Optical Systems
for Advanced Sensing Application
From environment to cultural heritage monitoring

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October 2025

Optical technologies are known for their capability of providing a core technology for the development of high-performances sensors for critical monitoring applications; however, their widespread adoption remains mainly limited by the costs, size, and complexity of the interrogation equipment.

This research addresses these challenge by investigating the design of simple, robust, and low-cost sensing devices, targeting the main application of extensive monitoring of chemical and biochemical quantities and parameters.

Current monitoring strategies largely rely on discrete sampling, followed by laboratory analysis using complex analytical instruments, which require specialized expertise. On the contrary, future developments are expected to promote ubiquitous, real-time, and non-invasive monitoring through compact and affordable optical systems. The approaches proposed in this thesis aim to enable continuous in situ assessment across diverse contexts, including environmental systems, water quality monitoring, agri-food sustainability and safety, as well as the protection of cultural and natural heritage.

This evolution aligns with several United Nations Sustainable Development Goals (SDGs), such as clean water and sanitation (SDG 6), sustainable agriculture and food safety (SDGs 2 and 3), and sustainable cities and communities (SDG 11). In addition, it can significantly contribute to improving cultural heritage preservation procedures, a sector particular relevant in Italy since it also represents a key economic asset.

The research explores and experimentally validates two main application areas: water monitoring and cultural heritage conservation.

For water monitoring, Fluorescence Spectroscopy (FS) and fiber-based Surface Plasmon Resonance (SPR) sensors, integrated with Artificial Intelligence (AI) algorithms, are developed for the detection and identification of contaminants. SPR-based refractometers enable the measurement of refractive index variations as indicators of contamination, while fluorescence combined with microfluidics allows accurate and continuous pH monitoring. The SPR sensor design is optimized through numerical simulations to identify the most suitable geometry for experimental implementation, followed by the development of an automated calibration procedure. Similarly, a dedicated calibration method is established for fluorescence-based sensing, ensuring accurate and repeatable pH measurements across the full operational range.

For cultural heritage applications, the combination of fluorescence imaging, Optical Coherence Tomography (OCT), and AI-powered segmentation algorithms enables the discrimination between pigment and varnish layers, providing a non-invasive and cost-effective alternative to traditional analytical methods. OCT techniques allow real-time estimation of the thickness and surface roughness of protective layers on artworks, supporting safer and more informed conservation treatments. The simultaneous use of fluorescence further enhances the capability to assess the state and thickness of protective layers in real time.

Overall, the results demonstrate the effectiveness and versatility of optical fiber and light-based sensing approaches for real-time, minimally invasive, and distributed monitoring. The developed solutions represent a significant step toward the practical implementation of compact, affordable, and high-performance optical systems for environmental and cultural heritage applications. Through careful sensor design, proper calibration, and the integration of complementary optical techniques, this research confirms that high measurement accuracy can be achieved while maintaining portability, low cost, and ease of use.