Implementing Underwater OpticalWireless Communication Using Visble Light LEDs: A Practical Prototype Approach

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Abstract:- This paper presents the design and experimental demonstration of a prototype underwater optical wireless communication (UOWC) system using visible light in the blue and green spectra. The transmitter employs an Arduino to encode and modulate data via serial communication, driving high- intensity blue and green LEDs through TIP122 transistor circuits. Optical signals propagate through a water channel and are detected by a light-dependent resistor (LDR) module coupled with an LM393 comparator circuit. The analog received signal is digitized using an MCP3208 analog-to-digital converter (ADC), and a Raspberry Pi processes the data stream for decoding and display. A 16x2 LCD screen shows decoded information, while real-time visualization of signal strength and data is displayed on a connected monitor for performance analysis. This study compares the underwater communication capabilities of blue and green LEDs, highlighting that blue wavelengths offer deeper pen- etration in water, whereas green wavelengths provide more stable intensity at shorter distances. The system achieves reliable short- range data transmission with cost-effective and scalable hardware components. The results demonstrate the feasibility of using such a UOWC system for applications in marine research, underwater robotic control, and environmental monitoring, addressing the challenges of underwater signal attenuation and bandwidth limitations with practical circuitry and software solutions.

Keywords: Underwater optical wireless communication, visible light communication, blue LED, green LED, Arduino, Raspberry Pi, light-dependent resistor, real-time signal processing, environmental monitoring.

1. Introduction

Underwater communication plays a critical role in diverse fields such as marine exploration, environmental monitoring, underwater robotics, and defense [2], [6]. Traditional communication technologies underwater, primarily acoustic and radio frequency (RF) methods, suffer from significant limitations including low bandwidth, high latency, and severe signal attenuation [3], [5]. Acoustic communication, although widely used, is constrained by its relatively low data rates and sus- ceptibility to environmental noise, while RF communication experiences very high absorption in water, resulting in short transmission ranges [3], [4].

Underwater optical wireless communication (UOWC) has emerged as a promising alternative to overcome these chal- lenges, thanks to its potential for high data rates, low latency, and enhanced security [2], [6]. Optical signals, particularly in the visible spectrum, can propagate through water with relatively low attenuation in specific wavelength windows. Studies dating back to the 1960s demonstrated that the blue-green spectral range (approximately 450 nm to 550 nm) exhibits minimum absorption and scattering in water, making it ideal for underwater communication [7], [8]. This characteristic has motivated considerable research on UOWC systems utilizing blue and green light sources.

Light-emitting diodes (LEDs) and laser diodes (LDs) are common optical sources in UOWC systems. While LDs offer higher modulation bandwidths and longer transmission distances, LEDs present a cost-effective, robust, and lower power- consuming choice suitable for medium-range applications [9], [10]. However, the bandwidth of typical LEDs is limited due to physical constraints such as junction capacitance and carrier recombination lifetime, necessitating equalization and modula- tion techniques to optimize communication performance [16], [22].

Recent advances have focused on improving LED band- width through hardware pre-equalization circuits such as T- bridge networks [21], [22] and digital waveform shaping filters [27], achieving data rates up to tens or hundreds of Mbps over meter-scale distances [37]. Moreover, modulation schemes including orthogonal frequency-division multiplexing (OFDM) and pulse amplitude modulation (PAM) have been explored to further enhance underwater optical transmission efficiency [11], [12], [14].

This paper presents a practical underwater optical wireless communication prototype using blue and green LEDs con- trolled by an Arduino and processed by a Raspberry Pi. The system investigates the comparative performance of blue and green LED wavelengths for short-range communication, lever- aging accessible hardware components and simple modulation techniques. The choice of components and system design aims to balance cost, complexity, and communication reliability, targeting applications in marine research, underwater robotics, and environmental sensing. The general system architecture is depicted in Fig. 1.

The remainder of the paper is organized as follows: Sec- tion II describes the literature survey. Section III details the methodology. Section IV presents results and discussion on the comparative analysis of blue and green LEDs. Section V concludes the paper and suggests future research directions.

2. LITERATURE SURVEY

Underwater optical wireless communication (UOWC) has gained significant research interest due to its potential to deliver high data rates and low latency compared to traditional underwater acoustic and RF methods [2], [3]. The fundamental

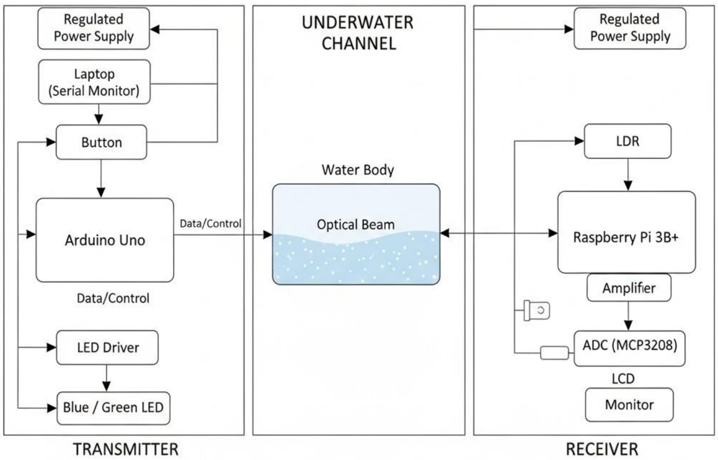


Fig. 1. Schematic block diagram of the proposed underwater optical wireless communication system.

challenge in UOWC lies in the high attenuation and scattering of light signals underwater, which varies strongly with wave- length, water type, and environmental conditions [5], [6].

Early foundational studies [7], [8] established that the blue-green visible light spectrum, roughly from 450 to 550 nm, experiences minimal absorption in water, making it the optimal window for UOWC systems. Schirripa Spagnolo et al. provided a detailed overview of underwater optical channel characteristics and discussed deployment challenges [6], [9]. More recently, Xu summarized underwater communication motivations and technology advances emphasizing visible light [4].

Optical sources for UOWC have predominantly included light-emitting diodes (LEDs) and laser diodes (LDs). LEDs are attractive due to their low cost, energy efficiency, and robustness, despite their inherently limited modulation band- width [9], [10]. Efforts to overcome this bandwidth limitation typically involve hardware pre-equalization circuits such as cascaded T-bridge equalizers and digital waveform shaping, boosting bandwidth from a few MHz to several tens or hundreds of MHz [21], [22], [27], [37].

Modulation techniques play a critical role in maximizing data throughput under physical constraints.

Orthogonal frequency-division multiplexing (OFDM) has been extensively studied [11]–[14], showing resilience against multipath effects and spectral efficiency improvements. Pulse amplitude modulation (PAM) and other adaptive bit-allocation schemes have demonstrated Gb/s data rates in visible light communication setups [15], [16], [26], [31].

There have been multiple experimental demonstrations of UOWC systems using blue and green LEDs [22], [28], show- casing reliable high-speed data links over short underwater distances. Advanced hardware such as GaN-based resonant cavity photodiodes and pre-equalization circuits have been employed for improved performance and wavelength selectivity [23]–[25]. The combination of practical circuit designs and sophisticated digital signal processing paves the way for scalable and real-world deployable UOWC systems [29], [30]. This survey highlights a clear trend towards cost-effective implementations that leverage accessible hardware while deploying advanced equalization and modulation techniques.

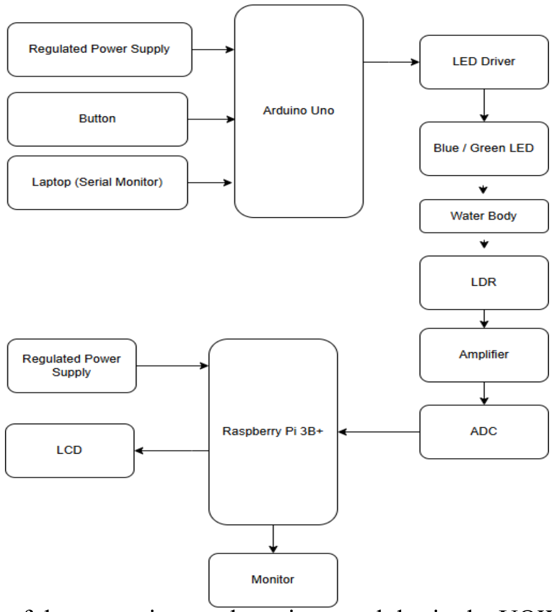


Fig. 2. Block diagram of the transmitter and receiver modules in the UOWC system.

This lays the foundation for the present work, which focuses on a prototype UOWC system utilizing blue and green LEDs with Arduino and Raspberry Pi platforms, to investigate comparative performance in a practical setting.

3. METHODOLOGY

The proposed Underwater Optical Wireless Communication (UOWC) system consists of a transmitter, underwater channel, and receiver as shown in the block diagram in Fig. 2.

A. Transmitter Side

The transmitter encodes the data stream using an Arduino microcontroller. The binary data is modulated through on-off keying (OOK) and used to drive high-intensity blue and green LEDs via TIP122 transistor driver circuits. The LEDs emit optical signals in the visible spectrum into the underwater channel. A collimating lens is used to focus the beam for better propagation through water.

B. Underwater Channel

The water medium exhibits wavelength-dependent absorption and scattering, with blue and green light wavelengths showing the least attenuation. Signal propagation characteristics are modeled by frequency response measurements using a Vector Network Analyzer (VNA).

C. Receiver Side

At the receiver, an LDR (light-dependent resistor) coupled with an LM393 comparator circuit detects the optical signal. The analog output from the comparator is digitized using an MCP3208 analog-to-digital converter (ADC). The digital data stream is processed by a Raspberry Pi, which performs.

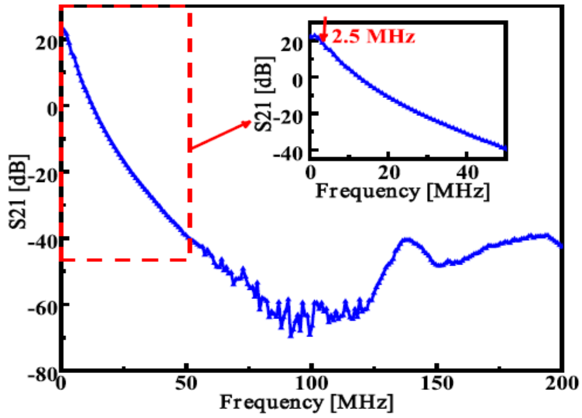


Fig. 3. Measured S21 frequency response curve

demodulation and error checking. Decoded data is displayed on a 16x2 LCD, and real-time plots of received signal strength and data are rendered on a connected monitor.

D. System Frequency Response

The frequency response of the UOWC system without any equalization is characterized by the S21 parameter, which quantifies the amplitude-frequency characteristic of transmit- ted to received signals. The measured S21 curve typically shows a narrow bandwidth mainly limited by the LED characteristics which is shown in Fig. 3. Mathematically, the S21 parameter magnitude response can be expressed as:

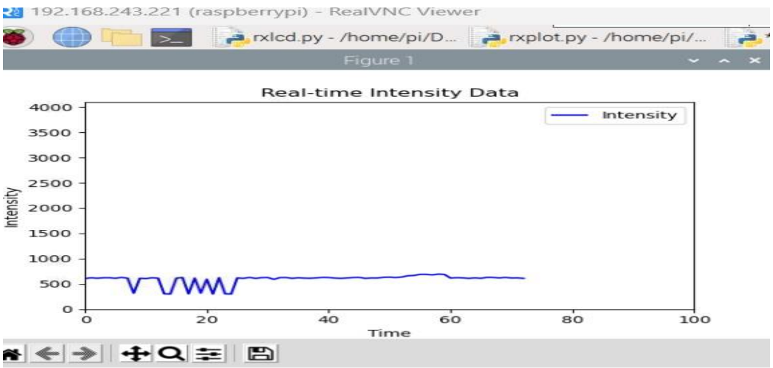
$$|S_{21}(f)| = \frac{V_{out}(f)}{V_{in}(f)} = \frac{A}{\sqrt{1+(\frac{f}{f_c})^2}}$$

where A is the amplitude at low frequencies, f is the frequency, and f_c is the 3 dB cutoff frequency characterizing bandwidth limitation of the LED. This roll-off behavior in the S21 curve causes distortion and limits data transmission rates.These baseline measurements motivate the use of hardware and software equalization techniques in our system to expand bandwidth and improve communication performance.

4. RESULTS AND DISCUSSION

This section presents the key experimental results of the underwater optical wireless communication prototype. The prototype system's performance is evaluated based on the optical intensity of green and blue LEDs, real-time intensity plots, and the quality of received data compared to transmitted data. Fig. 4 shows the measured optical intensity for the green LED as it transmits data underwater. The plot demonstrates a stable intensity profile, indicating reliable signal emission and reception over short-range distances.

Fig. 4. Optical intensity variation of the green LED over time, demonstrating stable signal strength suitable for underwater communication



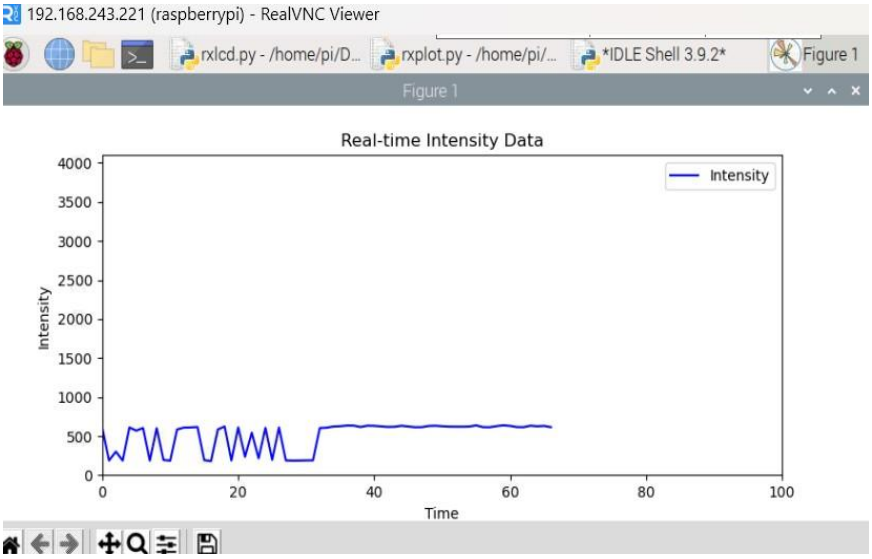


Fig. 5. Optical intensity variation of the blue LED over time, showing enhanced penetration characteristics underwater.

The real-time intensity graph for the blue LED presented in Fig. 5 demonstrates the receiver's ability to accurately capture modulated signals despite attenuations inherent to underwater propagation.

The physical layout of the prototype setup is depicted in Fig. 6, highlighting the positioning of Arduino-driven LEDs, the water tank, and the receiver apparatus including the LDR sensor. Fig. 7 focuses on the electronic interfacing details that facil- itate signal digitization and processing for real-time decoding and display. Fig. 8 captures the transmitted data stream before modula- tion, demonstrating the input to the communication system for testing.

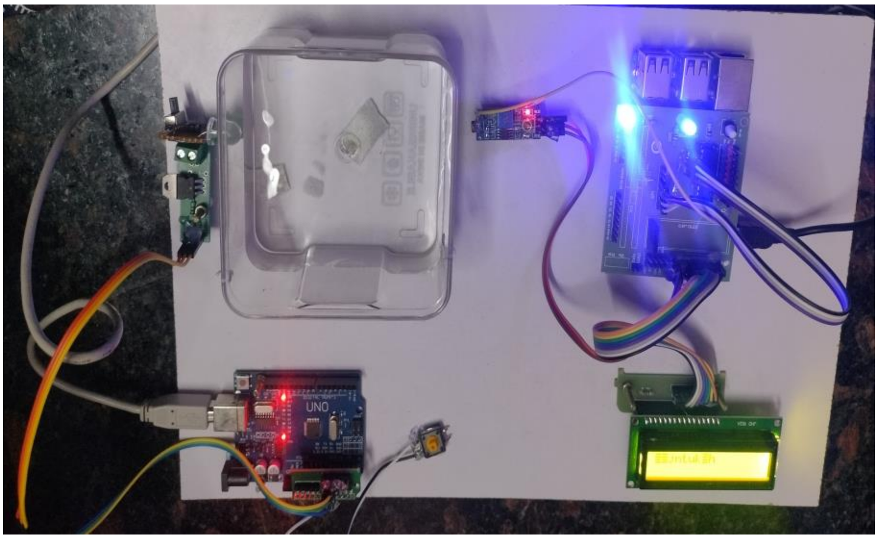


Fig. 6. First image of the underwater optical wireless communication prototype showing transmitter and receiver arrangement in the experimental water tank.

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Fig. 7. Second image of the prototype emphasizing the interfacing of MCP3208 ADC with the Raspberry Pi for digital signal processing.

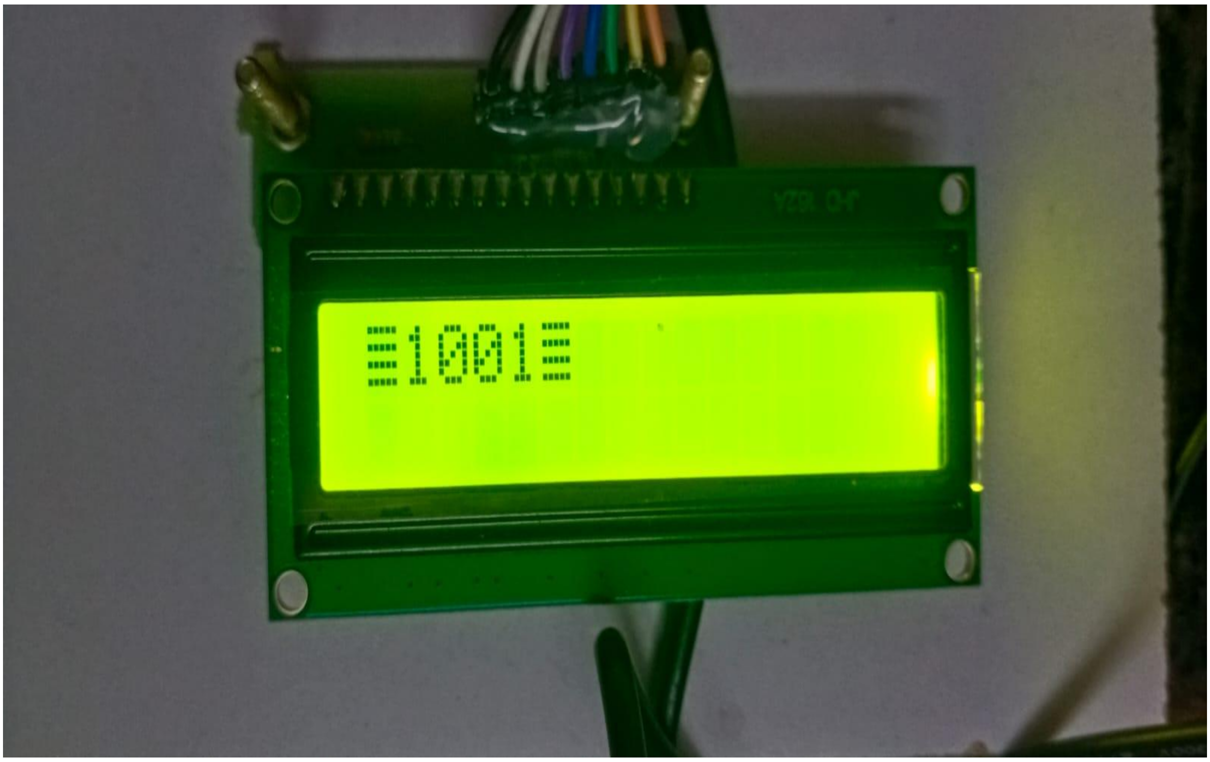

Fig. 8. Screenshot of transmitted data, as input to the Arduino for modulation and LED signal generation.

Fig. 9Screenshot of received and decoded data shown on the LCD and monitor, evidencing successful underwater optical communication.

The received data shown in Fig. 9 confirms effective decoding with minimal errors, validating the system's performance.

Discussion:

The experimental intensity graphs confirm that both green and blue LEDs can be effectively used for underwater optical communication with distinct advantages; green LEDs offer intensity stability while blue LEDs enable deeper penetration. Prototype images clarify the feasibility of the built system and its real-time operation capabilities. The comparison between transmitted and received data displays the reliability of signal transmission and decoding over the chosen underwater setup. These results underscore the potential of using accessible hardware components for scalable and practical UOWC systems [22], [37].

5. Conclusion and Future Scope

This paper presents a practical prototype for underwater optical wireless communication utilizing blue and green LEDs driven by Arduino and processed by Raspberry Pi. Experimental results demonstrate successful short-range data transmission with stable intensity profiles and real-time signal processing capabilities. The comparative study indicates that blue LEDs provide deeper penetration underwater, while green LEDs offer more stable intensity at shorter distances, confirming the suitability of visible light communication through the blue-green spectrum for various underwater applications.

The prototype system, built with cost-effective and accessible hardware components, shows promise for applications in marine research, underwater robotics, and environmental monitoring. The use of simple modulation schemes combined with digital signal processing and ADC interfacing enables real-time communication with reliable decoding performance. Future work includes extending communication range and data rates by integrating higher power LEDs or laser diodes, improving modulation techniques, and implementing adaptive equalization algorithms. Exploration of multi-wavelength multiplexing and advanced error correction codes will further enhance system robustness and throughput. Additionally, underwater channel modeling under diverse environmental conditions can optimize system design for real-world deployments. Overall, the study provides a strong foundation for developing scalable, affordable UOWC systems that can supplement existing underwater communication technologies with advantages in bandwidth, latency, and security.

References

[1] J. Xu et al., "OFDM-based broadband underwater wireless optical communication system using a compact blue LED," *Opt. Commun.*, vol. 369, pp. 100–105, 2016.

[2] Z. Zeng, S. Fu, H. Zhang, Y. Dong, and J. Cheng, "A survey of underwater optical wireless communications," *IEEE Commun. Surv. Tut.*, vol. 19, no. 1, pp. 204–238, First quarter 2017.

[3] N. Saeed, A. Celik, T. Y. Al-Naffouri, and M.-S. Alouini, "Underwater optical wireless communications, networking, and localization: A sur- vey," *Ad Hoc Netw.*, vol. 94, 2019, Art. no.

101935.

[4] J. Xu, "Underwater wireless optical communication: Why, what, and how? [Invited]," *Chin. Opt. Lett.*, vol. 17, no. 10, 2019, Art. no. 100007.

[5] W. Cox and J. Muth, "Simulating channel losses in an underwater optical communication system," *J. Opt. Soc. Amer. A, Opt., Image Sci., Vis.*, vol. 31, no. 5, pp. 920–934, May 2014.

[6] G. Schirripa Spagnolo, L. Cozzella, and F. Leccese, "Underwater optical wireless communications: Overview," *Sensors (Basel)*, vol. 20, no. 8, Apr. 2020, Art. no. 2261.

[7] S. Duntley, "Light in the sea," *JOSA*, vol. 53, no. 2, pp. 214–233, 1963.

[8] G. Gilbert, T. Stoner, and J. Jernigan, "Underwater experiments on the polarization, coherence, and scattering properties of a pulsed blue-green laser," in *Proc. Underwater Photo Opt. I*, 1966, pp. 8–14.

[9] F. Leccese and G. Schirripa Spagnolo, "State-of-the art and perspectives of underwater optical wireless communications," *Acta IMEKO*, vol. 10, no. 4, pp. 25–35, 2021, doi: 10.21014/actaimeko.v10i4.1097.

[10] E. F. Schubert, N. Hunt, R. J. Malik, M. Micovic, and D. L. Miller, "Temperature and modulation characteristics of resonant-cavity light- emitting diodes," *J. Lightw. Technol.*, vol. 14, no. 7, pp. 1721–1729, Jul. 1996.

[11] T. Essalih, M. A. Khalighi, S. Hranilovic, and H. Akhouayri, "Optical OFDM for SiPM-based underwater optical wireless communication links," *Sensors (Basel)*, vol. 20, no. 21, Oct. 2020, Art. no. 6057.

[12] S. Hessien, S. C. Tokgoz, N. Anous, A. Boyaci, M. Abdallah, and K.A. Qaraqe, "Experimental evaluation of OFDM-based underwater visible light communication system," *IEEE Photon. J.*, vol. 10, no. 5, Oct. 2018, Art. no. 7907713.

[13] J. Lian, Y. Gao, P. Wu, and D. Lian, "Orthogonal frequency division multiplexing techniques comparison for underwater optical wireless communication systems," *Sensors (Basel)*, vol. 19, no. 1, Jan. 2019, Art. no. 160.

[14] J. Du et al., "A comprehensive performance comparison of DFT-S DMT and QAM-DMT in UOWC system in different water environments," *IEEE Photon. J.*, vol. 13, no. 1, Feb. 2021, Art. no. 7900211.

[15] H. Chun et al., "LED based wavelength division multiplexed 10 Gb/s visible light communications," *J. Lightw. Technol.*, vol. 34, no. 13, pp. 3047–3052, Jul. 2016.

[16] X. Huang, S. Chen, Z. Wang, Y. Wang, and N. Chi, "1.2 Gbit/s visible light transmission based on orthogonal frequency-division multiplexing using a phosphorescent white light-emitting diode and a pre-equalization circuit," *Chin. Opt. Lett.*, vol. 13, no. 10, pp. 100602–100606, 2015.

[17] H. L. Minh et al., "High-speed visible light communications using multiple-resonant equalization," *IEEE Photon. Technol. Lett.*, vol. 20, no. 14, pp. 1243–1245, Jul. 2008.

[18] H. Li, X. Chen, J. Guo, and H. Chen, "A 550 Mbit/s real-time visible light communication system based on phosphorescent white light LED for practical high-speed low-complexity application," *Opt. Exp.*, vol. 22, no. 22, pp. 27203–27213, Nov. 2014.

[19] Bookstein, F. L., "Principal Warps: Thin-Plate Splines and the Decomposition of Deformations," IEEE Trans. Pattern Anal. Mach. Intell., vol. 11, no. 6, pp. 567–585, 1989.

[20] Lisa Gottesfeld Brown, " A survey of image registration techniques," ACM Comput. Surv. Vol.24, no. 4, pp. 325–376, Dec. 1992.

[21] MAGUIR~, G Q, JR., Noz, M E., LEE, E M, AND SHIMPF, J. H. 1985. "Correlation methods for tomographic Images using two and three dimensional techniques," In Proceedings of the 9th Conference of Information Processing m Medical Imaging (Washington, D.C., June 10-14). pp 266-279.

[22] Barnes, D. and Silverman, H. "A class of algorithms for fast digital image registration. IEEE Transactions on Computers," C-21(2), 179–186, 1972.

[23] Goshtasby, A. and Stockman, G. C. "Point pattern matching using convex hulls," Proc. IEEE Conf. on Pattern Recognition, 123–128, 1982.

[24] Goshtasby, A. (1987). “Piecewise cubic mapping for image registration. Pattern Recognition”, 20(5), 525–533.

[25] Broit, C. (1981). “Optimal registration of deformed images”. Ph.D. thesis, University of Pennsylvania.

[26] Price, K. E. (1985). “Relaxation matching techniques”. Proc. IEEE Conf. on Computer Vision and Pattern Recognition, 400–405.

[27] Rafael C. Gonzalez, Richard E. Woods and Steven L. Eddins “Digital Image Processing Using MATLAB”.

[28] Kovesi, P. (1999). “Image Features from Phase Congruency”. *Videre: Journal of Computer Vision Research*, *1*(3), 1-26.

[29] J. F. Canny. “Finding edges and lines in images”. Master’s thesis, MIT. AI Lab. TR-720, 1983.

[30] R. C. Gonzalez and R. E. Woods, “Digital Image Processing”, Second Edition, Prentice Hall, 2002.

[31] A. K. Venkataramanan, C. Wu, A. C. Bovik, I. Katsavounidis and Z. Shahid, "A Hitchhiker’s Guide to Structural Similarity," in *IEEE Access*, vol. 9, pp. 28872-28896, 2021.

[32] Asif Ali Laghari, Awais Khan Jumani, Rashid Ali Laghari, Haque Nawaz, “Unmanned aerial vehicles: A review, Cognitive Robotics,” in science direct, Volume 3,2023.

[33] Y. Li, W. Zhan and D. Zhu, "Infrared and Visible Image Registration Method Based on Fine-Grained Feature Capture and Multi-Feature Collaboration," 2024 4th International Conference on Electronic Information Engineering and Computer Science (EIECS), Yanji, China, pp. 251-257, 2024.

[34] W. Yang *et al*., "Adjacent Self-Similarity 3-D Convolution for Multimodal Image Registration," in *IEEE Geoscience and Remote Sensing Letters*, vol. 21, pp. 1-5, 2024.

[35] G. Yadav, S. Maheshwari and A. Agarwal, "Contrast limited adaptive histogram equalization based enhancement for real time video system," *2014 International Conference on Advances in Computing, Communications and Informatics (ICACCI)*, Delhi, India, pp. 2392-2397, 2014.