment have been investigated. Acoustic waves, radio-frequency electromagnetic (EM) waves, and visible EM waves are all applicable for underwater communication. In particular, the first type suffers of high latency and low data transmission rate (DTR) but has a very long range. The second type has a very short range, up to meters, and a quite good DTR, and the last has a very high DTR and a range of tens of meters. These last two suffer of absorption, which causes the low range, but have almost no latency, and low signal-to-noise ratio (SNR).

To have a better comprehension of the motivations of this project, in the next sections there is a review of related surveys about Underwater Optical Wireless Communication (UOWC) (Zeng et al., 2016) and some background knowledge that could be useful for the lasts sections.

2.1 Review of Related UOWC Surveys

In the last years, research has faced many challenges in the UOWC field, and several articles have been published to survey the subject. Khalighi et al. presented a brief review of some recent works on UOWC in channel models, modulation and coding schemes, and experimental works (Khalighi et al., 2014). Starting from this analysis, they show the performance study of a typical UOWC system with several simplified assumptions. Another study on UOWC channel models has been carried on by Johnson et al. (Johnson et al., 2013a). Different typical UOWC modeling methods such as Beer Lambert's law, radiative transfer function, and Monte-Carlo approach have been discussed. Johnson et al. (Johnson et al., 2014) introduced UOWC with a particular focus on aquatic optical properties. Arnon (Arnon, 2010) analyzed the link performance of a typical UOWC system and introduced a number of challenging issues associated with UOWC systems.

2.2 Background of UOWC

In this section, there are some background information which constitute the basis of UOWC research. First, the link configurations of UOWC will be presented. Second, the advantages and challenges of UOWC will be highlighted. In the end, we summarize the main works related to UOWC channel modulations in [Table 1].

2.2.1 Link Configuration of UOWC

Based on link configurations, UOWC can be classified into four categories (Johnson et al., 2014): 1) Point-to-point line-of-sight (LOS) configuration, 2) Diffused LOS configuration, 3) Retroreflector-based LOS configuration, and 4) Non-line-of-sight (NLOS) configuration.

- Point-to-point LOS configuration is the most commonly used in UOWC (Arnon, 2010). In this configuration, the receiver detects the direction of the transmitter. It commonly employs light sources, such as lasers with narrow divergence angle, and so it requires a precise pointing between transmitter and receiver which limits the performance in turbulent water environments.
- Diffused LOS configuration employs diffused light sources, such as high-power light-emitting diodes (LEDs), with large divergence angle to accomplish broadcasting UOWC from one node to multiple nodes. Broadcasting method can relax the requirement of precise pointing. However, compared with the point-to-point LOS configuration, this link suffers from aquatic attenuation due to the large interaction area with water. Relatively short communication distances and lower data rates are the two major limitations.
- Retro-reflector-based LOS configuration can be seen as one special implementation of the point-to-point LOS configuration. It is suitable for duplex UOWC systems with underwater sensor nodes having limited power and weight budget. There is no laser or other light sources in the retro-reflector end, and so, its power consumption, volume and weight are reduced. One limitation of this configuration is that the back-scatter of the transmitted optical signal may interfere with the reflected signal, thus degrading the system signal-to-noise ratio (SNR) and bit-error rate (BER). Moreover, since the optical signals go through the underwater channel twice, received signal will experience additional attenuation.
- NLOS configuration overcomes the alignment restriction of LOS UOWC. In this case, the transmitter projects the light beam to the sea surface with an angle of incidence greater than the critical angle. Therefore the light beam experiences a total internal reflection (Arnon and Kedar, 2009).

The receiver should keep facing the sea surface in a direction parallel with the reflected light to ensure proper signal reception. The main challenge of NLOS links is the random sea surface slopes induced by wind or other turbulence sources (Tang et al., 2013). These phenomena will reflect light back to the transmitter implying severe signal dispersion.

2.2.2 Advantages and Challenges of UOWC

UOWC is characterised by many advantages over the acoustic and RF methods, but achieving UOWC remains as a challenging task. The main challenges of UOWC are listed as follows.

- Optical signal suffers from severe absorption and scattering. The wavelength of transmission light has been selected in the blue and green spectrum to minimize the transmission attenuation effect (Duntley, 1963). This is due to the inevitable photon interactions with the water molecules and other particulate matters in water. Absorption and scattering still severely attenuate the transmitted light signal and cause multi-path fading. UOWC suffers from poor BER performance over a few hundred meters link distance in turbid water environment. This is due to the impact of absorption and scattering. In underwater environment, matters such as chlorophyll are capable of absorbing the blue and red lights. These matters and other colored dissolved organic material (CDOM) can increase the turbidity and shrink the propagation distance of the light. Moreover, the concentration of CDOM will also change with ocean depth variations, thus modifying the corresponding light attenuation coefficients (Johnson et al., 2013b). These undesirable impacts will increase the complexity of UOWC systems.
- Underwater optical links will be temporarily disconnected due to misalignment of optical transceivers. In many UOWC systems, blue/green lasers or LEDs have been implemented as the light sources for their narrow divergence feature. However, a precise alignment condition is needed (Arnon, 2010). Since the underwater environment is turbulent at relatively shallow depths, link misalignment will take place frequently, especially in the vertical buoy-based surface-to-bottom UOWC applications (Johnson et al., 2013b), (Yi et al., 2015). Random movements of sea surface will cause serious connectivity loss problem (Dong et al., 2013a).
- The implementation of UOWC systems needs reliable underwater devices. The underwater environment is complex: the flow, pressure, temperature and salinity of seawater will strongly impact the performance and lifetime of UOWC devices (Pompili and Akyildiz, 2009). Furthermore, if we consider that no solar energy can be exploited undersea and extended undersea operation time of UOWC devices, the reliability of device batteries and efficiency of device power consumption are critical (Pompili and Akyildiz, 2009).

3 METHODS AND MATERIAL

This section is dedicated to the physical implementation of the prototype discussed previously.

The main instruments needed for the project are two microprocessors whose interface is implemented in Arduino code. We are going to describe in detail why we have chosen these components and how we have built the circuits. In the last part we will describe more specifically the idea behind the software and the protocols used.

3.1 Hardware Realisation

In this section we will analyse specifically the hardware used. The main components are:

- Sipeed Maixduino
- Photo-diode
- Laser

Sipeed Maixduino. Maixduino (Figure 1) makes the Arduino IDE and libraries support the Maix series of development boards, making it easy to use a large number of existing open source Arduino libraries for rapid development and prototyping. We decided to use this micro-controller because it is cheap, fast and has a relatively large memory.

Photo-diode. Figure 2 shows the circuits needed to develop a photo-diode receiver. It requires at least a 3.3V voltage supply, which can be performed by the Maixduino board, and has as output a square wave. Further information can be found here[1].

Laser. We used an already implemented red-laser diode (Figure 3) which has a power < 0.9mW and a

[1]https://www.ebay.es/itm/EL0505-Receptor-Detector-Laser-Arduino-modulo-sensor-no-modulado-Rapsberry/331867336776

Table 1: Summary of Literature on UOWC Modulation Scheme.

UOWC modulations	Literature	Benefits	Limitations
OOK	(Jaruwatanadilok, 2008),(Akhoundi et al., 2015), (Ahmad and Green, 2012), (Wang et al., 2012)	Simple and low cost	Low energy efficency
PPM	(He and Yan, 2012), (Meihong et al., 2009), (Sari and Woodward, 1998), (Chen et al., 2006), (Anguita et al., 2010b), (Anguita et al., 2010a), (Tang et al., 2012), (Swathi and Prince, 2014), (Hagem et al., 2012)	High power efficency	High requirements on timing Low bandwidth utilization rate More complex transceivers
DPIM	(Gabriel et al., 2012), (Doniec et al., 2010a), (Doniec and Rus, 2010), (Doniec et al., 2010b), (Mi and Dong, 2016)	High bandwidth efficency	Error spread in demodulation Complex modulation devices
PSK	(Cochenour et al., 2007), (Sui et al., 2009), (Cox et al., 2011)	High receiver sensitivity	High implementation complexity High cost
QAM	(Cochenour et al., 2007)	High system spectral efficiency Better rejection on noise	High implementation complexity High cost
PolSK	(Cox et al., 2009), (Dong et al., 2013b), (Zhang et al., 2012)	High tolerance to underwater turbulence	Short transmission distance Low data rate
SIM	(Cox et al., 2011), (Cossu et al., 2013)	Increase system capacity Low cost	Complex modulation/demodulation devices and suffers from poor average power efficiency

OOK - On-Off Keying; PPM - Pulse Position Modulation; DPIM - Digital Pulse Interval Modulation; PSK - Phase-Shift Keying; QAM - Quadrature Amplitude Modulation; PolSK - Polarization Shift Keying; SIM - Subcarrier Intensity Modulation

Figure 1: Maixduino board.

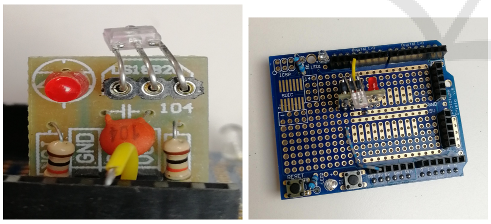

Figure 2: On the left, the photo-diode and his shield; on the right, the receiver's shield.

voltage range between 0V and 5V. More information can be found here[2].

3.2 Software Implementation

The main structure of the project is shown in (Figure 4).

A computer controls the first Arduino that sends messages using the laser to the second Arduino. This one, through a serial communication, sends back to the computer the information received via laser.

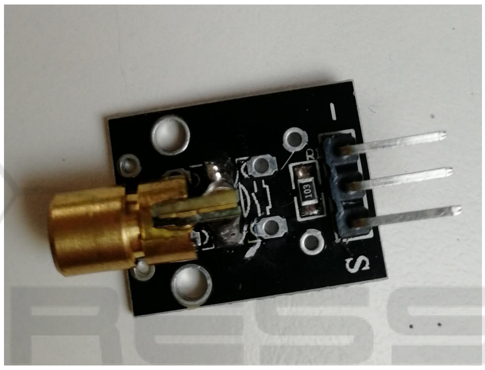

Figure 3: Laser.

More specifically, a Python script has been created to select an image from a dataset of size 100. Then, it sends the image to Arduino through a serial port. This Arduino unpacks the image and sends the information to a second Arduino. This last channel is managed via laser communication. The second Arduino has the task of sending the received data to the computer which analyses the final information.

3.2.1 Protocol

In this part we are going to describe specifically the protocols used in our prototype. For sake of simplicity we are going to refer to Figure 5.

- Firstly the transmitter and the receiver must synchronise;
- The transmitter wakes up the Python program;
- The laptop sends the size of the images that must be sent and waits for the same message to come back to check it, then sends the data;

[2]https://www.ebay.es/itm/EL0478-Modulo-Transmisor-LASER-5V-Rojo-650-nm-5mW-6mm-Diodo-Arduino/231695187553

Figure 4: This is the setup scheme.

- The Arduino 1 sends the number of bytes received to the laptop and then sends via VLC the type of the message, its size and finally the data;
- The Arduino 2 receives the information and, once the synchronisation with the laptop is done, sends to it all the information;

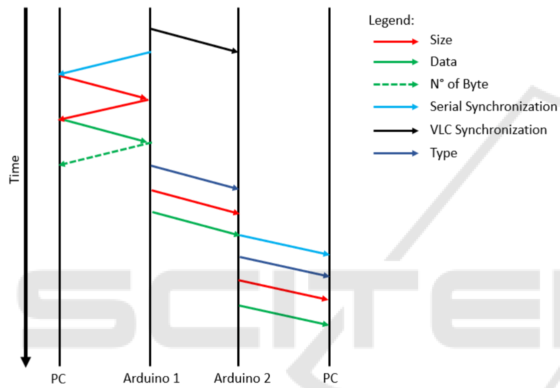

Figure 5: Protocol.

3.2.2 Morse

We used the Morse Code as method to encode the bit that must be sent via VLC. Specifically, we used only a fraction of the sample, given by the equation $sample = \frac{1}{frequency}$, to identify zeros or ones. So we used $sample \times 0.3$ to identify a zero, and $sample \times 0.7$ to identify a one. This choice allowed us to avoid many synchronisation problems but decreased the useful bandwidth.

4 EXPERIMENTAL SETUP

The following sections focus on the discussion, interpretation and evaluation of the results obtained through this study. The setup of the experiments can be seen in Figure 7: the laptop is connected to the Maixduino through a USB cable which sends via laser the information received; in the other side of the aluminium bar there is the second Maixduino which receives the information via laser and sends them to the laptop to check the data.

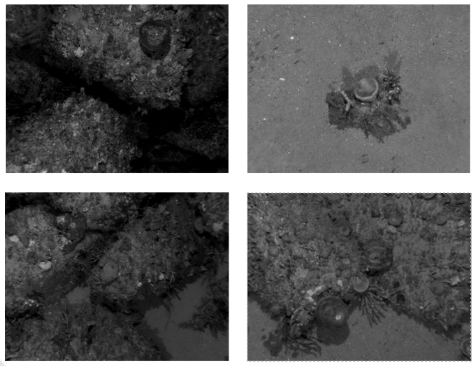

Figure 6: Four images taken by the dataset Scott Reef 25.

The data is composed of 100 images taken from the dataset Scott Reef 25[3] (Figure 6), compressed and resized to have different amount of Bytes. Finally they have been converted in `.txt` file. This process, useful for the data preparation, has been performed using a Matlab script. The experiments have been done in air and have been performed at four different distances, using the six different sizes of images (Table 2).

5 PRELIMINARY RESULTS

In this section we explain the results achieved through the experiments described above. Using this prototype we reached a frequency of communication via VLC of 2500 bit/s without losing big amount of data. The experiments have been conducted for six different cases, one for each size of the images, in which we varied the distance between the laser and the photodiode, as can be observed in Figure 2. It is possible to note that there are not significant differences between the results obtained through the six experiments conducted, meaning that the data received has not been compromised by a variation of the distance between the transmitter and the receiver. Moreover, it can be noticed that also the size of the message does not im-

[3]http://marine.acfr.usyd.edu.au/datasets/

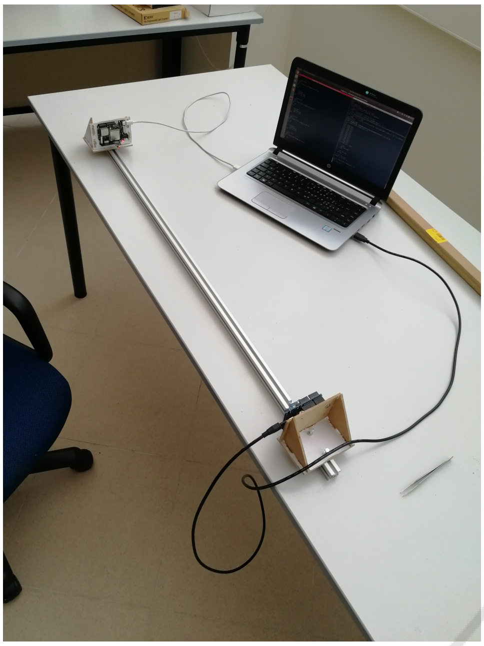

Figure 7: Experimental setup.

ply a loss of precision in the data received.

Another important consideration regards the time it took for the receiver to get the messages. Results about the time variation for each experiments are shown in Table 3: larger the size of the image, the longer it takes.

Table 2: Percentage of errors for each size of each image and distance (D).

Size (Bytes)	D = 0 cm	D = 25 cm	D = 50	D = 100 cm
588	0	0	0	1
884	0	1	0	1
1610	1	0	1	1
2255	0	0	0	0
3536	1	0	0	1
6279	0	1	1	0

Table 3: Time spent to send a dataset of 100 images.

Size per image (Bytes)	Total number of Bytes sent	Time Duration (s)	Bytes sent per second
588	59300	500	118.6
884	88900	605	146.9
1610	161500	871	185.4
2255	226000	1109	203.8
3536	354100	1580	224.1
6279	628400	2689	233.7

6 CONCLUSION

In this paper the study of Visual-Light Communication methods for future underwater robotic applications have been presented. In fact, the paper focuses mostly on the presentation of the state of the art, considering that wireless underwater communications need to be faced in a multimodal way. For example, for long distances in open sea sonar is preferred, while short distances can be faced via radio-frequency links, which give constant time-delays, and laser-based Visual-Light Communications under good visibility conditions.

Moreover, the paper shows a simple low-cost method to implement a VLC system, which still needs improvement in order to provide remote visual feedback. Further work will be focused on improving the communication protocol in order to maintain the reliability of the the system while obtaining greater bandwidth for the transmission of real-time underwater images.

6.1 Further Steps in Underwater and Radioactive Scenarios

In order to improve this system and apply it in underwater scenarios it would be necessary to use a more powerful laser, usually in the green band which, for security reasons, must only be used inside the water, confined in a sealed cylinder. The IRS Lab at UJI have used similar lasers for underwater experiments before, specially to create 3D maps from vision.

Also, for radioactive scenarios, the sealing is also required in order to avoid the radioactive dust to get into the electronics. These scenarios can use laser in the red band for short distances.

In both cases it is mandatory to assure the alignment of the transmitter and receiver, so they have to be mounted in a motorised pan-tilt device.

Further experiments will focus on this direction.

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