Collaborative Robotics and AI-Driven Computer Vision for the Automation of Rotating Disc Electrode (RDE) Atomic Emission Spectrometry in Lubricant Analysis

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Abstract: This paper presents the ASSIST project, an automation framework for the Spectroil 100 Rotating Disc Electrode (RDE) spectrometer based on a 6-axis collaborative robotic system. By integrating an AI-driven Computer Vision subsystem and a dedicated calibration interface, the system achieves sub-millimetric positioning accuracy and real-time consumable verification. The robotic system manages the sequential installation of disc electrodes, rod electrodes, and oil cuvettes through optimized "Macro-Movement" libraries. The primary outcome is a significant decrease in manual labor, with an improved repeatability and reduced operator exposure to potentially harsh working conditions. Validation trials conducted in industrial environments confirm the robustness of the approach. Furthermore, the system preserves the intrinsic environmental advantages of RDE spectroscopy, with direct sample analysis without chemical solvents or argon gas, representing a sustainable "green" alternative to Inductively Coupled Plasma-based techniques.

1. Introduction

In the field of condition monitoring and predictive maintenance, the ASTM-D6595 method [1] remains the primary choice for screening wear metals and contaminants in lubricants. While newer technologies like Inductively Coupled Plasma (ICP) are popular, they require extensive infrastructure, including specialized gases and chemical diluents. In contrast, RDE spectrometry provides rapid analysis with minimal sample preparation but is traditionally limited by manual operation, requiring skilled personnel. ASSIST preserves the "green" benefits of RDE, which requires no argon or solvents, while introducing the automation efficiency typically found in ICP systems.

The ASSIST system addresses these limitations by transforming a conventional Spectroil 100 RDE spectrometer into an automated analytical platform (Figure 1). By integrating collaborative robotics (Industry 4.0 robotic arm) and intelligent sensing, the system manages batches of up to 40 oil samples without human intervention.

This transition addresses the challenges of mechanical tolerances in legacy hardware while significantly improving reproducibility and operational safety.

Fig.1 – Assist autosampler overview

2. Engineering the ASSIST Architecture

The core of this automation is a **6-axis anthropomorphic robotic arm** (UFACTORY xArm 6), characterized by a 5 kg payload and an impressive repeatability of **±0.1 mm**. This level of precision is essential because the Spectroil 100 was not originally designed for automated operation and presents relatively loose mechanical tolerance. To address this challenge, the robot is programmed to replicate the fine motor skills of a human operator, performing tasks such as: loading fresh electrodes, positioning oil cuvettes, and carefully removing waste after analysis. To manage these complexities, the system utilizes a dual-computing strategy where a Linux node handles the high-level AI and motion, while a Windows unit manages the spectrometer's native software.

3. Structural Precision: The Supporting Frame

Achieving sub-millimetric accuracy requires more than just a smart robot; it requires a mechanically stable reference structure. The ASSIST system is enclosed within a stiff aluminum framework composed of structural beams and protective metal panels. This "sensorized" rigid case ensures that the spatial relationship between the robot and the spectrometer remains constant, even if components need to be disassembled for maintenance. Calibration is supported by dedicated APIs and reference pins allow the system to compensate for manual assembly tolerances, ensuring that the robot can grab electrodes and move oil-filled cuvettes without the risk of spills or mechanical collisions.

5. Advanced Robotics and Fluid Motion

The use of a 6-axis arm enables high dexterity, allowing complex manipulation tasks to be executed efficiently. Through the development of **"Macro-Movement" libraries**, the robot does not simply move in jerky, discrete steps; instead, it performs optimized, continuous sequences. This approach enables smooth execution of critical operations, such as electrode insertion and gap positioning, reducing mechanical stress and variability. Every movement has been stress-tested on dedicated benches to ensure that the robot's real-world performance matches its technical specifications, prioritizing both speed and the integrity of the delicate spectrometer components.

6. Optimized Workspace: Racks, Bins, and 3D Printing

The workspace layout is a result of careful 3D modeling and simulation to minimize cycle time and prevent contamination. Custom racks for electrodes and oil samples have been manufactured using **3D-printed resin**, avoiding metallic contamination that could interfere with spectrometric measurements. This choice ensures that no stray metallic particles can interfere with the lubricant's results. Furthermore, the system incorporates a structured waste management approach through three distinct bins: one for used rod electrodes (which can be sharpened and reused), one for oily disc electrodes, and one for contaminated consumables (burned oil and plastic holders). This separation contributes to maintaining a clean and "green" laboratory environment.

7. Sensory Awareness and Real-Time Monitoring

ASSIST is "aware" of its environment through a dense network of sensors. Magnetic sensors verify that the removable 10-sample rack lines are correctly seated, while visual sensors confirm that each slot actually contains an oil sample before the robot attempts to grab it. Capacity sensors monitor the "stock" of electrodes, ensuring the robot doesn't start a batch without enough electrodes. Even the spectrometer door and waste bins are monitored to prevent overflows or mechanical interference, creating a fully "closed-loop" system that can pause itself if a mismatch is detected.

8. AI-Driven Vision and Infrared Monitoring

A key component of the system is the AI-driven Computer Vision subsystem based on an Infrared (IR) camera, mounted outside the combustion chamber. Using Artificial Intelligence, the system generates comparative masks to verify that the analytical cell is clear before loading new consumables. Most importantly, the camera verifies the electrode gap distance required by ASTM-D6595, providing a digital fail-safe that human operators once had to check by eye.

9. Safety, Compliance, and the Human Element

While the robot does the heavy lifting job, human safety remains the priority. The entire system is enclosed in polycarbonate protective panels with interlocked sliding doors. If a door is opened during a run, the system immediately enters a safety mode and pauses all motion. The safety screen avoids the operator collision risks, reduce uncontrolled emissions of smoke, smell, noise, and to protect the oil samples from possible environmental contamination (dust). The system has successfully passed **CE compliance testing**, ensuring it meets international standards for industrial and laboratory safety.

10. Seamless Logic and User Interface

The ASSIST platform is controlled through a web-based interface designed to simplify interaction with the system. Operators can manage batches, view historical results, and monitor real-time telemetry from any connected device. The software architecture allows the robot to handle the sequential installation of electrodes and cuvettes while simultaneously communicating with a customized version of the Spectroil software via specialized APIs. This integration ensures that the standardization and daily checking protocols, traditionally the most tedious part of the day, are handled automatically.

11. Operational Workflow and Daily Routine

The daily workflow begins with system initialization and automatic verification procedure (daily check). The robot automatically warms up the instrument and runs standardization samples (0, 100, and 900 ppm) following Spectro-Sci procedures. Once the software confirms the results meet the required acceptability profiles, the operator is cleared to load the main analysis batch. The robot then takes over, managing the door, the electrodes, and the samples in a precise sequence. While the total cycle time per sample is slightly longer than a manual test to ensure safety, the "unattended" nature of the work is the true efficiency gain.

12. Field Validation: From Italy to Chile

The ASSIST system has undergone extensive validation in industrial environments. Currently, the system is a permanent fixture at the **Mecoil Laboratory in Italy**, where it serves as part of the routine analytical line. This "stress test" involves processing thousands of samples to fine-tune the algorithms and movement paths. Simultaneously, a second unit is undergoing pilot trials at **Proteco Chile SpA in South America** [2]. In the Chilean mining and heavy industrial sectors, where high-volume oil analysis is critical for preventing catastrophic machine failure, the ability to automate RDE spectrometry in harsh, non-laboratory environments has proven indispensable.

13. Conclusions: A Sustainable Future

The ASSIST system significantly reduces manual intervention in RDE spectrometry (over 80%) of the manual labor associated with RDE spectrometry. By freeing technicians from repetitive tasks and exposure to noise, it allows them to focus on high-value data interpretation., improving repeatability and operator safety while maintaining the intrinsic advantages of the technique. Furthermore, as a "green" solution that avoids the heavy gas and chemical requirements of ICP, ASSIST represents a significant step forward in sustainable laboratory practices for the global lubricant condition monitoring industry.

References

[1] *ASTM D6595-17 Standard Test Method for Determination of Wear Metals and Contaminants in Used Lubricating Oils or Used Hydraulic Fluids by Rotating Disc Electrode Atomic Emission Spectrometry*.

[2] https://youtu.be/3h9JEbPvmUA