

Current Status and Future Prospects of Analytical Instrument Automation: Toward the Realization of Plug & Play

UENO Kusuo

ISHIKUMA Toru

To promote laboratory automation, it is desirable not only to automate individual analyzers but also to respond flexibly to daily changing tasks such as pretreatment and test conditions, and to transfer samples and data between instruments without manual operation. This paper introduces LADS OPC UA, a standard promoted by JAIMA (Japan Analytical Instrument Manufacturers Association), and describes its current status.



Introduction

While automation has advanced in many manufacturing plants, most laboratory analytical instruments are still used as standalone devices, and their operation and data processing are not managed within an integrated system, resulting in limited automation. Furthermore, significant time is spent on manual sample preparation and transport, various measurements, data collection, and analysis, leaving researchers with little time for creative activities. Two major reasons can be identified for the lack of automation in laboratory instruments. First, daily tasks are not uniform and are subject to frequent changes. Second, there is no common communication standard, making the connection of analytical instruments labor-intensive. This paper explains the concept of plug-and-play, which will be required for future laboratory instruments, describes the current state of automation, and outlines the content and current initiatives of the LADS (Laboratory and Analytical Device Standard)^{[1]-[4]}, a communication standard promoted by JAIMA (Japan Analytical Instruments Manufacturers' Association). Finally, the paper discusses the issues that the industry should address.

Current Status and Challenges of Analytical Instrument Automation

Differences Between Factory and Laboratory Automation

Automation is often associated with factories, where labor-saving and manpower reduction have progressed, while laboratory automation remains limited. This is because the requirements for automation differ between factories and laboratories. The primary objective of factory automation is to improve production efficiency, aiming for higher throughput and reduced production costs. As a result, control and analysis targets, formulations, and operating conditions are often standardized within production technology, and the equipment and devices used are specialized for these purposes. The cost-effectiveness is substantial, justifying larger investments.

Conversely, the goal of laboratory automation is to free up researchers' time, and the ability to easily change procedures and conditions to accommodate diverse experiments is particularly important. Therefore, general-purpose equipment is typically used, and analysis targets and conditions are not fixed.

When considering laboratory automation, the diversity of targets often leads to high costs, and automation proposals

tend to only support fixed processes. Given the cost-effectiveness, manual operation remains more flexible, resulting in many cases where automation is abandoned.

Plug-and-Play for Analytical Instrument Automation

Why are the costs of automating analytical instruments and modifying automated systems so high? Two major factors can be identified. First, analytical instruments are often designed with the assumption that sample transport and maintenance are performed manually, making it difficult to automate operations such as opening doors and transporting samples with robots. Second, past laboratory automation efforts have relied on instruments with proprietary communication standards and result formats, requiring users and system integrators to understand each instrument's specifications for connection, which incurs significant costs.

To reduce the cost of introducing automated systems and facilitate system modifications, a plug-and-play mechanism is desirable, whereby instruments can be used simply by connecting them. Plug-and-play, as seen with USB or network-connected printers, allows devices to be automatically detected and appropriately configured upon connection. In the future, if laboratory instruments can be connected and the system can automatically recognize the type and functions of each device, the cost of automation for users will be significantly reduced. By adopting common communication standards and information models that describe device capabilities, the need for configuration during installation or modification will be minimized, and basic operations will be possible simply by connecting the devices. Achieving "plug-and-play for analytical instruments" is a key challenge for manufacturers going forward.

Emerging Automation Solutions in the Market

Recently, technologies supporting laboratory automation have advanced rapidly, and tasks previously reliant on manual labor are increasingly being automated. Here, representative examples of practical implementation are introduced, including autonomous experimental systems, informatics management solutions, and robotic automation of repetitive tasks.

Autonomous Experimental Systems

In the field of materials discovery, autonomous experimentation has progressed to the point where most tasks previously performed by humans are now automated and replaced by

robots. Robots can perform weighing, dispensing, and measurement, aggregate and analyze the resulting data, and use Bayesian optimization techniques to select subsequent experimental conditions. These systems autonomously control manufacturing and analytical instruments to search for optimal material or process conditions. Although challenges remain regarding process and task changes, there are examples of achieving results in about eight days for tasks that would take humans several months^[5], demonstrating significant achievements in materials discovery.

Informatics Management

Many companies provide Laboratory Information Management Systems (LIMS) as laboratory information management solutions. LIMS software efficiently manages laboratory information, offering functions such as sample management, data collection, tracking of analytical results, and report generation. Laboratories often have a mix of old and new equipment, and issues such as devices that cannot connect to LIMS or the use of printed records persist. However, informatics management technologies for integrating legacy instruments are emerging, and the adoption of standards such as OPC UA is expected to accelerate this integration.

Robotic Automation of Repetitive Tasks

Robotic automation of repetitive tasks is also advancing, with reports indicating that, for certain operations, robots can achieve greater experimental accuracy and reproducibility than skilled operators. However, challenges remain, such as the difficulty of teaching and adjusting movement coordinates. Recently, technologies have been developed that detect positional deviations using cameras and transport objects to the correct location, even if their positions shift slightly. If individual instruments can indicate the relative position from a reference point to the operation point, robots and automated devices can more easily recognize operation points. These approaches are expected to further simplify automation in the future.

At HORIBA, examples of robotic automation include the EMIA/EMGA series, which measure sulfur, carbon, hydrogen, nitrogen, and oxygen using infrared absorption and thermal conductivity. Since the 1980s, devices have been provided for transporting crucibles and automatically weighing auxiliary agents. In the LA-960 particle size distribution analyzer, which uses laser diffraction and scattering, automation includes automatic reading of sample bottle ID codes, opening and closing of bottle lids, and pipetting of additives and samples after the operator places the sample bottles.

Trends in Communication Standards for Analytical Instruments

Trends Toward Standardization

Generally, standardization progresses as markets expand, but the speed and extent of standardization vary by industry. For example, the GEM300 communication standard for semiconductor equipment is an internationally unified standard, allowing equipment manufacturers to communicate with users using essentially the same specifications. The unification of this communication standard has made a significant contribution to the development of the semiconductor industry.

In contrast, the standardization of laboratory automation is still at a stage where multiple proprietary standards coexist. While certain devices or specific parts of laboratory automation have seen progress in standardization, there is no comprehensive standard aimed at overall efficiency. Within this context, OPC UA (Open Platform Communications Unified Architecture) and LADS (Laboratory and Analytical Devices Standard), which is based on OPC UA and tailored for laboratory use, are introduced as promising candidates for communication standards.

LADS OPC UA is an international standard, including Japan, and can be commonly used for relatively simple devices such as flow meters and pumps, as well as for transport devices like robots, stirrers, and analytical instruments. As the number of compliant devices increases, automation is expected to become more accessible to users.

OPC UA

OPC UA has a long history as a communication standard, and the OPC Foundation, which develops and maintains its specifications, comprises over 1,000 member companies (as of May 2025), mainly from the industrial/manufacturing and IT sectors. Recently, more IT companies and end-user companies with manufacturing sites have joined, and the promotion of OPC UA adoption by end-users and implementation by IT companies are expected to accelerate its spread. In Germany, OPC UA is used as a core standard supporting Industrie 4.0, and both Singapore and China have adopted OPC UA as a national standard (Singapore: SS IEC62541:2019, China: GB/T 33863). As such, OPC UA is used as a communication standard in various industries and is considered a viable solution for plug-and-play of analytical instruments.

OPC (OLE for Process Control), from which OPC UA derives its name, was originally developed based on Microsoft^{®*1}'s OLE technology as a network technology for process automation. It has since evolved into a platform-independent form, becoming OPC UA (Open Platform Communications Unified Architecture), and continues to develop across various industries. OPC UA provides a unified framework for facilitating data exchange between different devices and systems, with the following four key features:

- **Platform Independence :**
OPC UA operates not only on Windows^{®*1}, but also on Linux^{®*2} and other operating systems.
- **Secure Communication :**
Robust security features are incorporated to ensure data confidentiality, integrity, and authentication.
- **Information Model :**
OPC UA supports flexible information models built with object-oriented principles to handle complex data structures, enabling standardized representation of device and software functions and information.
- **Communication Protocols :**
Multiple communication protocols are supported, including TCP/IP, HTTP, and WebSocket.

Recently, OPC UA has attracted attention for its high level of communication security, and its adoption as a cybersecurity measure is increasing. In the United States, the U.S. Cyber Trust Mark aims to strengthen the security of consumer IoT products, and in the EU, the EU Cyber Resilience Act is being enacted to regulate cybersecurity requirements for products with digital elements. OPC UA has a compliance mapping table for the technical requirements of IEC62443-4-2 Component, referenced by these cybersecurity standards, and can meet many requirements for cyber resilience. Additionally, OPC UA has received high safety ratings from Germany's Federal Office for Information Security (BSI) based on security evaluations.

*1 Microsoft Corporation's registered trademark in the United States and other countries

*2 Linux is a registered trademark or trademark of Linus Torvalds in Japan and other countries

As shown in Figure 1, OPC UA is developed and maintained by the OPC Foundation as a standard, neutral communication architecture, consisting of OPC UA basic services, OPC UA information models, industry-specific companion information models by OPC UA partners, and vendor-specific extension models. Thus, basic communication is standardized, while parts specific to industries or devices can be separately defined, providing a flexible structure.

LADS OPC UA: Purpose, Structure, and Use Cases

Since 2020, the development of LADS (Laboratory and Analytical Device Standard) has been led primarily by SPECTARIS, the German association for optical, analytical, and medical device industries, in collaboration with users, application developers, and device manufacturers. The purpose of LADS is to promote digital transformation in laboratories by providing a unified, robust, and secure common interface. The first edition of this communication standard was published in December 2023. In addition to the basic OPC UA specifications, LADS incorporates device management specifications (10,000-100 Devices), machinery and result transfer specifications (40,001-1 Machinery), and specifications for identification and information retrieval (10,000-110 Asset Management Basic (AMB)).

Figure 2 illustrates the target concept of LADS OPC UA. As shown in the figure, LADS aims to achieve plug-and-play connectivity, where devices are easily connected, and interoperability between devices.

Three use cases are defined for LADS OPC UA:

- **Basic Automation**: Remote monitoring, transmission and reception of alarm signals, and remote operation.
- **Orchestration**: Programs that coordinate the operation of multiple devices and management of data output from devices.
- **Service & Asset Management**: Maintenance based on preventive and failure prediction, and resource management for individual devices or groups of devices.

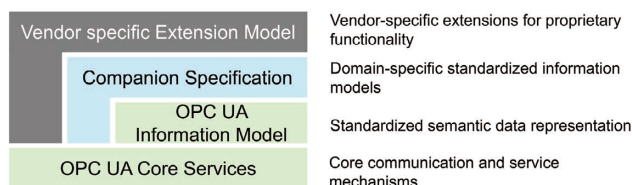


Figure 1 OPC UA base service and model structure.

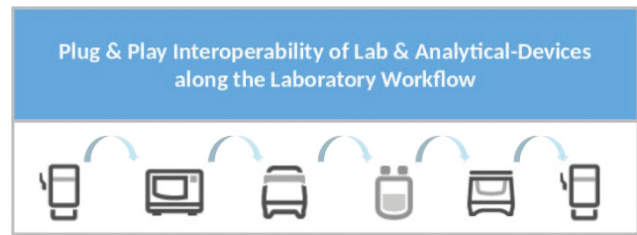


Figure 2 LADS target image

Given the variety of laboratory devices, LADS OPC UA is intended to be used for acquiring information from devices and issuing commands to them, with results and other data managed and referenced by higher-level applications such as LIMS.

To realize plug-and-play functionality for each device, LADS OPC UA provides standardized “function blocks” that represent the capabilities and features of laboratory devices. Rules for combining these function blocks have also been established. By having devices use these standardized function blocks according to specified rules, communication with devices becomes easier. For example, the “Function” block plays a crucial role in use cases involving remote monitoring and control. By utilizing these blocks, remote clients can easily search for and control device functions such as sensors, controllers, and timers. Furthermore, multiple “Functions” can be grouped into a “Function Unit” to perform larger tasks, enabling program execution and state transition monitoring at the unit level. Additionally, these data can be stored as audit-traceable records.

Collaborative and Competitive Domains for Automation

As discussed, the lack of a common communication standard—due to each company relying on proprietary protocols—remains a major barrier to automation. What, then, should analytical instrument manufacturers do to promote the adoption of communication standards?

For example, the workflow of laboratory automation can be generalized as a cyclical process: “Planning” → “Experiment/Operation” → “Recording” → “Analysis” → “Planning,” as shown in Figure 3. The communication standards connecting these process steps are not unified, with each company creating its own protocols. To address this, it is necessary to promote communication standards in the collaborative domain for inter-process connectivity. Meanwhile, to maintain competitiveness, companies should differentiate their products through proprietary technologies in areas outside

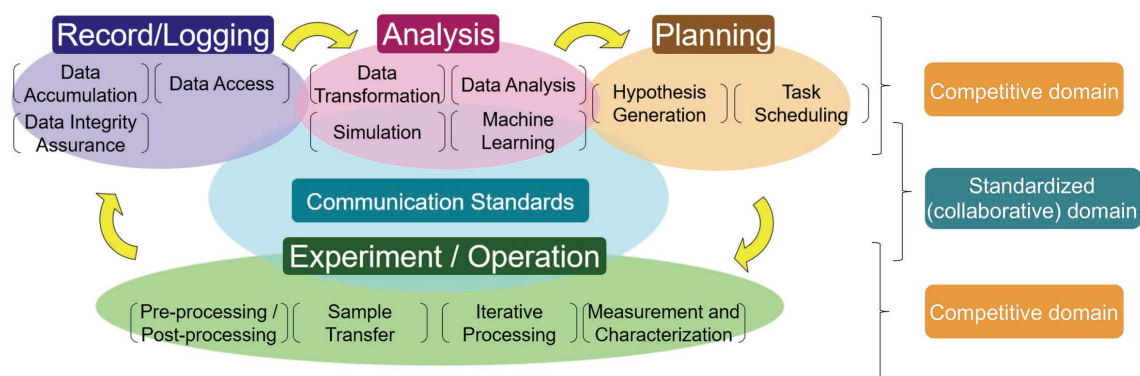


Figure 3 Laboratory works supported by communication standard

the common and standardized (collaborative) domains. By clearly defining the collaborative domain, companies can avoid developing everything from scratch and focus their development resources on the competitive domain.

Thus, appropriately distinguishing between collaborative and competitive domains is key to balancing industry-wide progress with individual competitiveness. Manufacturers are expected to actively pursue both collaboration and competition as part of their “standardization strategy”^[6].

To achieve this, it is important to regard information models and result formats in OPC UA as part of the collaborative domain, and to promote industry-wide efforts toward standardization and unification. By defining the structure and semantics of information in a common format, seamless data integration among devices from different manufacturers becomes possible, facilitating overall system integration. For analytical instruments in particular, standardizing measurement results and status information formats enhances compatibility with Manufacturing Execution Systems (MES) and production management systems, significantly advancing automation. Meanwhile, elements such as measurement algorithms and device control methods, which contribute to product differentiation, should be maintained as part of the competitive domain, allowing each company to further develop unique technologies. In this way, striking the right balance between standardization and differentiation is essential for both industry-wide development and the maintenance of individual competitiveness.

Conclusion

This paper has discussed the current status, challenges, and expectations regarding the unification of communication standards for analytical instruments across the industry.

Two major factors hindering laboratory automation were identified: the need for flexible adaptation to changes in operational tasks, and the absence of common communication standards among devices, which results in significant effort for device integration. To address these issues, the widespread adoption of common communication standards and the realization of plug-and-play functionality are essential. Achieving this requires the industry as a whole to clearly distinguish between collaborative and competitive domains, promoting standardization in areas where collaboration is possible while concentrating resources on competitive domains. Accordingly, analytical instrument manufacturers should actively engage with industry associations and standardization consortia, contributing to the development of information models and the establishment of open formats. JAIMA also plans to continue its participation in the standardization and development of LADS OPC UA, as discussed above, and will further promote awareness and dissemination through seminars and exhibitions.

* Editorial note: This content is based on HORIBA’s investigation at the year of publication unless otherwise stated.

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UENO Kusuo

Deputy Department Manager
Material Solution Dept.
Material & Semiconductor Center
HORIBA, Ltd.



ISHIKUMA Toru

Senior Adviser
Research Subcommittee
Technical Affairs Committee
Japan Analytical Instruments Manufacturers’
Association