AVANTES
MEMBER OF THE NYNOMIC GROUP

APPLICATION NOTE

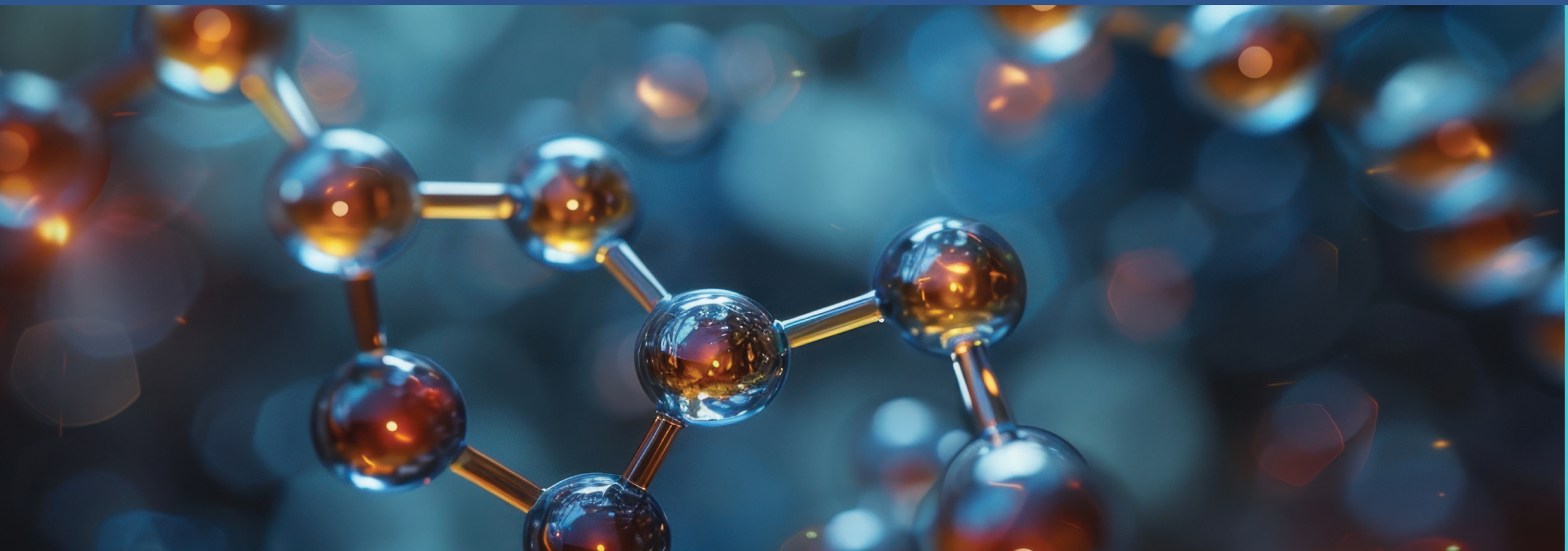
THE FUTURE OF SPECTROSCOPIC PERCEPTION IN PHYSICAL AI

FROM CLOUD AI TO PHYSICAL AI: SPECTROSCOPY AS THE FOUNDATION

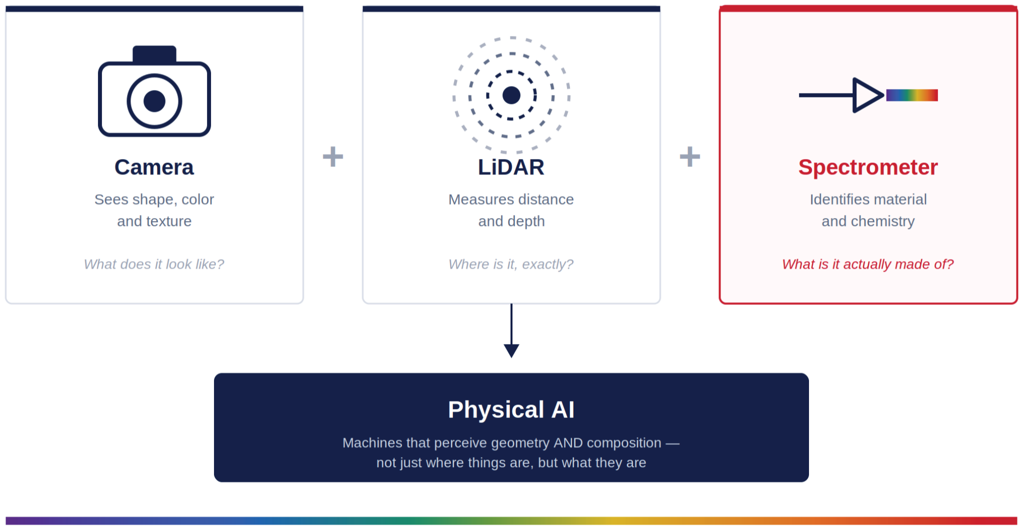
Dating back to well before the modern generative and agentic artificial intelligence (AI) renaissance, spectral data had long served as a foundational input for traditional machine learning neural networks which evolved into today's modern cloud-based AI. In computational drug discovery, machine learning models process massive spectral datasets of infrared and Raman spectra on servers to predict molecular properties and accelerate the screening of novel pharmaceutical compounds. Astrophysicists have widely utilized deep neural networks to analyze the emission and absorption spectra of distant stars and galaxies, categorizing exoplanets and identifying stellar compositions, allowing them to push beyond traditional linear algorithms such as principal component analysis. Furthermore, cloud-based chemometric models have been routinely deployed throughout the global supply chain to analyze agricultural imports to detect food fraud, such as honey adulteration or counterfeit olive oil. Across all of these models, optical spectroscopy acts as the high-fidelity chemical language that trains algorithms to interpret data, proving that light is a critical dataset for training AI models to interpret the physical world.

As AI integration expands beyond data centers, the requisite convergence of artificial intelligence and robotics is leading to the development of "physical AI." Physical AI is loosely defined as autonomous systems that operate within three-dimensional environments, and it is built on three primary pillars—perception, cognition, and action—in order to navigate physical spaces in real time. To operate efficiently without sacrificing size, weight, and power (SWaP) budgets, system engineers are increasingly recognizing the importance of shifting from traditional electronic sensing to photonics, especially in the perception layer.

Not only does utilizing photons rather than electrons drastically increase data bandwidth while simultaneously mitigating the thermal load associated with processing massive sensory inputs, but it also expands the sensory input space to allow for hyperspectral data analysis.



MINIATURE SPECTROMETERS ENABLING PHYSICAL AI



While photonic technologies like lidar and machine vision are foundational to physical AI due to their excellent spatial and geometric mapping, to achieve true comprehensive environmental perception, the future of robotics will require an understanding of chemical composition. Shifting from a paradigm where a robot simply avoids a liquid spill to one where it can identify the fluid's exact molecular structure requires us to effectively add “taste and smell” to complement the robot’s vision. These operational necessities are driving the demand for the integration of miniature spectrometers directly into the robotic perception layer. Just as today’s portable and edge-computing hardware is being designed to better withstand the shock, vibration, and thermal drift inherent in dynamic robotic platforms without compromising signal or throughput, the SWaP and durability of miniature spectrometers are rapidly improving to match. In many ways, this can be viewed as the culmination of decades of effort across the spectroscopy community to transition laboratory equipment into rugged, field-deployable instrumentation utilizing miniature OEM spectrometers.

Fiber-coupled miniature spectrometers are particularly well-suited for these applications since they allow designers to further decouple the optical and computing architectures from the distal end of the robot arm, typically referred to as the end-effector, by running low-absorption fiber-optic cables through the arm itself. Furthermore, this architecture places an interchangeable, lightweight, and highly durable spectral probe directly onto the moving end-effector while keeping the sensitive optical bench securely housed within the main robot chassis. Deep learning algorithms and chemometric models can now run directly on embedded microprocessors, rapidly translating raw spectral data into chemical classifications without cloud latency. Pushing miniaturization further, physical optics are increasingly being supplemented or replaced by computation to mathematically reconstruct high-resolution spectra from overlapping signals, delivering robust sensing in miniaturized footprints.

SPECTROSCOPIC DOMAINS FOR PHYSICAL AI

Precision Agriculture and Autonomous Crop Inspection

Precision agriculture provides a clear blueprint for how future physical AI could leverage more than just geometric awareness. For example, AI-powered drones are now routinely employing hyperspectral imaging to evaluate crop health and hydration status. Perhaps even more powerfully for true physical AI deployment, engineers have successfully integrated fiber-coupled, miniature near-infrared (NIR) spectrometers directly onto agricultural robotic end-effectors, demonstrating the potential to transition from broad mapping to automated point-by-point analysis. By employing NIR reflectance spectroscopy, these systems non-destructively measure the internal sugar content, or Brix value, of fruit while it remains on the vine. The robotic arm positions the fiber-optic probe against the fruit, capturing the overtone vibrational bands of O-H and C-H bonds, which allows edge AI to determine crop ripeness. While currently utilized for on-vine quality assessment (an integration rigorously validated in recent agricultural studies), this existing hardware architecture demonstrates exactly how a future, fully autonomous physical AI could make split-second decisions regarding chemical viability.

Autonomous Material Identification and Robotic Sensing

In robotic systems, laser-induced breakdown spectroscopy (LIBS) has long served as an exemplar demonstrating how miniature spectrometers are already deployed in extreme environments. From planetary analogue missions to high-speed scrap metal sorting facilities, autonomous rovers and robotic manipulators utilize high-energy laser pulses to ablate material targets. This generates a localized micro-plasma, the optical emission of which is collected via robust fiber optics and routed back to a compact, shock-resistant miniature spectrometer securely housed within the robot's main chassis. Crucially, extracting accurate elemental data requires precise, sub-microsecond synchronization between the laser firing and the spectrometer trigger to bypass the initial broadband continuum of the plasma. Moving forward, this established hardware architecture provides a direct pipeline for physical AI. Not only could an autonomous system classify material makeup in real time by analyzing elemental emission lines, but the AI could also dynamically optimize the trigger delay itself, adapting to varying material matrices on the fly to guarantee the highest possible signal-to-noise ratio.

AI-Enabled Surgical Robotics and Precision Medicine

Surgical robotics represents an even higher-stakes frontier, where the demand for label-free, in vivo molecular analysis is driving spectroscopy directly into the operating room. Endoscopic fluorescence and Raman probes have been gaining traction in biomedical diagnostics over the past two decades. While to date they have primarily been utilized for identifying cancerous tumors, they show great potential to be integrated into self-guided surgical robotics, particularly for enabling endoscopic continuum robots to navigate the human gastrointestinal tract. Mated to miniature Czerny-Turner spectrometers, these systems capture weak spectral signals, allowing embedded machine learning algorithms to map tumor margins. This precise robotic-optical integration creates the exact sensory framework that future physical AI models will need to autonomously interpret dynamic, living biological environments.

Environmental Monitoring / Water Quality Analysis

Moving off solid ground, autonomous surface vehicles and waterproof drones are changing how the industry monitors water quality across reservoirs, rivers, and coastal zones. Rather than relying solely on stationary buoys or manual sampling, these autonomous robotic platforms deploy multi-modal sensory stacks that rely heavily on miniature spectrometers. Utilizing fluorescence and absorbance spectroscopy, these systems monitor for hazardous chemical spills or map harmful algal blooms by measuring the fluorescence of chlorophyll-a and colored dissolved organic matter. The ultra-low power consumption of modern miniature spectrometers ensures these systems have the optical resolution to isolate specific fluorophores without burdening the drone's payload capacity or battery. The operational framework for these autonomous, spectrometer-equipped aquatic drones is well documented in applied environmental research, setting the stage for future AI-driven response systems.

Automated Recycling and Material Sorting

The industrial solid waste sorting sector highlights the processing speed achievable when miniature spectroscopy meets high-speed robotic automation, in high-throughput environments. Robots in modern material recovery facilities are tasked with sorting optically identical black plastics, a challenge where standard visible-light machine vision fails. To overcome this, engineers integrate miniature NIR spectrometers into the sorting line's perception layer. Operating in the 900 to 2500 nm wavelength range, these sensors capture the diffuse reflectance of plastics on a conveyor belt. Edge computing algorithms rely on unique NIR spectral signatures to differentiate between high-density polyethylene (HDPE) and polypropylene (PP) in milliseconds, creating a foundation for more complex physical AI to actively direct robotic arms in material sorting. The engineering principles behind this spectrally guided robotic sorting are widely cited in academic reviews on automated solid waste sorting technologies.

Autonomous Laboratories and AI-Driven Chemical Synthesis

Perhaps the area where spectroscopy-powered physical AI is having the most rapid impact is in the development of closed-loop, AI-driven laboratories, which rely on robotic platforms capable of real-time reaction monitoring and autonomous chemical synthesis. In these self-driving laboratories, mobile manipulators and robotic liquid-handling systems manage complex chemical reactions. To close the operational feedback loop, these systems utilize miniature UV-Vis and Vis-NIR spectrometers to perform transmission and absorbance measurements directly within reaction vessels. By passing a broad-spectrum light through a fiber-optic dip probe submerged by a robotic arm, these systems allow future physical AI models to monitor the concentration of active pharmaceutical ingredients or the formation of side products, dynamically adjusting parameters based on spectral data. The architecture of such autonomous synthesis environments is detailed in a wide range of recent chemical engineering and materials science frameworks.

THE NEXT FRONTIER OF ROBOTIC PERCEPTION

While AI development is moving too fast for anyone to make exact predictions with rigid timelines, one thing is certain: the role of miniature spectroscopy in physical AI will only grow. Algorithms are advancing rapidly, but a system's true capability will always depend on the quality of its sensory inputs. As edge computing hardware matures, the immediate future of robotic perception relies on true sensor fusion. The very near future will undoubtedly see autonomous systems overlaying precise, spectrometer-derived chemical signatures directly onto 3D lidar point clouds, enabling real-time decisions based on both spatial and molecular data.

To realize this potential, a fundamental shift in design philosophy is required. Engineers can no longer treat traditional machine vision and spectroscopy as siloed disciplines. To build the next generation of physical AI, they must design perception layers that integrate miniature spectrometers from the ground up. Ultimately, the transition from purely electronic, spatial sensing to comprehensive optical perception represents much more than a simple hardware upgrade; it is the necessary evolutionary step that will finally allow autonomous machines to interpret the true chemical reality of their environments.

BRIDGING THE HARDWARE GAP WITH AVANTES

Translating this vision into physical reality requires highly adaptable, rugged hardware. Avantes spectrometers are ideally suited to facilitate this shift, particularly as robotic and drone-based physical AI deployments demand an ever-growing diversity of spectroscopic modalities across the UV, Visible, and NIR regions of the spectrum. Furthermore, Avantes offers a wide variety of fiber-coupled light sources and interchangeable spectral probes, all of which are specifically designed for the strict SWaP constraints of OEM systems integration.

Beyond the optics, successful physical AI requires seamless sensor fusion. All of Avantes' OEM modules can be integrated into multichannel rack-mount systems that communicate via USB and Ethernet. The native digital and analog input/output capabilities of the Avantes AS7010 electronics board provide a superior interface for triggering and syncing with other devices, such as LiDAR or robotic controllers. Additionally, the Avantes AvaSpec DLL package—featuring sample programs in C#, C++, Python, LabVIEW, and MATLAB—enables system architects to easily develop custom, embedded sensor-fusion code.

For more information about the full range of OEM spectrometer options available for physical AI integration, please visit www.avantes.com or contact our applications specialists at +1 (303)-410-8668.

CONTACT

WE'RE HAPPY TO HELP

Curious how spectroscopy will help you reveal answers by measuring all kinds of material in-line, at your production facility, in a lab, or in the field? Visit our website or contact one of our technical experts. We are happy to help you!

Avantes Headquarters
Phone: +31 (0) 313 670 170
Email: info@avantes.com
Website: www.avantes.com

Avantes Inc.
Phone: +1 (303) 410 866 8
Email: infousa@avantes.com
Website: www.avantesUSA.com

Avantes China
Phone: +86 (0) 108 457 404 5
Email: info@avantes.com.cn
Website: www.avantes.cn

Follow us on social media: