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ABSTRACT

Computer vision has become a powerful tool in the field of biosensing, aiding in the development of innovative and precise systems for the analysis and interpretation of biological data. This interdisciplinary approach harnesses the capabilities of computer vision algorithms and techniques to extract valuable information from various biosensing applications, including medical diagnostics, environmental monitoring, and food health. Despite years of development, there is still significant room for improvement in this area. In this perspective, we outline how computer vision is applied to raw sensor data in biosensors and its advantages to biosensing applications. We then discuss ongoing research and developments in the field and subsequently explore the challenges and opportunities that computer vision faces in biosensor applications. We also suggest directions for future work, ultimately underscoring the significant impact of computer vision on advancing biosensing technologies and their applications.

I. HOW COMPUTER VISION BENEFITS BIOSENSORS

Biosensors are analytical devices that combine biological elements with transducers to detect and quantify specific biological or chemical substances. They are used in a wide range of applications, including medical diagnostics,[1–3] chemical substance detection,[4–6] environmental monitoring,[7–9] food safety,[10–12] and biotechnology.[13–15] In the past few decades, biosensors have grown significantly with the advancements of nanotechnology,[16–18] signal amplification strategies,[19] and hardware.[20] For example, nanomaterial-based electrochemical signal amplification has great potential to improve the sensitivity and selectivity of biosensors.[21] However, all biosensors inevitably have drawbacks such as irregular signal noise, poor stability, difficult integration, and automation.[22] Therefore, researchers are seeking other breakthroughs to improve the performance of biosensors. Here, we survey the intersection of computer vision and biosensing, focusing on research in biosensing imaging, as well as based on 2D image signals such as electrochemical signals and spectral signals, which represents the vast majority of current computer vision applications for biosensors. Computer vision is a field of research that focuses on enabling computers to interpret and understand visual information in images or videos. It involves the development of algorithms, techniques, and models to extract meaningful information from visual data.[23] The application of computer vision improves the ability to analyze and interpret data, thereby enhancing the performance of biosensors.[24] For example, it can provide highly accurate analysis and detection that can help overcome the specificity and selectivity problems of the sensors themselves.[25] Another advantage is that it can efficiently process extensive sensing data with complex matrices or samples, which can significantly improve the efficiency and speed of data collection.[26] It also provides real-time monitoring with the advantages of being non-invasive, automated, and high throughput.[27] These advantages make computer vision a vital tool in the field of biosensors and will be a way to transform conventional biosensors into intelligent biosensors. Figure 1 shows the overview of the progress, challenges, and prospects for computer vision in biosensor applications.

Computer vision can analyze raw sensing data from biosensors in several ways: (1) Classification: Algorithms can classify sensed signals into different categories based on the target analyte. Especially for unsupervised learning, machine learning can help us achieve signal clustering in cases where humans cannot categorize signals explicitly.[28] (2) Noise reduction: Sensed signals always contain noise. Biosensors may have severe signal interference or noise. Therefore, machine models can be trained to distinguish between signal and noise.[29] (3) Anomaly detection: Biosensors are inevitably affected by the sample matrix and operating conditions. When biosensors are used in the field, they may be severely disturbed by contamination. Computer-learned adaptivity not only detects the signal but also corrects for variations in sensor

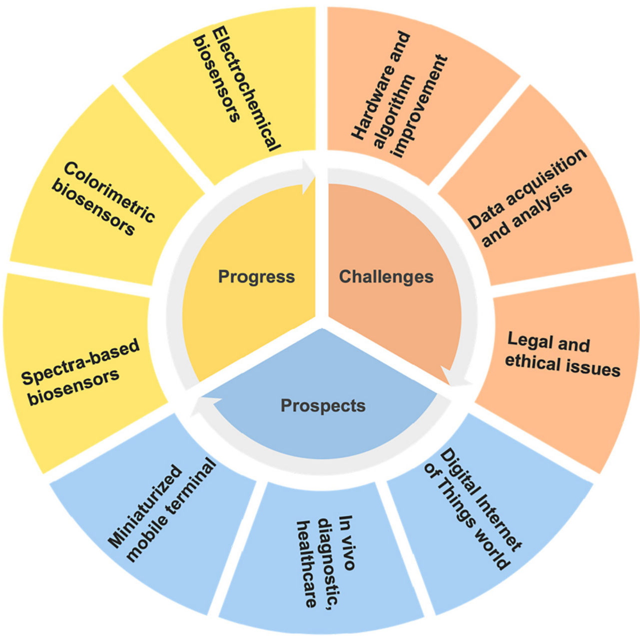

FIG. 1. Overview of the progress, challenges, and prospects for computer vision in biosensor applications.

performance due to biological contamination and interference in the actual sample.[30] (4) Data visualization and interpretation: Computer vision techniques can help visualize and interpret data obtained from biosensors, making it easier for researchers and users to understand and draw conclusions from complex biological information.[31] In summary, computer vision can directly, automatically, accurately, and quickly help biosensors read out data, which is important for on-site inspection or diagnosis.

II. DIFFERENT BIOSENSORS POWERED BY COMPUTER VISION

Computer vision technology can directly, automatically, accurately, and rapidly assist in reading biosensors and processing acquired images to extract relevant information for analysis and diagnostics. This technology is commonly combined with microfluidics,[32] lateral flow assay,[33] microscopy,[34] etc., which significantly improves the accuracy and convenience of detection. Recently, our lab has developed a disposable chip for SARS-CoV-2 detection using computer vision technique,[35] which can improve the reliability and accuracy of naked-eye based detection; Zhao *et al.* integrated optical microscopy with a microfluidic platform for computer vision-based analysis,[36] enabling simultaneous analysis of multiple biomarkers and antibiotics. Electrochemical biosensors are another widely used systems that generate data in the form of electrochemical signals whose spatial distribution can be captured by imaging techniques and then analyzed using computer vision algorithms. A common problem with electrochemical biosensors for real sample detection is that the reproducibility and stability are relatively weak.[37,38] Rong *et al.* developed a support vector machine (SVM) model to analyze the electrochemical impedance spectroscopy (EIS) data without equivalent circuit fitting.[39] The SVM with radial base function kernel was demonstrated to have the optimal performance for classifying the training dataset with an accuracy of 98%. Combining single-molecule electrical biosensors with computer vision can improve the accuracy and precision of single molecular identification with applications in DNA sensing,[40] RNA sequencing,[41] and pathogen detection.[42] The overlapping of current signals in many electrochemical sensors cannot satisfy the detection and identification of multiple analytes. This challenge can be addressed by using computer vision to analyze the current temporal waveform.[43] Arima *et al.* introduce a nanopore platform integrated with machine learning for the digital diagnosis of virus infection.[44] Surface plasmon resonance (SPR) and other spectra-based biosensors are also promising tools for the rapid and nondestructive detection.[45–50] Li *et al.* developed a chemically based SPR imaging technique for fingerprint surfaces that can facilitate subsequent computer vision for analysis or identification.[51] Computer vision can also simplify the detection process of point-of-care (POC) biosensors by providing rapid and on-site analysis of biological samples. For example, smartphone-based microscopy has become a promising POC device for the applications in diagnostics.[52] The images can be acquired, calculated, and analyzed in real time by a smartphone camera. Xu *et al.* developed a smartphone application named Tick Phone App, which can rapidly identify the ticks using this App.[53] There are also *in vivo* imaging biosensors using computer vision to visualize and analyze biological processes inside living organisms. They often involve non-invasive imaging methods,[54,55] such as fluorescence imaging,[56] optical coherence tomography,[57] or multimodal fusion approaches[58] to study tissues and organs *in vivo*.[59] Some biosensors employ computer vision to assess and monitor environmental conditions, such as water quality,[60] air pollution,[61] or soil health.[62] These biosensors can detect changes in biological indicators to assess the environmental impact.

III. CURRENT CHALLENGES AND FUTURE DIRECTIONS FOR COMPUTER VISION IN BIOSENSORS

The use of computer vision in biosensor applications has been increasingly compelling, but many challenges remain to realize its full potential.[63] Data availability is a major driver for computer vision applications and also a major obstacle. Machine learning requires large amounts of data, and the scarcity and lack of data pose a serious challenge, especially for biosensors and biomedical related data. In clinical practice, data from various modalities may not always be accessible for all samples, primarily due to cost constraints and limitations in data collection. Therefore, innovative methods must be developed to deal with different modalities of missing patterns. Fortunately, various interpolations,[64] estimations,[65] matrix-completion algorithms,[66] etc. have been successfully applied to optimize algorithms for practical applications.

Another challenge is data acquisition and analysis. Biological samples may have complex sample morphology, necessitating accurate recognition and segmentation, even when structure overlaps are irregular.[67] The quality and quantity of data used to train and test computer vision algorithms can greatly affect the performance of the algorithms.[68] It is critical to obtain annotated datasets that accurately represent the diversity and complexity of biosensor samples. In particular, analyzing single-molecule detection data is challenging and is largely limited by poor signal-to-noise ratio, signal overlap, and signal dispersion.[69] The development of new machine learning methods to reduce noise and extract multidimensional signal features can improve the resolution of pattern recognition and the sensitivity of objective identification.[70]

Improving the performance of computing hardware has become a significant challenge and is currently a bottleneck in the field. First, achieving effective biosensing through computer vision depends on the quality of hardware, such as cameras and sensors. Higher-quality equipment is necessary to achieve high accuracy. Second, computer vision applications often demand substantial computational resources and necessitate enhancements in hardware performance, such as GPUs, TPUs,[71] and the introduction of new chip architectures.[72] Faster storage devices and higher-speed network connections are also areas that require enhancement. Additionally, ongoing maintenance and updates contribute to the overall high cost. While computer vision algorithms require high-performance hardware, they also need to consider energy efficiency and cost reduction. Fortunately, with the advent of the new industrial era, there is more room to optimize these issues, such as the use of hardware accelerators and emerging computing paradigms like quantum computing.[73,74]

With the advent of the big data era, technological advances and the protection of privacy, security, and ethical principles have become paramount issues.[75] The proliferation of data-driven technologies, including computer vision, means that our personal information, once considered private, is increasingly likely to be exposed to the public. In the context of biosensor applications, computer vision may involve the analysis of large amounts of personal biological data.[76] This convergence of powerful technologies with private personal information highlights the urgent need to address the legal and ethical issues associated with data privacy and security. It is critical that strong security measures and strict access controls be put in place to protect this sensitive information from destruction, disclosure, or any form of exploitation. We hope and expect that the coming era of big data will continue to explore these trade-offs and find new ways to balance the various interests of humanity.[77]

Addressing these challenges requires advanced computer vision techniques, data preprocessing, machine learning, and domain-specific knowledge. Researchers and engineers in the field will continue to develop innovative solutions for successfully integrating computer vision into biosensor applications to improve healthcare,[78] diagnostics,[79] and medical.[80] Over the past few years, algorithmic advances have ushered in a new era of capabilities and possibilities for computer vision. The development of novel models such as deep learning models,[81] migration learning models,[82] Generative Adversarial Networks (GANs),[83] and semi-supervised and self-supervised learning techniques[84] has played an important role in addressing data labeling challenges. With the rapid development of mobile terminals such as smartphones,[85] tablets,[86] and wearables,[87] future artificial intelligence (AI) systems will indeed move toward miniaturization and portability. Miniature devices can perform many tasks locally without sending user data to the cloud for processing, helping to protect user privacy and sensitive information. The computing power of mobile terminals is increasing, making it possible to execute complex AI algorithms on small devices. As algorithms are carried out and enhanced, the ability to perform computer vision can be greatly improved.

Traditional biosensing methods offer major advantages, such as portability, simplicity, and low cost.[88] However, combining them with emerging technologies like computer vision further improves the overall performance and reliability of biosensing systems. The application of computer vision in biosensors holds great promise, yet it confronts some challenges that need attention. These challenges encompass enhancing computer hardware performance, optimizing sensor material performance, and refining biological applications. As research advances, data collection and sharing methods continually improve, and the cost and accessibility of disease surveillance technologies continue to decrease. Machine learning algorithms emerge as a promising avenue to further expedite progress in the field of biosensors. In the coming era of artificial intelligence, future biosensors may incorporate technologies, such as artificial intelligence, the Internet of Things, big data sets, and cloud computing to build AI systems for themselves.[89] Leaving digital traces can unlock vast opportunities. The digital realm mirrors the physical world, enabling us to migrate experimental designs and entire industrial processes to the cloud, allowing for the virtual extrapolation of our world. This has the potential to usher in a new era of industrial revolution.[90]

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Li Liu: Writing – original draft (equal). **Ke Du:** Supervision (equal); Writing – review & editing (equal).

DATA AVAILABILITY

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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