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Design and Development of Visible Light Communication-based Underwater Communication System for Recreational Scuba Diving

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ABSTRACT

Visible light communication (VLC) is a type of data communications which uses the visible light spectrum in the 350-800nm wavelength range. Light signals are converted into electrical pulses to indicate a specific information which in this case, diving instructions. In this study, VLC is used in an underwater communication system for recreational diving activities in order to reinforce the conventional hand signaling protocols. Wearable LED-based transmitter and phototransistor-based receiver were used. The hand-held transmitter was used to emit different light pulses corresponding to 16 commands in which 13 are standard scuba diving hand signals. The goggle receiver process and translates these pulses into an audio signal which can be heard by the diver through waterproof earphones. The VLC system developed was able to achieve an average signal reception accuracy of at least 97.0% on a series of tests conducted underwater with a maximum transmitter-to-receiver distance of 5m using white LEDs.

Key words: Visible light communication, light emitting diodes, light pulses, underwater, scuba diving

1. INTRODUCTION

Visible light is the portion of the electromagnetic spectrum seen by the human eye. A typical human eye can respond to wavelengths from 380nm to 750nm which has an equivalent frequency of 790THz - 400THz. This spectrum consists of the basic colors Magenta, Red, Red Orange, Orange, Yellow Orange, Yellow, Green Yellow, Green, Cyan, Blue, Blue Violet, and Violet [1]. Visible light has been a research interest in the development of underwater visible light communication systems which are used for tourism and in the protection of under the ocean conditions in the Okinawa Region, a popular Diving spot in Japan [2]. Light emitting diodes (LED) are commonly utilized as light sources as they offer a number of potential advantages over conventional lighting technologies taking the lead in low power consumption. LED light beam can project up to a maximum of 20m. More than this, its luminous energy will be scattered away [3].

Recreational scuba diving or sports diving is a professional underwater that requires skills and familiarity with the usage of scuba diving equipment. This also requires a high level of training and a certain number or hours of diving experience in order to be aware of the different hazards and conditions associated on how it is conducted. Divers Alert Network (DAN) is the largest diving industry association that focuses on scuba diving safety. In 2015, DAN reported 127 scuba diving fatalities around the world and most of these cases are due to the loss of communication between the divers or between the lead and the distress diver [4]. The conventional way of communication in recreational diving is through the Recreational Scuba Training Council (RSTC) approved hand signals which can be flawed when panic and low visibility situation occur under water [5]. With this, an alternative method of communication is proposed by this study. The channels used for underwater wireless communication may differ as compared to those used in radio and tv broadcast [6]. Unused frequencies in this spectrum may not be useful due to underwater wave behavior like diffraction, Doppler Shifts and spreads to name a few. Communication under water is usually through ultrasonic communication but has not been deployed in recreational diving. Ultrasonic waves experience noise due to the water surface reflections and this is not easy to use since this mode of communication could confuse divers in identifying the speaker when there are several divers are present in the same area [2].

This study presents a developmental design of a visible light communication (VLC) system for recreational diving by integrating electronic communication devices as part of scuba diving equipment. This could give divers not just a flexible bidirectional communication system but also an alternative mean of relaying information underwater.

2. METHODS

As in a typical communication system, the proposed VLC system is composed of a transmitter and a receiver equipped with transmission and reception protocols. Standard hand signals are assigned in keypad buttons which when pressed, transmits unique light patterns for the receiver to decode [7]. The transmitter light source is a specialized flashlight with a parabolic reflector that creates a narrow beam. Figure 1 shows the radiation pattern of the light source. It shows the high directivity of the light source. Not only that the parabolic reflector allows focused light beam, it is also equipped with three LEDs for higher and farther illumination. The LEDs are part of the transmitter electronics and sealed properly for waterproofing requirements. Information were sent using pulsating light signals that travel in water. This was done using On-Off Keying (OOK) modulation technique where the LEDs are turned on or off according to the bit representation of the equivalent character sent. The ASCII code for each keypad symbol was used as a bit string identifier of the diving instruction assigned to it. The said bit string is encapsulated into a frame and the bits are sent to the LED driver circuit to control LED switching at a rate of 4kbps. On the receiving end, the receiver module is integrated into a standard scuba diving goggle equipment housed in a GoPro casing. The GoPro casing provides the necessary waterproofing requirements for the electronic parts. The waterproof earphones are operated by the receiver module that utilizes a specialized audio player circuit board. The decoded light patterns were converted to audio signals that correspond to a command or a diving instruction. The audio player is equipped with a storage memory circuit that contains the set of audio signals to be played through the earphones. The process of playing the audio files is quick as early as light signals are received by the sensors of the receiver. The sensors used for the receiver are also spread along the goggles' strap which faces four major directions relative to the user's head: front, right, back and left. This means that it is possible to communicate with each other even if the receiving user is not looking directly to the transmitting user. The distance between the transmitter and receiver was considered as well as the water depth where the communication took place. Initial tests were done in a swimming pool for prototyping and calibration.

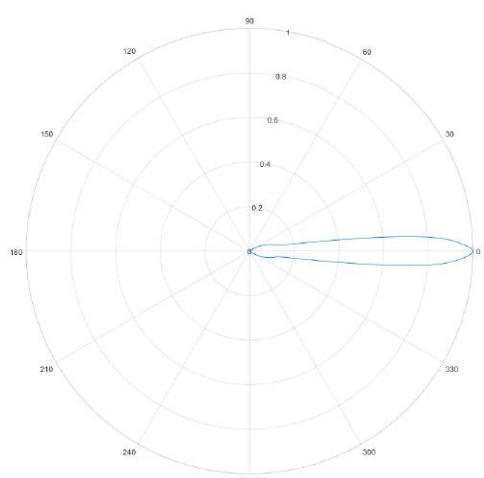

Figure 1: Light Transmitter Radiation Pattern

2.1 System Overview

The VLC system, as shown in Figure 2, is composed of a transmitter and a receiver equipped with separate power sources, I/O devices, drivers and controllers. The transmitter sends pre-programmed light signals that correspond to the diving instructions. The pulsating light signals will travel in water and will be received by the receiver at a maximum distance of 5m. Noise and interference are expected and are dealt by a set of filter gates. The light signals received will be decoded and converted into audio signals which the diver can hear using waterproof earphones.

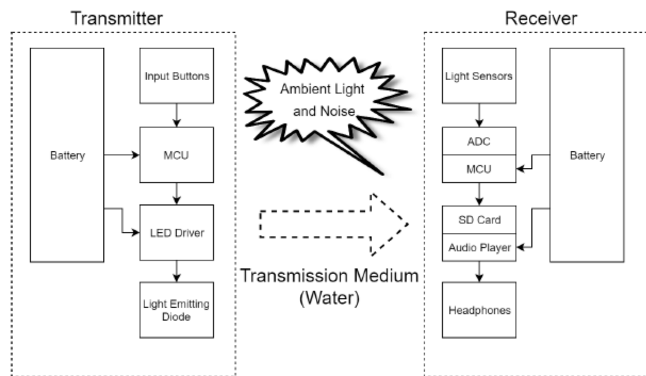

Figure 2: VLC system transmitter and receiver

2.2 VLC Transmitter

The transmitter is composed of a 4x4 matrix keypad, Arduino-nano microcontroller, TIP3055 LED driver transistor, 3 white LEDs with a parabolic reflector, DC - DC boost converter as its voltage regulator, an ACS720T current sensor, two 3.7V lithium ion 3000 mAh batteries, and a TP4056 lithium battery charger circuit. These components were integrated together and attached in a typical scuba diving hand strap as shown in Figure 3. The 4-by-4 matrix keypad is utilized to provide 16 buttons for different instructions as shown in Figure 4. The goggle receiver, as shown in Figure 5, is composed of four 3DU5C phototransistors for detecting the light coming from the transmitter. The STM32F103C8T6 microcontroller performs decoding conversion of pulses to audio signals which are played through the waterproof earphones.

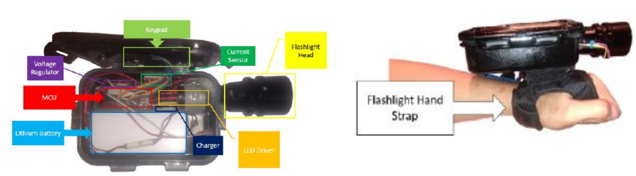

Figure 3: Hand-held VLC Transmitter

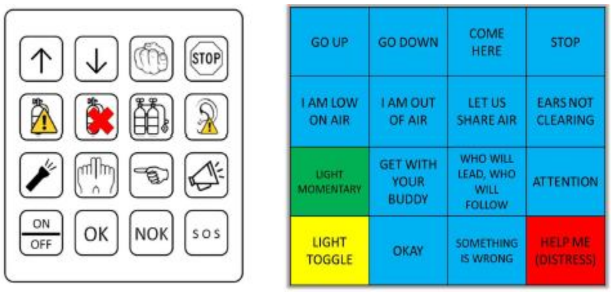

Figure 4: Keypad Configuration

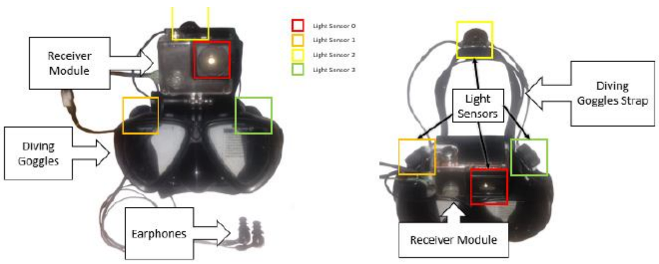

Figure 5: VLC Goggle Receiver

2.3 VLC Receiver

The receiver circuit uses a flat-square type lithium-ion battery as its power source. A DC-DC boost converter is used to provide $5V_{dc}$ for the microcontroller. Four phototransistors were used positioned in-front, rear, right and left sides of the goggles. The views are shown in Figure 6. A simple circuitry for power buttons is wired to allow the user to switch the receiver on or off. The MP3 player installed is for playing the audio files in the SD card attached at its back. The microcontroller connects to the earphones wherein the diving instructions are played.

Figure 6: Four views of the VLR Goggle Receiver

For the communication protocol, a 16-bit or 2-byte frame was used to transmit signal information using 0's and 1's. The first 8 bits represent the preamble data (0101) and the address data (0101) that allows the receiver to distinguish between the signal containing the actual transmission and noise. The next 8 bits contain the character that the user intends to transmit. The frame time is 4 ms and for as long as the user is pressing a button specified for transmission, the frame will be repeated every 5 ms. Figure 7 shows a sample bit frame of transmitting an "OK" message to the receiver. Data bits for this are 0101010100001100.

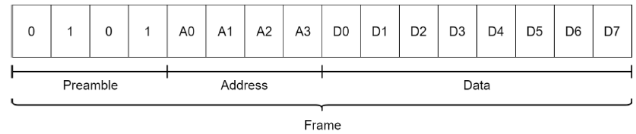

Figure 7: Communication Bit Frame

3. RESULTS AND DISCUSSION

The binary bits are transmitted in terms of voltage highs and lows. The minimum value is 0V while the maximum value is around 3.7V. Data transmission is using a white LED at 4kbps data rate. A sample of this signal is shown in Figure 8 that corresponds to a "Help Me (Distress)" message.

Figure 8: Transmitter Signal Waveform (for diving instruction "Help Me (Distress)")

The diving hand instructions were given a unique 8-bit binary code with their specific voltage, current and power measures as shown in Table 1. These quantities were obtained in order to monitor how long the device will last under water while doing the diving activity.

Table 1: Diving instruction button assignment, binary code and quantities

ID	Instruction	Binary Code	Voltage (V)	Curren t (A)	Power (W)
1	Go up	00110001	2.7	0.5	1.4
2	Go down	00110010	2.7	0.6	1.6
3	Come here	00110011	2.8	0.6	1.6
A	Stop	01000001	2.6	0.6	1.5
4	Low in air	00110100	2.7	0.6	1.7
5	Out of air	00110101	2.8	0.6	1.7
6	Share air	00110110	2.8	0.7	1.8
B	Ear/s not clearing	01000010	2.6	0.6	1.4
7	Light On momentarily	11111111	3.5	1.0	3.6
8	Go with your buddy	00111000	2.7	0.6	1.5
9	Who will lead, who will follow	00111001	2.8	0.6	1.7

C	Call attention	01000011	2.7	0.6	1.5
*	Light On Hold	11111111	3.5	1	3.6
0	Ok	00110000	2.6	0.5	1.4
#	Something is wrong	00100011	2.7	0.6	1.6
D	Distress	01000100	2.6	0.5	1.3
-	Flashlight off	00000000	1.7	0.0	0.0

The electric quantities are stable at their usual values except when Button 7 and Button * are pressed. These buttons correspond to flashlight functions which draw more power from the energy source. It is also noticeable that they have similar binary code as seen in Table 1. They just differ in terms of how long the buttons were pressed. Figure 9 shows the voltage, current and power levels when each button is pressed. Higher values are obtained when flashlight functions were used as more power were needed to energize the LEDs.

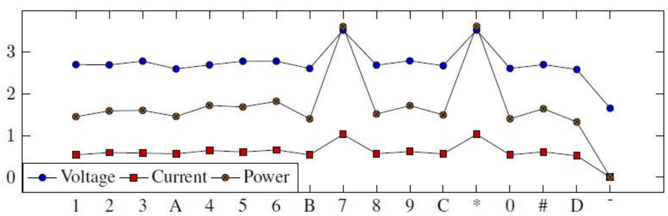

Figure 9: Voltage, Current and Power Quantities

At the receiver side, the signal received is reconstructed in order to fit the signal structure required by the audio converter. This is done by utilizing an analog-to-digital converter which converts the analog light signals into its digital counterpart. The sampling rate used was 100kHz for 10 ms. This corresponds to 1000 samples per unit of time at the light sensor receivers. The weak signals were amplified with a signal amplification gain calculated based on the average peak-to-peak voltage quantities. Bit transition occurs whenever there is a high rate of change in the voltage signal in the raw data. The adjacent samples are compared, and the difference was taken to determine the rate of change. The resulting waveform shows spikes indicating the boundaries of bits. An upward spike indicates a transition from 0 to 1 and a downward spike indicates a transition from 1 to 0. Upper and lower thresholds were set for the original digital signal to be reconstructed. Figure 10 shows the raw signal and the reconstructed signal of Button D.

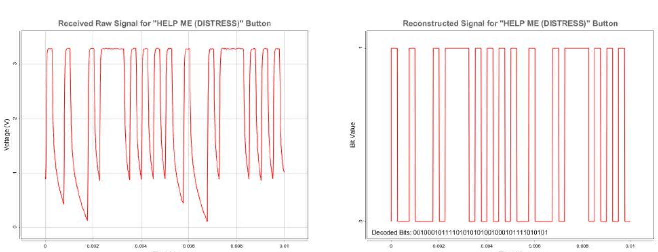

Figure 10: Received Raw and Reconstructed Signal

The accuracy of the signal received at the receiver's end were obtained by testing if the sensors are receiving the correct code for each diving instruction. The distances of transmission considered were 1m, 3m, and 5m at a water depth of 152.5 cm. Results are shown in Table 2. Accuracy is high at distances closer to the source and decreases as it goes farther away which complies with the basic concept similar to the inverse square law [8] and the path loss as waves propagate in communication channels [9].

Table 2: VLC Communication Accuracy

Distance (m)	Accuracy				
	Sensor 1	Sensor 2	Sensor 3	Sensor 4	Mean
1	100%	100%	100%	100%	100%
3	100%	100%	100%	100%	100%
5	96.86%	96.86%	97.65%	96.67%	97.01 %

The accuracy of the receiver was also tested beyond the 5-meter mark from the transmitter to possibly determine how far the transmission can still be more than 80% accurate. The reception diagram is illustrated in Figure 11. The diamonds in the red box are the direct test points. To address the tilting or indirect locations under water, other angles were considered with a 1-meter allowance at the sides. Tests were done at a deviation of 0.5m and 1m from the centerline. The tabulated accuracy is shown in Table 3. As the receiver module moves away from the transmitter while keeping it at the beam centerline, the accuracy drops to about 36.8% at the 8-meter mark. At an assumed 80% acceptable accuracy, results show that the acceptable distance is 7m along the centerline, and 3 to 5m when the receiver is 0.5m from the sides of the centerline. The 2-meter mark is acceptable both sides at 1m away from the centerline. Coming too close at the 1-meter mark between the transmitter and receiver makes it behave like the 3 to 5m mark. This positionings are important for the divers to know how far they should be from the source of the diving instructions.

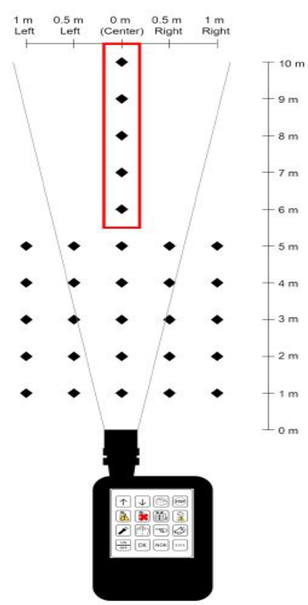

Figure 11: Transmitter Set-up for Tilting Reception

Table 3: Receiver Accuracy from the Centerline

Distance (m)	1m Left	0.5m Left	Centerline	0.5m Right	1m Right
10	-	-	17.7%	-	-
9	-	-	17.7%	-	-
8	-	-	36.8%	-	-
7	-	-	80.9%	-	-
6	-	-	87.1%	-	-
5	52.7%	87.6%	97.0%	86.9%	51.8%
4	65.3%	87.5%	98.8%	86.6%	65.9%
3	78.3%	86.0%	99.8%	87.0%	79.1%
2	81.3%	86.7%	99.8%	85.7%	80.0%
1	17.7%	87.7%	99.9%	86.4%	17.7%

4. CONCLUSION

A VLC system for recreational diving was designed which incorporates the standard diving instructions as a complementary communication method for divers while they are under water. A transmission accuracy level of at least 97% using white LEDs was obtained at a transmission rate of 4 kbps reaching a 5-meter distance mark. Transmission accuracies vary with respect to locations thus, it is important for divers to be aware of the features and capabilities of this proposed equipment.

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