

Li-Fi Based Autonomous Underwater Vehicle with Integrated Optical Communication and Obstacle detection

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Abstract— Underwater communication remains a significant challenge due to the severe attenuation of radio frequency signals in water. This paper presents the design and implementation of a compact underwater obstacle detection and real-time image transmission system using laser-based Light Fidelity (Li-Fi) technology. The proposed system employs a Raspberry Pi Pico microcontroller to coordinate obstacle detection, optical modulation, and signal processing. A laser-based reflection mechanism is utilized to detect obstacles within short range underwater environments. Upon detection, an image of the obstacle is captured and enhanced using contrast improvement and edge enhancement techniques to improve visibility under low-light and scattering conditions. The processed image is resized and converted into binary format for efficient transmission. The binary data modulates a laser diode, where ON-OFF keying represents digital '1' and '0' states, enabling optical wireless communication through the water medium. At the base station, a photodiode coupled with an amplification circuit detects the modulated laser pulses and reconstructs the transmitted image. The received image is displayed on an embedded LCD and a PC interface for monitoring purposes. Experimental evaluation in controlled water conditions demonstrates reliable short-range data transmission with improved image clarity through enhancement techniques. The proposed system offers a low-cost, energy-efficient, and scalable solution for underwater robotics, vessel monitoring, marine inspection, and surveillance applications, providing an alternative to conventional acoustic or wired underwater communication systems.

Index Terms- Autonomous Underwater Vehicle (AUV), On-Off Keying (OOK), laser Li-Fi, radio frequency (RF)

1. INTRODUCTION

The need for this project arises from the growing limitations of traditional underwater communication methods in supporting modern Autonomous Underwater Vehicle (AUV) operations. As underwater missions demand faster data transmission, real-time control, and safe environmental interaction, conventional acoustic and RF-based systems fall short due to slow speeds, high latency, distortion, and limited signal penetration. Acoustic signals are not only slow but also disruptive to marine life, while RF waves are largely ineffective in water. Therefore, a faster, safer, and more efficient alternative is essential. Li-Fi technology, which uses visible light for data transmission, meets these requirements by offering high-speed, low-latency, and secure communication. This makes it a highly suitable and necessary solution for evolving underwater applications such as marine research, defense operations, and real-time image or sensor data transfer, where reliability and performance are critical.

Conventional underwater communication systems primarily rely on acoustic waves or radio frequency (RF) signals to transfer data between underwater devices. Acoustic communication is widely used due to its ability to propagate over long distances in water. However, it suffers from several drawbacks including low data transmission speed, high latency, and susceptibility to environmental noise and distortion. Additionally, acoustic signals can be harmful to marine life, disrupting their natural behavior and habitats. RF communication, while effective in air, faces severe attenuation in underwater environments, especially in saltwater, limiting its effective range and making it

unsuitable for real-time or high-volume data transfer. These limitations highlight the need for a more efficient, high-speed, and environmentally safe alternative, which is addressed by Li-Fi-based optical communication systems.

II. LITERATURE SURVEY

Recent progress in underwater wireless communication and Visible Light Communication (VLC) has made data transmission in water more efficient. Researchers have studied Li-Fi technology, MAC protocols, and optimization methods to boost reliability and system performance. In the study [1] various MAC protocols has been analyzed and designed for Underwater Wireless Sensor Networks (UWSNs) and highlighted challenges such as high propagation delay, limited bandwidth, and energy constraints. This study, emphasized the need for efficient channel access mechanisms to improve network throughput and reliability. The paper [2], explored how Li-Fi could be used for high-speed data communication. The results showed that visible light communication offers secure, high-bandwidth transmission, making it a good choice for short-range systems.

The paper [3] proposed a practical system for sending digital information with LEDs. The experiments showed that Li-Fi can provide reliable communication with little interference, which is helpful where radio frequency communication does not work well. The work [4] focused on underwater optical communication system model using visible light for underwater data transmission and showed it could achieve better data rates than traditional acoustic systems. The study on Image Transmission Technique using Low-Cost Li-Fi Test Bed [5] presented a low-cost setup for sending images with Li-Fi. The results showed that the system could transmit multimedia data like images with very few errors when lighting conditions were controlled. Another study [6], showed a VLC-based system that can send both text and images. The system used LEDs to transmit and photodiodes to receive data, proving that visible light is an effective way to communicate. Further experimentation was carried out in the work on Image Transfer using NI-USRP [7] where a software-defined radio platform was implemented to transmit image data. In this work, the flexibility of NI-USRP-based communication systems for testing and validating digital communication algorithms was highlighted. Besides communication systems, researchers have used optimization techniques to improve data processing. The paper [8] suggested a pre-processing method to handle imbalanced datasets. This approach improved classification by balancing the data with particle swarm optimization

. In research work [9] hybrid communication systems combining satellite and underwater communication technologies was analysed. In this work, the results indicated that integrating satellite links can significantly improve communication reliability in underwater environments. In autonomous marine systems, the paper [9] illustrates how swarm intelligence can help coordinate multiple unmanned surface vehicles. Here the swarm-based algorithms were used to improve cooperative search, navigation, and mission tasks in marine settings. These studies summarizes that Li-Fi and visible light communication are promising for underwater data transmission. Using optimization algorithms, hybrid systems, and autonomous marine platforms can make underwater networks more efficient and reliable. Still, issues like water turbidity, light loss, and alignment need more research.

Recent studies[11][12][13] have sought to make underwater visible-light communication systems more reliable and efficient. Researchers have suggested using intelligent reflecting surfaces to boost signal strength and increase communication range underwater[14]. Real-time UWOC systems [15][16] that use LED transmitters have demonstrated they can reliably send data with a wider modulation bandwidth. Other new methods [17][18], such as compressed sensing for channel estimation, beam tracking, and adaptive communication frameworks, help mitigate problems caused by underwater channels. High-speed optical

systems[19][20] using DWDM technology have also reached multi-gigabit data rates, which makes visible light communication a strong option for future Internet of Underwater Things (IoUT) applications.

III. MOTIVATION

The motivation behind this work stems from the critical need for high-speed, reliable, and secure underwater communication in autonomous underwater vehicles (AUVs), where traditional RF and acoustic methods face significant limitations. RF signals suffer extreme attenuation in water, while acoustic systems have low bandwidth and high latency. Li-Fi, using visible light, offers a promising alternative by enabling higher data rates and minimal latency. This research is driven by the objective to develop a robust Li-Fi system capable of real-time data exchange, such as image transmission, for enhanced underwater exploration, surveillance, and navigation in complex aquatic environments.

IV. STATEMENT OF CONTRIBUTION

The problem domain lies in the development of efficient underwater wireless communication systems for Autonomous Underwater Vehicles (AUVs), where conventional technologies such as radio frequency and acoustic communication exhibit major limitations. RF signals are severely attenuated in water, especially in saline environments, restricting their usability. Acoustic communication, while commonly used, suffers from low bandwidth, high latency, and vulnerability to multipath distortion and ambient noise. These limitations hinder real-time, high-speed data transmission, particularly for applications requiring image or video transfer. This creates a critical need for alternative communication modalities such as Li-Fi, which leverages the high bandwidth and low latency characteristics of visible light.

Autonomous Underwater Vehicles (AUVs) require efficient, high-speed wireless communication systems to support real-time data transmission for tasks such as imaging, monitoring, and navigation. Traditional methods, including acoustic and radio frequency (RF) communication, face significant limitations underwater due to low bandwidth, high latency, and severe signal attenuation. This work addresses the problem of developing a Li-Fi based underwater communication system capable of achieving reliable, low-latency, and high-throughput data transfer. Key challenges include managing light absorption and scattering in water, maintaining line-of-sight alignment, minimizing noise from ambient light sources, and optimizing power efficiency within the AUV's constraints.

This research presents the development of an optical wireless communication system using Li-Fi technology for Autonomous Underwater Vehicles (AUVs). By replacing conventional acoustic and RF methods, this system utilizes visible light to enable high-bandwidth, real-time data exchange. The solution incorporates dynamic modulation techniques, robust alignment mechanisms, and low-power embedded processing for effective operation in underwater conditions. It aims to enhance data integrity, reduce latency, and support reliable image and sensor information transfer, improving underwater navigation, exploration, and monitoring capabilities. An innovative enhancement introduced in this work is the integration of image preprocessing and postprocessing techniques within the Li-Fi communication framework. Prior to transmission, images are subjected to preprocessing steps such as grayscale conversion, contrast enhancement, and noise reduction to optimize them for bandwidth-constrained optical channels. On the receiving end, postprocessing techniques including error correction, image reconstruction, and edge sharpening are employed to recover and enhance the visual clarity of transmitted images affected by underwater distortions. This end-to-end optimization significantly improves the quality, reliability, and efficiency of real-time image transmission in

underwater environments, setting this system apart from conventional Li-Fi implementations.

V. METHODOLOGIES

A. Design Methodology

The proposed system implements a Li-Fi-based communication framework for an Autonomous Underwater Vehicle (AUV), designed to capture, process, and transmit visual data wirelessly using light. The complete process is divided into two major sections: the transmitter unit and the receiver unit. Fig.1 shows the work flow for the proposed model .

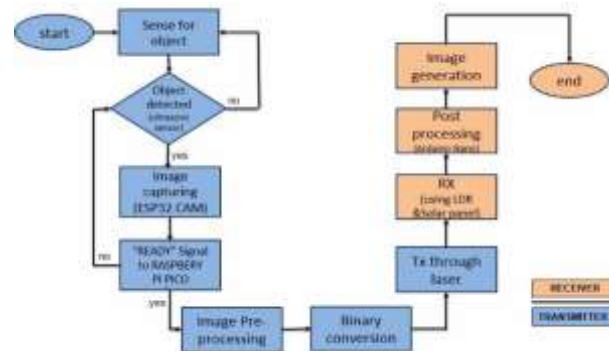


Fig. 1 Workflow for the proposed Li-Fi based Autonomous Underwater Vehicle
Step 1: Obstacle Detection

- 1) The ultrasonic sensor is responsible for detecting obstacles in the underwater environment. When the sensor detects an obstacle, it sends a signal to the ESP32-CAM module via a General Purpose Input/Output (GPIO) pin.
- 2) The ultrasonic sensor measures the time it takes for sound waves to bounce back after hitting an obstacle, which helps the system determine the distance to the object as shown in fig 2.

Step 2: Image Capture

- 1) Upon receiving the signal from the ultrasonic sensor, the ESP32-CAM captures an image of the detected obstacle
- 2) The captured image is saved on the SD card attached to the ESP32-CAM. This image is stored temporarily for further processing.

Step 3: Image Preprocessing and Binary Conversion

- 1) The Raspberry Pi Pico accesses the image stored on the SD card.
- 2) The Pico then performs preprocessing steps, such as grayscale conversion (to simplify the image) and resizing (to reduce the image size for easier transmission).
- 3) Once the image is processed, the Pico converts the image into binary data, representing the image as a series of 1s and 0s.

Step 4: Data Transmission via Laser

- 1) The Raspberry Pi Pico uses a laser diode to modulate the binary data onto light.
- 2) The Pico controls the laser by turning it on and off, with each state corresponding to a "1" or "0" in the binary data. This modulation creates a laser beam that transmits the data from the sender to the receiver
- 3) The laser is used for point-to-point communication, making it suitable for short-range underwater transmission. The system relies on clear line-of-sight between the transmitter and receiver for successful data transmission.



***Fig. 2 Li-Fi based Autonomous Underwater Vehicle Transmitter Unit
Step 5: Data Reception and Processing***

- 1) On the receiver side, the LDR (Light Dependent Resistor) detects the modulated laser signal. The LDR senses the intensity of the light, which varies based on whether the laser is on or off, thus capturing the binary data.
- 2) The Arduino Nano processes the signal from the LDR, converting the changes in light intensity back into binary data described in fig.3.
- 3) The Arduino Nano decodes the binary data, reconstructing the original image or information that was transmitted.

Step 6: Data Output

- 1) Once the data is decoded by the Arduino Nano, it can be used for various purposes, such as displaying the reconstructed image on a screen or using the data for further processing or decision-making in the underwater environment



Fig. 3 Li-Fi Enabled Autonomous Underwater Vehicle Tranceiver unit

B. MATLAB Simulation

In underwater optical communication, several physical phenomena critically influence signal transmission. The most significant among these are absorption and scattering, which together contribute to attenuation—the reduction of light intensity as it travels through water. Absorption refers to the conversion of optical energy into heat, primarily influenced by the water's molecular structure and dissolved substances. Scattering, on the other hand, occurs when light is deflected by particles or suspended matter in the water, leading to loss of signal direction and intensity.

As attenuation increases with distance, the SNR drops, resulting in lower image quality and potential data loss. Accurately modeling these phenomena is essential for simulating and optimizing underwater Li-Fi systems using MATLAB.

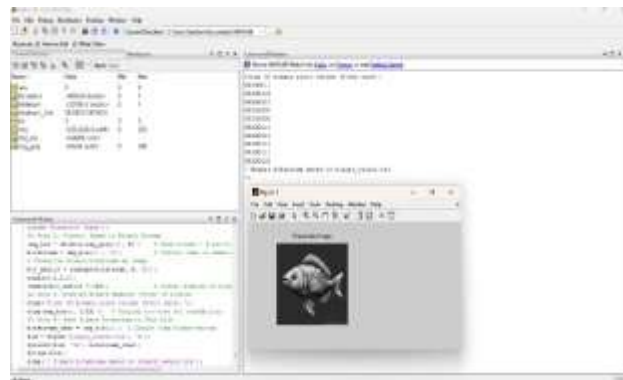


Fig. 4 Implementation of Binary Image Conversion Using MATLAB

This MATLAB simulation explores how images can be transmitted underwater using optical signals, taking into account real- world challenges like absorption, scattering, and noise in different water types. The process starts with a grayscale version of a 64×64 image, which is converted into a binary stream shown in fig.4—just like how actual digital data would be transmitted through light in an underwater environment. The simulation examines three kinds of water: Pure Water, Ocean Water, and Dusty Water. Each has its own absorption and scattering characteristics—Pure Water causes the least signal loss (0.1 dB/m and 0.05 dB/m), while Dusty Water has the highest loss (1.0 dB/m and 0.8 dB/m) as shown in table 1 & 2. These values reflect how much the water "absorbs" or "scatters" the light carrying the data, depending on the environment and distance.

To make the model more realistic, random noise is added to the signal—mimicking what happens in nature as light travels farther through murky or turbulent water. The received signal is then cleaned up using a threshold to regenerate the binary data, which is converted back into an image. The simulation also calculates the Signal-to-Noise Ratio (SNR) to see how much the image quality has been affected at each water type and distance. Side-by-side comparisons of the original and received images show how clarity drops depending on the environment: Pure Water maintains good quality, Ocean Water introduces moderate blur, and Dusty Water significantly degrades the image. Histograms are also used to compare how the pixel values shift, giving insight into contrast loss and signal distortion. Overall, the simulation shown in fig. 5 and 6 describes how underwater optical image transmission is affected by different environmental conditions. It demonstrates that while optical communication works well in clear water, murky or dusty environments present serious challenges.

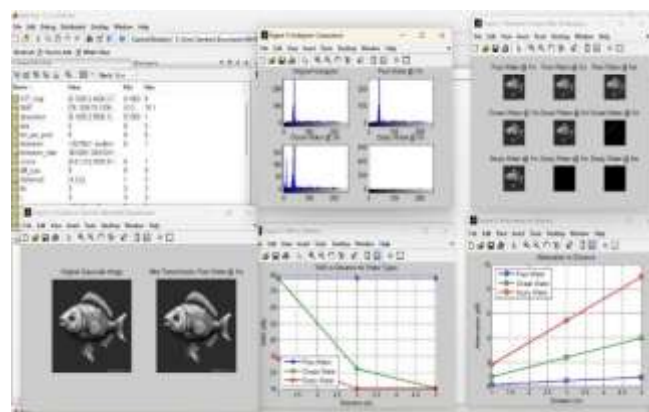
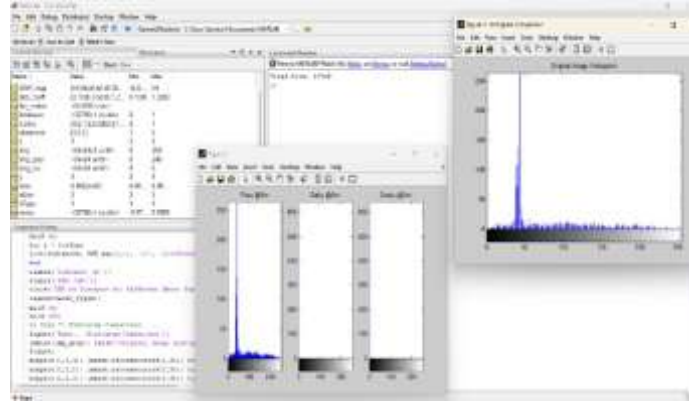


Fig. 5 Histogram-Based Analysis of Underwater Signal Variation Using MATLAB**Fig. 6 Histogram Analysis of Signal Distribution**

As an image travels farther underwater, it becomes less clear because water absorbs and scatters light. This effect increases with distance. In the simulation shown in fig.9, both image quality and SNR (Signal-to-Noise Ratio) decline as the distance increases. This demonstrates why underwater optical systems often require additional support, such as signal boosters, advanced correction techniques, or more powerful light sources, to maintain signal strength over long distances.

VI. RESULTS AND DISCUSSION

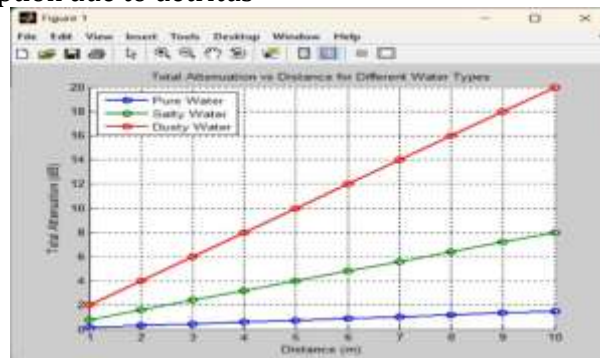
A. SYSTEM OPERATION IN UNDERWATER ENVIRONMENT

(a) Attenuation coefficient

$$c(\lambda) = a(\lambda) + b(\lambda) \quad (1)$$

$$a(\lambda) = a_w(\lambda) + a_{CDOM}(\lambda) + a_{phy}(\lambda) + a_{det}(\lambda) \quad (2)$$

where, $a_w(\lambda)$ represents absorption due to pure seawater, $a_{CDOM}(\lambda)$ represents absorption due to CDOM, $a_{phy}(\lambda)$ represents absorption due to phytoplankton and $a_{det}(\lambda)$ be the absorption due to detritus

**Fig. 7 MATLAB Simulation of Total Attenuation vs Distance in Underwater Environment****Table. 1 Absorption and Scattering Coefficients for Various Water Types**

Water Type	Absorption (dB/m)	Scattering (dB/m)	Total Coefficient
Pure Water	0.1	0.05	0.15
Salty Water	0.5	0.3	0.8

Dusty Water	1.2	0.8	2.0
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The attenuation of optical signals in underwater communication is determined by the absorption and scattering properties of water. Clear ocean water exhibits minimal absorption and scattering, resulting in a low total attenuation coefficient and enabling extended communication distances. In contrast, coastal and turbid harbour waters contain higher concentrations of suspended particles, which increase both scattering and absorption, leading to greater total attenuation and a reduced transmission range as depicted in fig. 7 and 8. The total attenuation coefficient, defined as the sum of the absorption and scattering coefficients serves as a critical parameter for modelling and designing underwater visible light communication (UVLC) systems.

(b) Scattering coefficient

$$b(\lambda) = b_w(\lambda) + b_{phy}(\lambda) + b_{det}(\lambda) \quad (3)$$

where, $b_w(\lambda)$ denotes scattering due to pure seawater, $b_{phy}(\lambda)$ represents scattering due to phytoplankton and $b_{det}(\lambda)$ represents scattering due to detritus

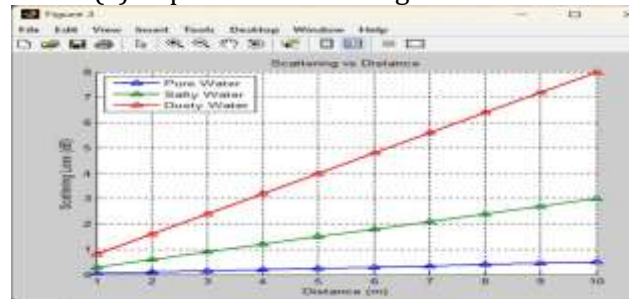


Fig. 8 MATLAB Simulation of Scattering vs Distance

Table.2 Absorption and Scattering Coefficients for Various Water Types

Distance (m)	Pure Water (0.05)	Salty Water (0.3)	Dusty Water (0.8)
1	0.05	0.3	0.8
5	0.25	1.5	4.0
10	0.5	3.0	8.0

(c) Signal-to-Noise Ratio (SNR)

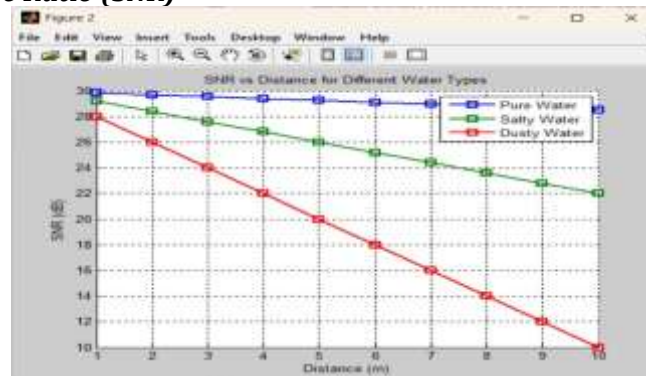


Fig. 9 Matlab plot for SNR vs Distance

The system was tested under controlled underwater conditions and demonstrated reliable performance for short-range line-of-sight communication. Image data was transmitted efficiently, and reception was validated using both embedded displays and computer interfaces. The project design emphasized low cost, compact form factor, and ease of replication making it accessible for educational, industrial, and exploratory applications.

VII. COMPARISON OF RESULTS

Compared to referenced systems that rely heavily on tethered communication or acoustic modems with limited bandwidth and high latency, our Li-Fi based AUV offers a lightweight and low-latency alternative suitable for short-range, high-speed underwater data exchange. The system efficiently handled dynamic underwater scenarios with minimal preprocessing, as evidenced by the successful transmission and reconstruction of object images using laser-based communication. The use of optical components such as an LDR and solar panel for reception demonstrates an innovative yet cost-effective approach to underwater signaling. These results validate the feasibility of using Li-Fi for real-time visual data sharing in submerged environments, offering a scalable solution for exploratory, surveillance, and environmental monitoring applications. Furthermore, the simplified architecture enhances deployability in resource-limited settings, supporting the goal of building an intelligent, compact, and affordable underwater communication platform.

VIII. CONCLUSION

The performance of the system was evaluated based on its ability to detect obstacles, capture and process images, transmit binary data using laser light, and accurately decode the transmitted information at the receiver end. Various experiments were conducted to verify the functionality of each module, including the ESP32-CAM, Raspberry Pi Pico, laser diode transmitter, and the receiver system built with an LDR and Arduino Nano. The results demonstrate the efficiency of the Li-Fi system in transmitting image data over a short distance underwater, with successful real-time obstacle detection and image reconstruction. The following sections detail the outcomes of these experiments, supported by observations, transmitted images, decoding accuracy, and transmission speed, confirming the practical viability of the proposed underwater communication approach.

IX. FUTURE WORK

To enhance the capabilities and reliability of the current Li-Fi based Autonomous Underwater Vehicle (AUV) system, several future improvements are proposed. First, incorporating adaptive beam tracking would enable real-time laser alignment, compensating for movement caused by underwater currents or vehicle dynamics. This would ensure stable communication despite physical displacement. Second, the integration of robust error correction algorithms, such as Forward Error Correction (FEC), can significantly improve data reliability by enabling the system to recover lost or corrupted bits without the need for retransmission. Third, systematic range and depth testing in diverse aquatic environments—including murky and saline waters—would provide critical performance benchmarks and insights into system limitations. Lastly, by integrating the communication module with autonomous navigation systems driven by AI, the AUV can make real-time decisions and execute tasks based on transmitted commands or sensor feedback, moving toward greater operational independence and intelligence.

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