Dean&Francis

ISSN 2959-6157

Integration of Optical Coherence Tomography (OCT) Systems and Its Prospects in Remote Diagnosis and Treatment

Jiajin Liu[1,*]

[1]College of Science, Northwest A&F University, Xi'an, 712100, China
*Corresponding author: ljiajin@nwafu.edu.cn

Abstract:

The concept of optical coherence tomography (OCT) originates from low-coherence interferometry techniques in the 1980s. Since its discovery, OCT has attracted attention with unique imaging advantages. But the technology still faces challenges such as slow scanning speeds and demanding imaging conditions. Therefore, this study employs a system integration approach to further summarize the application potential of OCT and explore its future prospects. Inspired by system integration, this paper proposes several improvement strategies. It would focus on infrastructure-related aspects to reduce the application cost of OCT. Aiming to promote device miniaturization and image quality optimization, this study would advance the use of OCT in telemedicine. As for expected outcomes, the enhanced device features a compact design that improves portability and supports essential real-time monitoring. Furthermore, image quality will be significantly improved, reducing misdiagnosis caused by artifacts. Finally, the optimized system is refined to form a more convenient diagnostic and treatment solution. This paper comes up with several measures to facilitate the application of OCT technology and offers policy recommendations for its future development to some extent.

Keywords: Optical Coherence Tomography; System Integration; Image Enhancement; Telemedicine.

1. Introduction

Discovered in the 1990s, optical coherence tomography (OCT) has gained extensive attention and application in the biomedical field owing to its high resolution and non-invasive imaging capabilities [1, 2]. OCT is based on low-coherence interference, and generates imaging through the detection of optical signals. Its applications have expanded from ophthalmology to various clinical fields such as cardiology

ISSN 2959-6157

and dermatology. For example, OCT angiography (OCTA) can assess diabetic retinopathy and capture functional and morphological information such as structural integrity and vascular stenosis in the coronary system.

Early time-domain OCT (TD-OCT) employed mechanical scanning of the reference arm for depth detection. Although simple in structure, it suffered from some problems such as slow imaging speed, low signal-to-noise ratio, and vulnerability.

To improve imaging performance, Fourier-domain OCT (FD-OCT) was developed to replace mechanical axial scanning with Fourier transform principles [3]. This innovation significantly enhanced imaging speed and signal-to-noise ratio, advancing the clinical adoption of OCT.

Nevertheless, OCT technology still meets several challenges. Light scattering in biological tissues increases with depth, thus leading to signal attenuation and reduced image quality. Besides, conventional OCT systems are often bulky, operationally complex, and relying on specialized operators, so their deployment in primary care and remote settings is limited. To address these limitations, system integration is a great alternative.

System integration refers to the process of efficiently combining components or subsystems into a coherent system to optimize resources and enhance functionality, often focusing on system interfaces and user interactions. This approach offers a viable solution for developing miniaturized, high-performance, and intelligent OCT devices through synergistic integration of hardware, software, and data processing modules.

The paper reviews recent advances in OCT from a system integration perspective, covering hardware miniaturization, functional expansion, and AI-enabled capabilities. It also analyzes the architecture, applications, and challenges of OCT within telemedicine systems.

Recently, OCT innovations based on system integration have continuously emerged. For instance, a dual-modality system combining OCT with ultrasound (US) has been applied in intravascular imaging, providing complementary multimodal information. What' s more, integration of advanced light sources and optical designs has enabled ultra-high-resolution (UHR) retinal imaging [4]. This paper further elaborates on OCT system optimization and seamless integration with high-performance optoelectronic devices, aiming to comprehensively improve imaging speed, quality, and functionality.

Telemedicine is gradually becoming a key solution to address healthcare resource distribution and strengthen primary care. By integrating high-performance, portable OCT devices with 5G networks, cloud platforms, and expert systems can be established. This integration provides an efficient way to medical treatment. This study further explores the potential value of OCT system integration in promoting universal health coverage and transforming healthcare models.

2. OCT Technology Principles and Development

2.1 Basic Principles of OCT

OCT technology could make images by producing and detecting interference signals using the principle of low-coherence interferometry [5]. The system consists of a light source and a Michelson interferometer, which employs a beam splitter to generate both a measurement beam and a reference beam [6]. These two beams are reflected back to the interferometer after passing through the sample and the reference mirror. The resulting signal is then captured by a detector. Processing and analyzing this signal allows the reconstruction of microscopic structural images of the object under study.

2.2 Evolution of OCT Technologies

Early OCT systems were based on time-domain (TD-OCT) technology. TD-OCT alters the optical path difference through mechanical displacement of the reference mirror, acquiring depth-resolved reflectance profiles point-by-point (A-scan). However, this approach is slow and inefficient.

Spectral-domain OCT (SD-OCT), developed subsequently, operates on Fourier transform principles. The modulation period varies linearly with the optical path difference in the interferometer. Spectral interference manifests as fringes whose number increases with larger optical path differences. SD-OCT provides a significant sensitivity advantage, capable of measuring all light echoes simultaneously and scanning multiple structures in a single pass, greatly enhancing imaging speed. Nonetheless, SD-OCT requires high-resolution spectrometers and high-speed line-scan detectors.

Another approach, swept-source OCT (SS-OCT), employs a high-speed frequency-swept laser, providing extended imaging range and improved sensitivity. However, its performance is limited by the capabilities of the swept laser technology.

In summary, enhancing scanning speed and image quality remains essential for broadening the applications of OCT. Scanning speed is constrained by hardware processing capabilities, scanning mechanisms, and algorithmic efficiency. Image quality depends largely on light source characteristics (e.g., bandwidth and coherence length), detector performance, and image processing algorithms

[7]. Scanning speed can be improved through synergistic optimization of scanning mechanisms, hardware processing, and algorithms from a system integration perspective, while image quality may be enhanced via advanced light sources and image processing techniques.

3. Technological Advances in OCT System Integration

To achieve miniaturization and high performance in OCT systems, technologies such as microelectromechanical systems (MEMS) and photonic integrated circuits (PICs) have been introduced and are now major research focuses [8, 9]. Among these, PIC technology integrates all necessary optical components into a single chip, providing functionality equivalent to traditional discrete devices while also enabling novel capabilities beyond conventional optical systems. MEMS technology emphasizes microfabrication and plays a vital role in the miniaturization of OCT systems. Furthermore, it contributes to optimizing specific functional aspects of OCT devices.

3.1 Miniaturized and Low-Cost Broadband Light Sources

Currently, broadband light sources are primarily implemented using superluminescent light-emitting diodes (SLDs) and erbium-doped fiber amplifiers with amplified spontaneous emission (ASE) [10, 11]. In general, combining multiple light beams into one broadband output via a fiber coupler can substantially reduce structural costs. However, the difficulty of coupling SLDs to single-mode fiber systems limits their practical application. With the ongoing refinement and maturation of rare-earth-doped fiber technology, ASE-based sources have become increasingly popular among researchers.

Various configurations have been proposed for erbium-doped fiber ASE broadband light sources to achieve stable output characterized by high flatness, broad bandwidth, and high conversion efficiency. Examples include a single-pass backward-umping structure and a double-pass structure implemented using a fiber-optic reflection loop.

These designs originate primarily from optical fiber communications and must meet specific conditions (e.g., bandpass control) to optimize source performance. Erbium-doped fiber ASE broadband light sources allow straightforward integration with fiber systems to produce a flattened output spectrum. By improving the coupling efficiency between broadband sources and optical fiber systems, a miniaturized light source module can be realized. This approach reduces cost while maintaining performance, thereby supporting the development of compact OCT systems.

3.2 MEMS Mirrors for Miniaturized Scanning

MEMS mirrors (Micro-Electro-Mechanical System Mirrors) are miniaturized actuated devices fabricated using micro-electro-mechanical system technology, which achieve precise beam deflection by controlling the mirror's rotation angle.

Conventional OCT scanners generate A-scans through point-by-point acquisition, exhibiting limited scanning speeds. In contrast, MEMS mirrors utilize high-speed stroboscopic techniques to project two-dimensional sinusoidal fringe patterns. The use of dual-axis mirrors for fringe projection significantly enhances the imaging speed of OCT systems. Furthermore, MEMS mirrors feature a compact form factor, facilitating easier integration and optimization within OCT systems. As such, they represent a core enabling technology for portable OCT devices.

3.3 Integrated Detection and Real-Time Processing

The balanced detector is a core component in optical coherence tomography (OCT), primarily converting weak optical signals into high-fidelity electrical signals to enable high-resolution imaging. Balanced detection helps eliminate certain types of noise in the detection system, thereby improving sensitivity [12]. Thus, high-performance balanced detectors play a crucial role in enhancing overall image quality.

Conventional OCT balanced detectors typically consist of discrete photodiodes and amplifiers, which require complex interconnection mechanisms and supporting integrated circuits to function properly. To optimize the detection system, enhancements are needed at both the functional component and chip integration levels.

At the device level, the adoption of PIN photodiodes—featuring high sensitivity, low noise, and miniaturization (with dimensions down to millimeter scale) —offers a promising approach to improving conventional detection architectures.

At the chip level, embedded FPGA-based real-time processing systems can be employed to implement core algorithms directly in hardware, substantially reducing image processing time [13]. Furthermore, such systems support highly integrated designs that incorporate ARM cores, DSP modules, and high-speed interfaces, significantly boosting the processing capabilities of OCT systems.

3.4 System Packaging and Power Optimization

System packaging integrates multiple bare dies with different processes and functionalities into a single package.

ISSN 2959-6157

This approach enables flexible chip arrangement and interconnections, thereby realizing fully functional chip module systems [14]. Such integration significantly reduces device size, improves user experience in outdoor OCT applications, and enhances scanning speed by leveraging the synergistic effects of multi-module integration.

Power consumption optimization further reduces circuit heat generation, slows the aging process of electronic components, and helps lower overall costs. Many modern microprocessors utilize dynamic voltage and frequency scaling (DVFS) technology, which adjusts operating voltage and frequency dynamically according to system workload to achieve low power consumption [15]. This optimization simplifies thermal management design and minimizes heat generation, enabling stable operation in high-temperature outdoor environments without the need for high-capacity cooling fans.

3.5 Functional Extensions and AI Integration

3.5.1 Functional Imaging Expansion

Optical microangiography (OMAG) is a label-free angiographic imaging technique that effectively distinguishes static tissue signals from dynamic blood flow signals within tissue, thereby generating three-dimensional microangiographic images. This technology clearly visualizes micrometer-level blood vessels, providing richer sample information. Its non-invasive nature also makes it readily adopted in clinical practice, further promoting the integration of OCT technology.

Polarization-sensitive optical coherence tomography (PS-OCT) enhances the imaging of microstructures by detecting changes in the polarization state of light propagating through biological tissues. This allows extraction of additional information, such as tissue birefringence properties. Compared to conventional OCT, PS-OCT reveals more detailed microstructural information, thereby improving both image quality and diagnostic accuracy.

3.5.2 Artificial Intelligence Empowerment

Deep learning-based image enhancement techniques learn mapping functions from low-quality to high-quality images through neural network models, enabling automatic optimization of image quality. This approach can reconstruct high-resolution images from low-resolution inputs, restoring fine details and significantly mitigating recognition difficulties caused by artifacts. Its strong adaptability greatly facilitates the application of portable OCT systems.

4. OCT Integration in Telemedicine Systems

4.1 Telemedicine Application Scenarios

Telemedicine-capable OCT technology offers considerable application value by helping alleviate the shortage of ophthalmic resources in primary care settings to some extent [16]. Unlike traditional ophthalmic examinations that require patients to make multiple hospital visits, remote OCT enables rapid scanning and report generation within a short time frame, further encouraging the adoption of OCT technology.

Within remote ophthalmic diagnostic networks, community hospitals or primary care centers can quickly perform tissue scans and upload the data in real time to higher-tier medical institutions. AI algorithms automatically annotate potential lesions, allowing specialists to remotely assess the images and develop treatment plans, greatly streamlining the diagnostic workflow.

By leveraging the low-latency features of 5G technology, real-time transmission of intraoperative OCT images becomes feasible. The overlay of guidance markers on surgical displays can assist in proposing solutions to mitigate risks during complex procedures.

Integration of OCT with wearable devices enables continuous data synchronization. The system automatically detects abnormal structural changes in OCT images, while cloud platforms conduct comprehensive analysis of full-body health metrics to generate personalized intervention plans. These plans guide physicians or patients through subsequent stages of treatment.

4.2 System Architecture for Remote OCT

To realize OCT technology with remote diagnostic capabilities, the integration of dedicated hardware and technical optimizations is essential. Below, we propose several reference architectures:

At the sensing terminal, fundamental OCT imaging devices are required to acquire tomographic images of affected tissues. To achieve high-speed scanning and precise imaging, auxiliary devices such as slit-lamp cameras can be integrated. These provide complementary data to OCT, helping to establish a multidimensional diagnostic framework. In addition, built-in algorithms leveraging AI and deep learning can further enhance image quality and output.

For the transport network layer, a hybrid architecture is recommended, employing optical fiber for cross-regional data exchange and 5G for terminal-to-base-station transmission [17]. By capitalizing on the complementary strengths of these technologies, a highly efficient, stable, and adaptable communication system can be established.

At the cloud platform layer, virtualized servers can facilitate 3D reconstruction of OCT images. A large-scale model repository can also be implemented, integrating OCT image data with electronic health records to identify common clinical challenges and support continuous system optimization.

On the end-user terminal module, AR/VR technologies can be deployed for immersive 3D visualization of OCT images [18], allowing medical personnel to thoroughly evaluate patient conditions. Furthermore, deep learning-based image enhancement can be applied to aid in subsequent diagnosis and treatment procedures.

4.3 Challenges and Future Directions

The widespread adoption of OCT technology at the primary care level still faces several challenges. The primary obstacle is cost, necessitating a reduction in equipment prices without compromising performance—for instance, through the use of optimized light sources and scanning mechanisms. Second, establishing a functional telemedicine system demands advanced technological infrastructure, calling for the development of cost-effective implementation strategies. Additionally, ensuring proper operation of portable OCT devices by patients remains a significant concern. Inconsistencies in image formats across devices may further complicate diagnostic processes.

5. Conclusion

This paper systematically reviews the major challenges currently facing optical coherence tomography (OCT) technology and proposes several feasible improvement strategies from a system integration perspective. Building on this analysis, we further explore potential obstacles that may arise during the clinical application and broad adoption of OCT. With continuous advancements in optics, microelectronics, and artificial intelligence, OCT devices are expected to be increasingly deployed in primary healthcare settings, promoting the refinement of diagnostic and treatment systems in ophthalmology and related specialties. It is anticipated that the widespread use of OCT will in turn drive further research and development. Ultimately, low-cost, high-performance, and miniaturized OCT systems are likely to become a core competitive advantage and a major future direction in the medical device industry.

References

[1] Bouma B E, Boer J F, Huang D, et al. Optical coherence tomography. Nature Reviews Methods Primers, 2022, 2(1): 79.

[2] Psomadakis C E, Marghoob N, Bleicher B, et al. Optical coherence tomography. Clinics in Dermatology, 2021, 39(4): 624-634.

[3] De L R , Muldera J, Takida Y, et al. Swept-source optical coherence tomography based on a backward terahertz-wave parametric oscillator achieving depth super-resolution. Optics Express, 2025, 33(19): 40739-40754.

[4] Zhang Pengfei, Wahl D J, Mocci J, et al. Adaptive optics scanning laser ophthalmoscopy and optical coherence tomography (AO-SLO-OCT) system for in vivo mouse retina imaging. Biomedical Optics Express, 2022, 14(1): 299-314.

[5] Hu Jiye, Chen Long, Huang Liyuan, et al. Measurement of optical biological parameters of eyes based on low coherent light interference. Progress in Biochemistry and Biophysics, 2022, 49(9): 1810-1820.

[6] Zhang Jinze, Mazlin V, Fei K, et al. Time-domain full-field optical coherence tomography (TD-FF-OCT) in ophthalmic imaging. Therapeutic Advances in Chronic Disease, 2023, 14: 20406223231170146.

[7] Rank E A, Nevlacsil S, Muellner P, et al. In vivo human retinal swept source optical coherence tomography and angiography at 830 nm with a CMOS compatible photonic integrated circuit. Scientific Reports, 2021, 11(1): 21052.

[8] Rank E A, Agneter A, Schmoll T, et al. Miniaturizing optical coherence tomography. Translational Biophotonics, 2022, 4(1-2): e202100007.

[9] Reche J, Stocker A B, Henchoz V, et al. High-resolution optical coherence tomography in healthy individuals provides resolution at the cellular and subcellular levels. Translational Vision Science & Technology, 2023, 12(7): 12-12.

[10] Gupta A K, Meng R, Modi Y S, et al. Imaging human macular pigments with visible light optical coherence tomography and superluminescent diodes. Optics letters, 2023, 48(18): 4737-4740.

[11] Maes F, Sharma M, Wang Lixian, et al. High power BDF/EDF hybrid amplifier providing 27 dB gain over 90 nm in the E+S band. Optical Fiber Communication Conference. Optica Publishing Group, 2022: Th4C-8.

[12] Guiomar F P, Fernandes M A, Nascimento J L, et al. Coherent free-space optical communications: Opportunities and challenges. Journal of Lightwave Technology, 2022, 40(10): 3173-3186.

[13] Ahmadi-Pour S, Saha S, McDonald-Maier K, et al. MESSI: Task mapping and scheduling strategy for FPGA-based heterogeneous real-time systems. ACM Transactions on Design Automation of Electronic Systems, 2025, 30(3): 1-29.

[14] Casper T, Römer U, De Gersem H, et al. Coupled simulation of transient heat flow and electric currents in thin wires: Application to bond wires in microelectronic chip packaging. Computers & Mathematics with Applications, 2020, 79(6): 1781-1801.

[15] Kulkarni V, Sahoo S K, Thanikanti S B, et al. Power systems

ISSN 2959-6157

automation, communication, and information technologies for smart grid: A technical aspects review. Telecommunication Computing Electronics and Control, 2021, 19(3): 1017-1029.

[16] Blinder K J, Calhoun C, Maguire M G, et al. Home OCT imaging for newly diagnosed neovascular age-related macular degeneration: a feasibility study. Ophthalmology Retina, 2024, 8(4): 376-387.

[17] Bhadani U. Smart grids: A cyber–physical systems perspective. International Research Journal of Engineering and Technology (IRJET), 2024, 11(06): 801.

[18] Beams R, Brown E, Cheng W C, et al. Evaluation challenges for the application of extended reality devices in medicine. Journal of Digital Imaging, 2022, 35(5): 1409-1418.