ISSN 0915-9916

Readout

HORIBA Technical Reports

April 2026
English Edition No. 60

HORIBA's Digital Transformation

Foreword : The Challenge of Transitioning from Product-Oriented to Solution-Oriented Approaches *NAKAMURA Hiroshi*
Guest Forum : History and Development of AI, Future Society and Civilization *AMARI Shunichi*
Digitalizing the Laboratories: Expectations for instrument manufacturers *HITOSUGI Taro*

HORIBA

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In this issue, we introduce real-world examples of what HORIBA can deliver through its automation and digital transformation technologies in a rapidly digitalizing society. We highlight applications across a wide range of fields, including automotive testing and development, materials analysis, air and water quality monitoring, healthcare and pharmaceuticals, fuel cells, semiconductors, and even service and support.

Name of this Journal

This Journal is named “Readout” in the hope that “the products and technology we have created and developed will be read out and so become widely known”.

HORIBA’s Digital Transformation

Foreword

Guest Forum

Review

Feature Article

Energy & Environment

-Photographer MATSUI Hideo-
(Member of Nikakai Association of Photographers)

Having heard the news that the lotus had begun to bloom, I visited a lotus pond close to a village. The sparrows playing on the lotus leaves and petals looked just like little children chatting with their friends, and the scene made me smile warmly.

Bio & Healthcare

Materials & Semiconductors

Foreword

The Challenge of Transitioning from Product-Oriented to Solution-Oriented Approaches

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Senior Corporate Officer
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Dr. Eng.

As part of its growth strategy outlined in the medium- to long-term management plan called MLMAP2028, HORIBA has set forth the goal of "accelerating the shift from product sales to solution sales, and expanding its business through solutions centered on automation and data management." The digital transformation (DX) of manufacturing and development facilities is progressing in many industries, not only as a means of labor-saving through automation, but also as data-driven AI-based materials development (materials informatics). On the other hand, the DX and automation of analytical and measurement instruments have yet to advance sufficiently, representing a significant business opportunity for us. HORIBA has long been engaged in DX and automation for the automotive industry, and a review of this history suggests that it can be broadly divided into three generations.

The first generation was automation, aimed at streamlining business processes. HORIBA began developing and manufacturing exhaust gas measurement instruments in the 1950s. Subsequently, as exhaust emission regulations were enacted worldwide, the procedures and calculations for testing became increasingly complex, making it difficult to manage everything manually. In the 1970s, HORIBA acquired Inter Automation in the United States, and began offering the Test Automation System software, which centrally manages multiple measurement instruments and outputs test results in formats tailored to the requirements of each country. In a sense, this marked the beginning of HORIBA's outward-facing digital transformation (DX).

The second generation emerged in the 1990s: the optimization of business procedures through big data analytics and data science. During this period, nearly all automobile functions became electronically controlled, leading to a dramatic increase in the number of control parameters. Consequently, the volume of experiments required for parameter optimization grew exponentially, necessitating greater efficiency. In 2000, HORIBA established the joint venture SRH in the United Kingdom with RICARDO and Schenck, integrating RICARDO's expertise in Design of Experiments (DOE) for engine development into its automation platform. This enabled the proposal of optimized experimental workloads through efficient experimental planning and statistical analysis.

The third generation, starting in the 2000s, was characterized by innovation through virtualization and digital twin technologies. The advancement of hybrid technologies in the automotive industry led to increased complexity, with the addition of batteries and fuel cells to engines and motors. Traditional development methods resulted in longer evaluation and adjustment times as system components increased. In 2005, HORIBA acquired Schenck's DTS division and, particularly through the team in Troy, Michigan, in the United States, acquired technologies for virtualizing engines, batteries, and drivetrains. These technologies made it possible to evaluate systems even when physical test objects were not available by combining virtual models with real test subjects. Virtualization fundamentally transformed business procedures, enabled front-loading of development tasks, and dramatically shortened development cycles. Although the term "digital twin" did not exist at the time, these virtual models can be considered its forerunners.

Leveraging this extensive experience in automotive development, we believe that applying automation for business process streamlining, data science for procedural efficiency, and virtualization and digital twin technologies to other fields will make it possible to achieve a major shift from product sales to solution sales. In the fields of "energy and environment," "bio and healthcare," and "materials and semiconductors," which are our areas of focus, competition in advanced materials development and data management is intensifying. There is a growing need for innovation in development and manufacturing processes utilizing materials informatics. In these domains, we aim not only to provide analytical and measurement technologies, but also to offer solutions that automate and optimize development and production operations, transform business processes, accelerate advanced materials development, and contribute to solving societal challenges in each field.

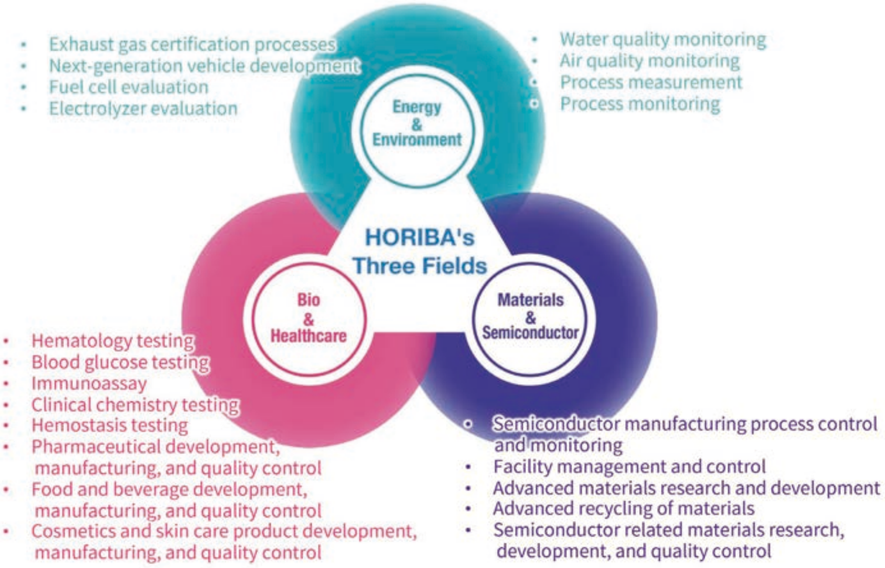

Figure 1 HORIBA's three challenging fields

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

Guest Forum

History and Development of AI, Future Society and Civilization

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Introduction

The 2024 Nobel Prize in Physics was awarded to Professor Geoffrey Hinton of the University of Toronto, and to Professor John Hopfield of Princeton University, for their contributions to the development of artificial intelligence. Physics is traditionally the study of the “principle of matter,” so many were surprised that the Nobel Prize was awarded for work associated with AI, which deals more with the “principle of phenomena.” AI is a rapidly developing technology with a significant impact on society, and the Nobel Committee demonstrated foresight in recognizing this trend. It was truly a historic achievement. Today, we possess two types of intelligence: natural intelligence based on the human brain, and artificial intelligence. In this article, I would like to explore the history of both forms of intelligence, compare them, and reflect on how AI is influencing our society and civilization.

History of AI Development — The First Boom

Here, I will briefly outline the history of AI. In the late 1950s, computers began to proliferate and became accessible to researchers. Computers are Turing machines, that is, universal machines, possessing universality not only in numerical computation but also in logical computation. With this, expectations rose that human intellectual functions could be realized on computers. Consequently, an AI conference was held at Dartmouth in the United States, where, at the invitation of McCarthy, prominent scholars including Shannon, von Neumann, and Simon engaged in discussions over the course of a month. There was a surge of momentum toward realizing intelligence on computers through programs that made full use of symbols and logic.

On the other hand, human intellectual functions are supported by neural networks, which begin in infancy and become sophisticated through learning, eventually reaching completion. In fact, progress through learning continues throughout life. Therefore, the idea emerged that by constructing models resembling neural circuits on computers and applying learning to them, universal intellectual functions could be realized. This idea was advocated by cognitive scientist Frank Rosenblatt, who called this device the perceptron*. The success of modern AI is nothing other than the advanced development of the perceptron.

These two streams were enthusiastically received at the time, a period referred to as the first AI boom. However, the capabilities of computers at that time were far from sufficient to realize intellectual functions, and the initially anticipated results were not achieved. After about ten years, the enthusiasm faded, and the "winter" period of AI research arrived. It was not until the 1980s, after twenty years, that enthusiasm returned.

*The perceptron is an algorithm modeled after the neural circuits of the human brain. It receives multiple inputs, applies weights, and outputs a single signal.

The AI Winter and Japan

Turning to the situation in Japan, the central challenge of neuroscience is to study the mechanisms of the brain. However, the brain is exceedingly complex, and linking its structure to intellectual functions is extremely difficult. Although individual findings regarding neurons and their synaptic connections, which constitute the brain, were accumulated, these were still far from being connected to information processing, let alone intellectual functions.

Therefore, from the perspective of information science, research arose to create theoretical models and explore the fundamental principles of what kinds of information processing are possible in neural networks. This is the study of neural models. In Japan, research in this field progressed hand in hand with physiological studies, guided by outstanding leaders such as Professor Masao Ito of the University of Tokyo, who foresaw future developments.

While there was a "winter" period in Europe and the United States, in Japan during the 1960s and 1970s, research budgets were small from the outset, so even during the winter period, there was little room for further cuts. Thus, unlike in the West, there was no true "winter" period; researchers could immerse themselves in research they found interesting and important. Consequently, world-leading research emerged in Japan during this era.

I myself became interested in learning in multilayer neural networks, or perceptrons. At that time, only the final layer of neurons in multilayer networks underwent learning, while the neurons in the intermediate layers did not. Naturally, the intermediate layers should also learn, but because the basic model used was the McCulloch-Pitts neuron, which could take only binary values (0 or 1), an effective learning method could not be found.

To overcome this, I published the stochastic gradient descent learning method, which forms the basis of learning, in 1967, enabling intermediate layers to learn as well (Figure 1). This was possible because I adopted an analog neuron model. The same concept did not emerge in the West until nearly twenty years later, during the second boom, with the error backpropagation method by Rumelhart, Hinton, and others. Using computers, which had just been introduced at the time, I conducted simulations and demonstrated that the method worked successfully. I succeeded in discriminating between two groups of pattern classes that were not linearly separable. I believe this was the world's first simulation example of deep learning.

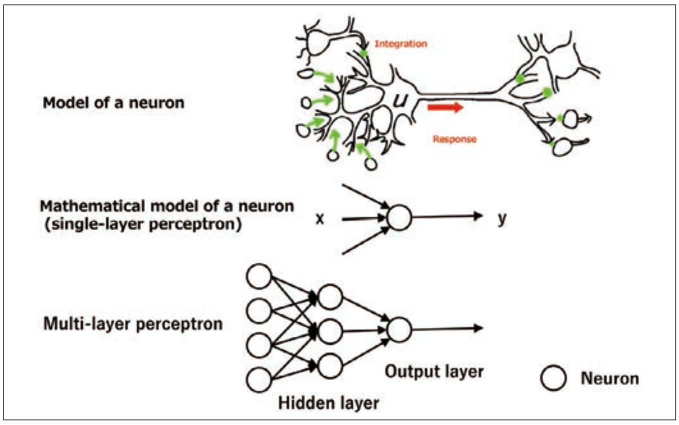

Figure 1　Neural circuit models, mathematical models of neurons (single-layer perceptron), and multilayer perceptions.

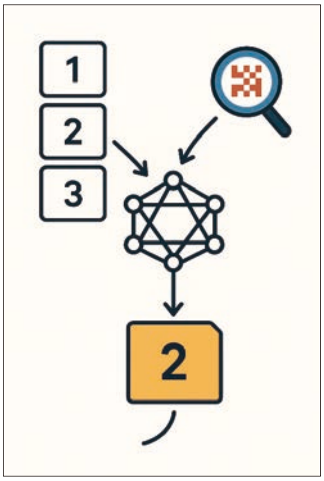

Figure 2　Associative memory model

Building on this, I was fascinated by the potential of neural networks as models of the brain and published a model of associative memory in 1972 (Figure 2). Human memory differs from computer memory. On computers, memory items are assigned addresses and written precisely; retrieval is conducted using these addresses as cues. However, human memory is much more ambiguous. Although its mechanism remains unclear, humans recall memory items based on related information. Memory items are not stored exactly as they are but are associated with various items, which become key patterns for recall. This process could be described as generating memory items from keys.

I proposed a mechanism in which several memory items are stored in a simple neural model and are recalled and generated from associated key patterns. This model included both the recall of fixed patterns and sequential memory, where a series of items are recalled one after another from a given pattern. Surprisingly, ten years later, Hopfield published a model of associative memory and discussed the issue of memory capacity using random patterns. While this was an excellent study, his model was identical to the one I had proposed (indeed, mine was more general, as it included sequential recall).

Although I have presented two examples, I also conducted research on statistical neurodynamics and self-organization theory. Research during this period in Japan was not limited to my own work. Kaoru Nakano, preceding me, proposed an associative memory model, and Kunihiko Fukushima published the mechanism of convolution in multilayer neural networks in 1978, naming it the Neocognitron. This is a fundamental technology still used in modern deep learning.

The Second Neuro Boom

Entering the 1980s, the winter period for neural models came to an end. Before this, symbolic and logical AI shifted from the grand dream of realizing intellectual functions to a more practical approach: implementing the vast knowledge possessed by experts into computers, storing expert knowledge as rules for "if this, then that," and reasoning based on these rules. This approach, though steady and practical, yielded certain results.

However, cognitive science, which had progressed in tandem with AI research based on symbols and logic, was not satisfied with this. They made a dramatic shift in policy, asserting that human intelligence is realized by parallel computation based on information distributed and stored in neurons—a concept known as Connectionism. As a result, research intensified on neural network models, with the participation of physicists and hardware researchers joining the rising tide, merging with traditional neural model studies to create a massive boom.

When the first international conference on neural networks was held in 1986, Japan was recognized as a hidden leader, and both Kunihiko Fukushima and I delivered invited lectures. Subsequently, the International Neural Network Society was established, and we became founding directors. Later, I was nominated as president. However, contrary to widespread expectations, the computers of that era could not produce useful results in realizing intellectual functions. Of course, many achievements were further accumulated during this period. Nevertheless, entering the 1990s, another winter period arrived.

The Third AI Boom

Even during the so-called "winter" periods, fundamental technologies continued to advance without interruption. During this time, computers achieved remarkable progress, and databases were systematically developed. Entering the 2010s, these advancements exploded onto the scene. The initial breakthrough occurred in image recognition competitions, where deep learning neural networks participated and overwhelmingly outperformed traditional methods that relied on programmed rules, demonstrating the superiority of learning-based approaches. Furthermore, the capabilities of deep learning have now surpassed even human recognition abilities.

Moreover, AI has entered the world of Go, quickly exhibiting performance that surpasses human players. Today, professional Go players use computer AI to study and improve their skills. In this domain, alongside deep learning, a technique called reinforcement learning is employed. This method involves sequentially manipulating game states to achieve optimal outcomes. Developers of Go game AI applied this technique to predict the three-dimensional structures of proteins from molecular formulas, resulting in the development of AlphaFold—a groundbreaking technology that was awarded the Nobel Prize in Chemistry. Notably, this technology has been made freely available and is proving invaluable across numerous industries, including pharmaceuticals and materials chemistry.

The progress is not limited to image processing. Text consists of sequences of symbols over time. Large Language Models (LLMs) have emerged to process such sequential linguistic information. These models can accurately answer questions posed in natural language, perform translations between different languages, and even generate computer programs according to instructions. The innovation does not stop here. In image generation, new technologies have appeared that, in response to prompts, process white noise to create remarkable images (Figure 3).

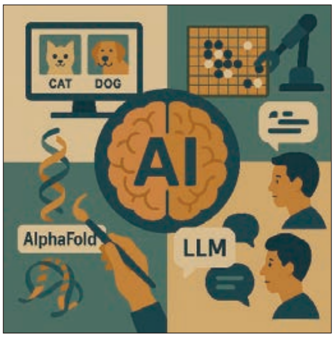

Figure 3 The third wave of AI

Remarkable Advances in AI Technology

AI technology is now developing at an astonishing pace, with its capabilities improving daily. The number of users of generative AI, such as ChatGPT, is increasing exponentially, and these tools are being conveniently utilized not only by students and researchers but across all workplaces.

At the foundation of these technologies lie methods such as stochastic gradient descent, associative memory models, and convolution techniques for multilayer circuits, which were originally proposed in Japan. These techniques have now been dramatically advanced. The Nobel Prize was awarded to Hinton and Hopfield, not for the origins of these ideas, but for their direct contributions to the modern development of AI since the 1980s. This is reasonable, as Japan lacked both the vision to realize these ideas as practical technologies and the execution to create new industries from them.

AI has now scaled up to an extraordinary degree, boasting immense computational resources, and its power consumption alone is no trivial matter. AI centers now require power supplies on the scale of power plants.

AI continues to develop at a relentless and formidable speed. This momentum cannot be stopped and will undoubtedly transform society. Major information technology companies are fiercely competing for dominance in AI, and governments are providing large-scale support. In terms of scale, Japan cannot hope to catch up. However, this does not mean that Japan has no role to play. Currently, large-scale implementation is leading the way, while theoretical understanding lags behind. If the mechanisms and principles underlying AI's success can be theoretically elucidated, it should be possible to achieve similar performance without such massive scale. Such AI would operate with lower power consumption and could be easily deployed at the endpoints of individual production sites. These kinds of theories and technologies should be Japan's forte.

AI and Human Intelligence

The performance of large language models released by major companies, such as ChatGPT and DeepSeek, is truly astonishing. Of course, if one looks for flaws, it is easy to provoke hallucinations (false outputs). Nevertheless, interacting with these models reveals their convenience and lack of discomfort. How, then, do these differ from human intelligence?

Human intelligence has been shaped through a long evolutionary history. We possess consciousness and reason logically. Yet, in everyday conversation, words often precede thought, and we may later realize what we have said. We sometimes review and revise our statements as necessary.

More broadly, we possess minds. The mind encompasses emotions such as joy, anger, sorrow, and pleasure, with consciousness forming just one part. We act according to the dictates of our minds. Humans live in societies. In collaborative activities, it is convenient to communicate our intentions to others. To do so, we must first be aware of our own intentions—this is the origin of consciousness. Furthermore, emotions such as joy and sorrow elicit empathy from others and strengthen the sense of unity among members of society.

AI does not possess these functions automatically, but it may be possible for humans to instill them. Regarding consciousness, if AI were aware of what it was about to answer and sensed something amiss, it could reconsider using other information. While current AI cannot do this, it is conceivable that it could review its responses before outputting them, and, if necessary, re-examine and refine them.

More broadly, how might AI handle human emotions such as joy and sorrow? When AI-equipped robots interact with humans, they must understand that humans possess minds and act according to their emotional states. Recognizing this, it is easy for robots to predict human emotional responses and to act as if they themselves are experiencing joy or sorrow. Humans quickly empathize, and thus perceive the robot as understanding them. The objective is thereby achieved; however, in reality, robots do not truly experience joy or sorrow. They act based on cold calculation, merely pretending to feel emotions. Robots do not become distracted by happiness or incapacitated by sadness. They remain rational, and it is better that they do not possess minds.

AI and Neuroscience

AI has drawn numerous insights from neuroscience, realizing the fundamental mechanisms of information processing through technological means. This trend will continue unabated in the future. Conversely, successful AI now provides hints for elucidating the workings of the brain. For example, by examining the structure of well-functioning, trained deep neural circuits and the representation of information within them, we can gain clues about how information might be represented in the deep circuits of the brain. Furthermore, the associative functions of large language models may be studied as models of human thought.

Human thinking is flexible and complex. In its initial stages, processes similar to those in large language models may occur. However, humans go further, driven by intellectual curiosity. Since ancient times, humans have observed the movements of celestial bodies, discerned their mysterious patterns and regularities, and constructed calendars. They could even predict solar and lunar eclipses—a task that would be easy for AI. Yet, Kepler discovered that planets move in elliptical orbits around the sun, which was a remarkable insight.

Still, humans did not stop there. Newton pursued the reason why planets move in elliptical orbits around the sun, introducing new concepts such as mass, force, universal gravitation, velocity, and acceleration, and elucidated their relationships to construct Newtonian mechanics—a monumental discovery. It is difficult for today’s AI to make such leaps.

However, such revolutionary thinking is not possible for just anyone; it is achieved only by a genius who appears once in a century. Nevertheless, once established, these insights become embedded in culture and accepted by all.

Society and Civilization in the Age of AI

AI is extremely convenient, and everyone must acquire the skill to use it effectively. However, there is a danger in relying too heavily on AI, believing oneself to be adept while actually diminishing one's own capacity for independent thought. Suppose that in the future, AI takes over most production, and humans live comfortably on basic income. Is this desirable? Such a society would be a grave mistake, amounting to the self-domestication of humanity.

Humans enjoy work and find meaning in it; they also enjoy play. Such curiosity and inquisitiveness have driven human evolution and led to the development of our technological civilization. In the future, humans will inevitably choose to work. Indeed, a society will emerge in which work and play are integrated, and people engage enthusiastically. Work as play might include amateur scientists, artists, agriculturalists, and more. However, the path to such a society will be arduous.

The Misuse of AI and the Collapse of Civilization

AI will become smaller and appear in every industrial context. However, its negative side effects could be immense. Even now, AI is used in military technology, resulting in loss of life. Countless instances of AI misuse have also emerged. Furthermore, if current trends continue, the gap between rich and poor will widen without limit. We must overcome these challenges to build a new society.

Throughout history, many civilizations have flourished and then perished. Civilization is fragile. It must be acknowledged that our current civilization is also in crisis. Our remarkable civilization is truly a cosmic miracle brought about by evolution. We must not allow it to perish.

Digitalizing the Laboratories: Expectations for instrument manufacturers

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The digitalization of laboratories in materials and life sciences research is advancing rapidly. The emergence of automated and autonomous experimental systems using machine learning and robotics is expected to accelerate discovery. In particular, analytical instruments manufacturers and the robotics industry can contribute to this revolution. It is crucial for researchers and industry to collaborate to promote the digitalization of laboratories, with a shared vision to enable new research approaches. Future issues include data sharing, standardization, and collaboration between human researchers and digital laboratories.

Introduction

In recent years, experimental methods employing machine learning and robotics have advanced rapidly worldwide in materials research (chemistry, materials, and physical property studies) and life sciences[1]-[3]. These developments have enabled the collection and analysis of vast amounts of experimental data, facilitating rapid discoveries and the pursuit of experiments that would be difficult for humans to conduct alone. There is strong demand to establish research environments that fully harness researchers' creativity while also addressing challenges such as shortages of researchers and the transfer of technical expertise to the next generation.

In countries such as the UK, Canada, the US, China, South Korea, and Japan, massive investments have driven the development of automated and autonomous experimental technologies, and the use of generative AI for materials design has become increasingly active. Companies such as Microsoft and Google have joined these research efforts, resulting in significant progress[4]-[6]. Notably, both the 2024 Nobel Prizes in Physics and Chemistry were awarded for research related to machine learning, with a researcher from a Google-affiliated company receiving the Chemistry Prize.

This article focuses on research environments that use machine learning and robotics in materials science. To accelerate materials research and swiftly address environmental issues, climate change, and the circular economy, the proactive adoption and utilization of digital technologies are essential. Some of the discussions presented herein are also applicable to life sciences. This article begins by describing the motivations for digitalization, discusses future developments, and finally outlines expectations for the analytical instruments manufacturers. To accelerate digitalization, it is vital that manufacturers and researchers establish mutually beneficial relationships. I would like to explore how we can further advance science.

Motivation for Laboratory Digitalization

Here, a vision for the ultimate goal is shared. The current objective is to construct a knowledge base in which data and knowledge are integrated into foundational models and can be freely utilized (**Figure 1**). This vision can be explained using a familiar example.

Today, it is possible to conduct surveys and generate ideas using generative AI. Technologies such as ChatGPT and Gemini have already become indispensable for researchers.

If these are combined with detailed domain knowledge of materials or life sciences, even more precise answers can be provided. To achieve this, it is necessary to integrate proprietary data not available on the internet into foundation models. This integration enables access to insights derived from a knowledge base that others cannot obtain—allowing researchers to generate original research findings and ideas. The key to generating such proprietary data lies in digitalization—automated and autonomous experimental systems powered by machine learning and robotics. These experimental systems are designed to collaborate with human intuition, skills, experience, and experiments that only humans can conduct.

The necessity of digitalization is not limited to building knowledge foundation models. Here, I discuss two perspectives (Figure 2). The first is the effective use of research funding. In scientific research, funding can be broadly divided into investments in people and instruments (Figure 2, left). Investment in people includes the employment of researchers, technical and administrative staff, and expenditures for international exchange, training, travel, publications, and related activities. Investment in instruments includes experimental apparatus, maintenance, utilities, consumables, and expenditures for lab space, electricity, and building maintenance.

Currently, there is fierce competition for talent across various fields. Every field is looking for a qualified person. Thus, from the perspective of science, it is imperative to increase investment in people. It is vital to improve the working environments of researchers and technical staff, promoting international exchange, and establish human resource development system. There is a risk that talent will not be attracted to natural sciences—materials (chemistry, materials research) and life sciences.

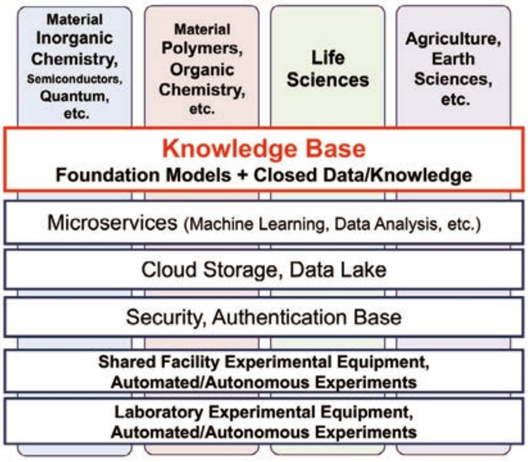

Figure 1 Future Vision: Integrating Data into the Knowledge Baselight-duty-chassis-testing/

This movement is already occurring. Wages in the information industry are high, attracting talented individuals. This is evident in Japan, as seen in the popularity of university departments and majors, which is reflected in entrance exam ratios. To advance research and development, it is essential to invest more in people, improve research environments, and link these efforts to research outcomes.

Logically, more investment in people means that less funding is available for instruments. To maximize research output while minimizing instrument costs, it is urgent to promote shared use and improve utilization rates of experimental instruments. In Japan, government-led initiatives to promote instrument sharing are already underway. The idea is to share general-purpose instruments rather than each researcher owning them. The benefits of shared use include improvements in experimental space utilization and instrument utilization rates. Another advantage is that having technicians constantly maintain shared instruments reduces the maintainance efforts on the laboratory.

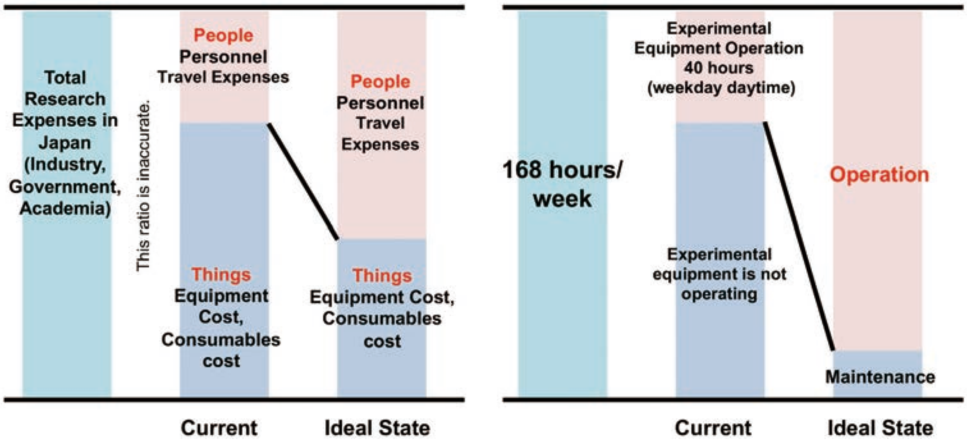

Figure 2 Allocation of research funds and time

The second point is improving instrument utilization rates (**Figure 2**, right). From a management perspective (ROI: Return on Investment), this is an urgent issue. There are only 168 hours in a week. If we assume standard working hours are 40 hours (5 days × 8 hours), researchers can use instruments for only about one-quarter of a week. That is, instruments remain idle for three-quarters of the week. In reality, few instruments are run for the full 40 hours, so actual idle time is even longer. These low utilization rates indicate low investment efficiency. Therefore, it is necessary to improve instrument utilization rates.

For these reasons, automated and autonomous experimentation is essential to maximize instrument utilization. They do experiments 24 hours a day, even on weekends. Shared use further enhances utilization rates. Automated and autonomous experimentation increases effective research time, and addresses the decrease in the number of researchers. Furthermore, it provides tools for leveraging data to generate new ideas, maximizing the creativity of researchers.

Here, an important question arises: If instrument utilization rates increase and sharing progresses, will the number of units shipped from analytical instrument manufacturers decrease? In other words, how should these companies consider economic rationality? This point will be discussed in the final section. Such concerns are unnecessary, as both sales volume and revenue are expected to increase.

Our challenge

We have been developing automated and autonomous experimental systems[7]-[9]. By connecting modularized experimental instruments, we demonstrated a system that maximally utilizes machine learning and robotics to accelerate research (**Figure 3**) [10],[11].

We connected synthesis instruments (sputtering deposition), various measurement and analysis instruments (X-ray diffraction, Raman spectroscopy, UV-Vis spectroscopy, scanning electron microscopy, electrical property evaluation, etc.), and performed automatic data analysis. This system was constructed in collaboration with many companies, including HORIBA, JEOL, Rigaku, Shimadzu, DENSO WAVE, and Pascal. In 2023, we publicly presented system details at Japan Analytical Scientific Instruments Show (JASIS)[12].

In this system, data formats output by different instruments are unified. Data are output in the MaiML format, registered as a JIS standard in May 2024[13], and stored in the cloud. We also demonstrated cloud-based analysis. Currently, data are stored on the MDX (Data-Driven Society Creation Platform) at The University of Tokyo. We have also demonstrated autonomous experimentation using cloud-based Bayesian optimization using these data.

We further established the Digital Laboratory Study Group[14],[15] in collaboration with the Japan Fine Ceramics

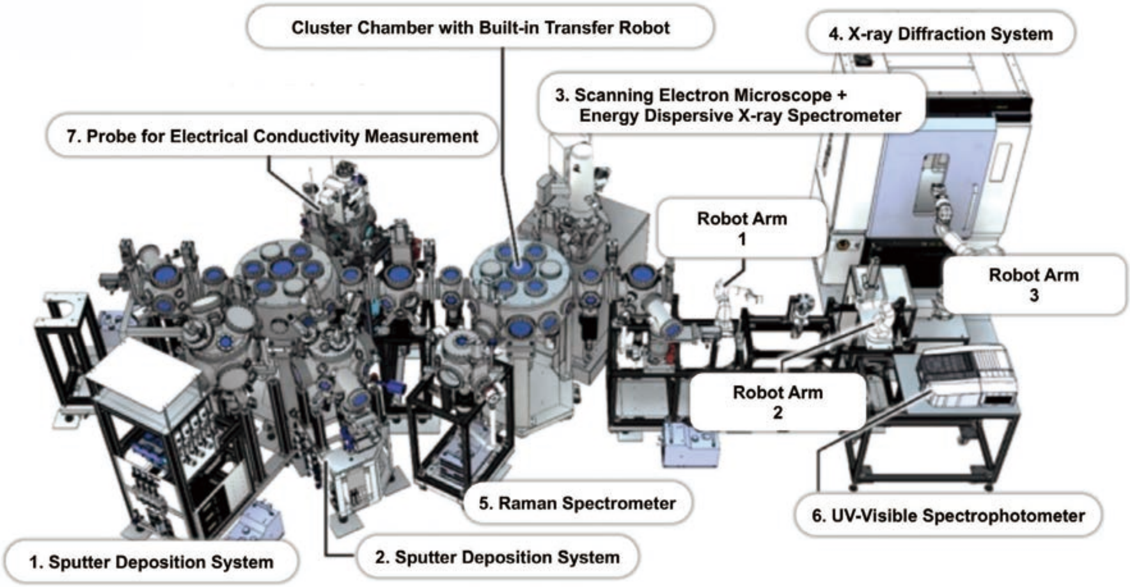

Figure 3 A synthesis system (sputter deposition system) and various measurement and analysis devices [X-ray diffraction (XRD), Raman spectroscopy, UV-visible spectroscopy, scanning electron microscope, energy dispersive X-ray spectroscopy] are connected. The shape of the sample holder and the communication protocol when each module is connected are available on the Internet.

Association (JFCA) and the Japan Analytical Instruments Manufacturers' Association (JAIMA). More than 50 private companies have joined, with membership continuing to grow. The study group hosts information exchanges, site visits, and seminars on the latest technological trends.

Furthermore, with eight companies of the study group, including materials and analytical instrument manufacturers, we established a collaborative laboratory[16]. This laboratory aims to develop digital technologies (machine learning and robotics) to automate experiments, including fully automated weighing, synthesis, firing, pelletization, crushing, property evaluation, and analysis of ceramic and powder-based materials.

What we can do together globally

Strong Scientific Instrument Manufacturers

To achieve a sustainable society, it is essential to accelerate materials science research. Instrument companies play key roles in guiding materials scientists toward new data-driven research approaches by developing digitalized instruments and leading the data utilization. Instrument manufacturers enable flexible and rapid experimentation across many scientific disciplines. Research cannot succeed without the cooperation between instrument companies and researchers. In addition, collaborating with robot manufacturers is critical.

Tacit Knowledge, Skills, and Experience in Materials

To proceed with digitalization, it is extremely important to make full use of the domain knowledge of materials science. Therefore, industry-academia collaboration in materials science has become more critical. The distance between fundamental research and applications narrows in digitally integrated laboratories.

Future Challenges and Prospects

To strengthening material innovation, promoting smart laboratories, that is, (development and implementation of autonomous research methods using AI, IoT, robotics, etc.)[18].

To promote data-driven science[19] utilizing automated and autonomous experimental systems, industry-academia-government collaboration is essential. The following are key initiatives for the future.

Expansion of Automation/Autonomization: Modularization and Standardization

Making automated and autonomous experimental systems available and usable by anyone is crucial. This democratization requires preparing various experimental modules and developing environments where they can be freely combined for research. Global standardization (device connection methods, sample holders and sizes, communication protocols, etc.) must be pursued so that each module can be "plug and play" in constructing automated experimental systems. Modularization also leads to cost reduction. Collaboration with scientific instrument manufacturers is indispensable.

Development and Utilization of Robots Adaptable to Experimental Situations

In actual research environments, it is necessary to handle complex human operations, intricate experimental flows, and diverse sample shapes and types. Moreover, it is important to adapt in real-time to changing experimental situations (what we define as "artisan skills"). This is a key difference between manufacturing factories and research labs. Implementing automated and autonomous experiments with robots requires developing systems that digitize tacit "artisan skills" and robot-control technologies grounded in human vision and language. Thus, new research methods that integrate researchers' experience and intuition with robotic "artisan skills" must be established. This is also cutting-edge robotics technology. Scientific instruments must be designed to facilitate robotic operation.

Accelerating Human Resource Development

It is urgent to foster researchers with domain knowledge who understand digital technologies[20]. It is desirable for researchers to understand basic knowledge of machine learning and robotics, and develop the ability to identify problems and propose solutions related to automation and autonomization.

Human resource development in companies is also urgent. Academic societies and industry associations should jointly lead the development of training programs and curricula to foster talent.

Promotion of Data Accumulation and Sharing

Accumulating experimental and simulation data in digital formats and centralizing their management enhance data usability. Standardization of data formats should be promoted, and cloud technologies should be used to enable seamless data sharing among research institutions and companies.

Unified standards for data management are essential for improving the reliability and reproducibility of research results. Promoting data openness and clarifying guidelines will accelerate new discoveries and value creation by accumulating the collective knowledge of the research community.

Development of Systematization Technologies: Standardization and International Collaboration

To make automated and autonomous experimental systems widely accessible, a flexible and scalable microservices architecture is essential. Microservices are standard in internet-related fields, with modularization and weak coupling as key concepts. The system should have a layered structure centered on orchestration software that coordinates each module (Figure 4). This layered structure enables flexibility in research. Experimental data are stored in a unified format in a data lake and used with analytical microservices. Recently, AI agent technology has advanced drastically, and the introduction of these technologies is anticipated.

When implementing microservices, it is important to develop APIs (Application Programming Interfaces) and proceed openly in international collaboration. For this, research hubs are needed.

Research Hubs and International Partnerships

To exchange globally and democratize the technologies, it is essential to establish research hubs. These hubs should consist of divisions promoting instrument sharing and divisions advancing domain research through industry-academia collaboration using various automated and autonomous experimental systems.

The research hub would operate as “shared facilities” and, ideally, sustain themselves independently. Materials industries use the hub as stable users, maintaining high utilization rates. Operations should be centered on technical staffs, who should interact with clients rather than spending all their time on routine work—which should be delegated to automated and autonomous systems. Such facilities should be managed with a business mindset and aim for profitability. Government support may be necessary for instrument renewal.

For the latter domain research divisions, they should bring together materials researchers, robotics experts, information scientists, and materials informatics specialists “under one roof” to drive R&D. Their mission is to pioneer new R&D methods and create new domain knowledge. These hubs will accumulate expertise in digitalization and data.

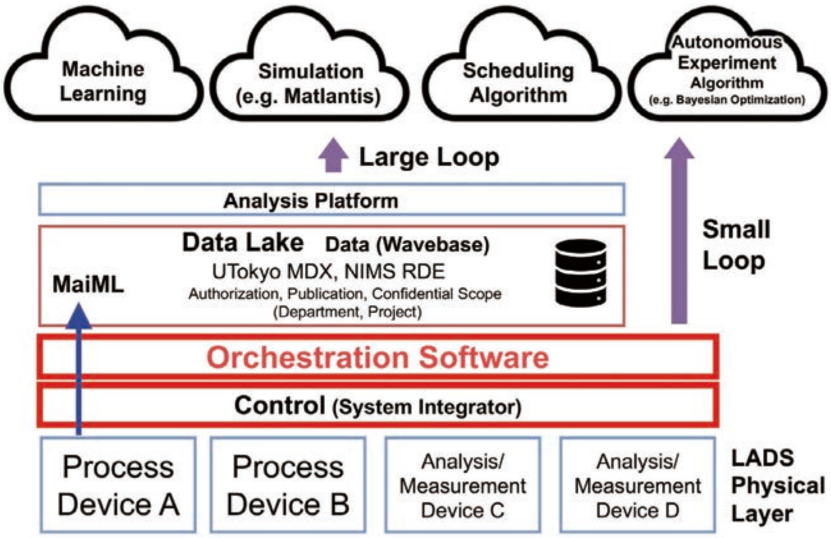

Figure 4 Layered structure of the system. It is a collection of microservices. Below the orchestration software is the physical layer.

They should also serve as testing grounds for new initiatives by scientific instrument companies. These research hubs are expected to drive the transformation of “how R&D is conducted.”

Such hubs should also promote data sharing and standardization, serve as centers for human resource development, along with consultation to beginners.

To realize such research hubs, government, industry, and academia must collaborate and invest based on a long-term vision. The digitalization of research environments will certainly continue to advance, and it is urgent to build a sustainable R&D infrastructure and accelerate the social implementation of new technologies.

Currently, in the semiconductor industry, TSMC has become a global shared platform. As manufacturing is commissioned from around the world, know-how and data are accumulated. Furthermore, prediction accuracy improves, and the feedback enhances manufacturing (Figure 5). The world has become so dependent on TSMC. It is only a matter of time before this model spreads beyond semiconductors to materials and life sciences.

Opportunities and Expectations for Scientific Instrument Manufacturers

The essence of digitalization is said to be sharing. Indeed, digitalization has accelerated sharing in automobiles, bicycles, and even the resale of goods. If the sharing of experimental instruments progresses as described, it may appear that the market for experimental instruments will not expand significantly. Moreover, automation and autonomization are just beginning, and immediate sales volumes may not justify development costs. How, then, can researchers and scientific instrument companies establish win-win relationships? Several considerations follow:

1. Only a small portion of experiments will be shared, so the impact on unit sales will be limited. As devices become more automated and user-friendly, more people will be able to use them. Cost reductions should lead to increased sales. Furthermore, globally, investment in research is increasing, and sales of experimental equipment are expected to expand.

2. New markets will be created. Rather than standalone instruments, the integration of analytical and measurement instruments with process instruments will increase. Researchers seek as much data as possible, particularly precise data on synthesis processes and instrument status, to support optimization and elucidation of mechanisms (process informatics). Thus, there is increasing value in operando or in situ analysis. This is a market expansion opportunity.

3. Move beyond simple product sales. Researchers do not want “instrument” in itself, but the “data” it produces. The value lies in data. Pricing models based on the amount of data, including maintenance, can be considered.

4. Profit through systemization. Laboratory system integrators will become extremely important. This integration

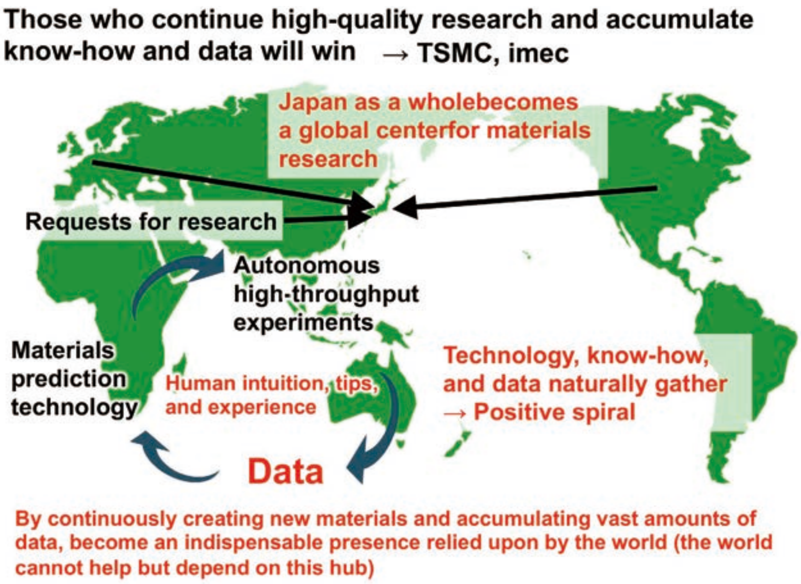

Figure 5 Building a research infrastructure that the world can rely on

business involves understanding researchers' needs and building entire experimental and data processing systems. In addition, operation and maintenance is additional business opportunities. For example, HORIBA has already become a laboratory system integrator for engine exhaust gas evaluation[21],[22]. This technology can be leveraged in building many laboratories besides exhaust gas evaluation. Unlike traditional "automated system integrators," this requires domain knowledge, which analytical instrument companies are expected to acquire.

5. A balance between high-end and general-purpose instruments is always necessary. Even general-purpose instruments must be attractive to users. Building ecosystems that include hardware, software, and services is a common approach. Business models like those of Apple and NVIDIA are instructive. Diversified revenue structures, including licensing, are also important.

6. Instrument design should shift from human-friendly to robot-friendly. If experiments are not performed by humans, entirely new experiments become possible. Realizing new experimental workflows requires the cooperation of scientific instrument manufacturers. Simply replacing humans is mere digitization; true digitalization is the transformation of experiments and workflows. This true digital transformation opens up an entirely new market.

I hope scientific instrument companies lead digitalization of research laboratories.To achieve this, researchers and manufacturers must share a common vision and build win-win relationships. Currently, communication between researchers and companies is insufficient. It is also important that instrument manufacturers, materials manufacturers, robot manufacturers, academia, and government collaborate to advance digitalization.

Conclusion

Analytical instrument manufacturers are central to the digital transformation of scientific research. To build intelligent automated experimental modules, a detailed understanding of experimental processes (domain knowledge) is essential. Only with deep knowledge of experimental processes can truly useful modules be developed. Thus, scientific instrument manufacturers must go beyond expertise in measurement and engage more deeply with domains (materials, life sciences, agriculture, earth sciences, space, etc.). It is essential to incorporate researchers' intuition, skills, and experience into the development of experimental and scientific instruments. Ultimately, human creativity and ingenuity are always central. Product and system development that incorporates the originality of researchers and engineers is desired in scientific instrument development.

Figure 6 Bird's-eye views open up new directions and reveal new areas to explore.

Finally, I would like to state the significance of this new approach to R&D. The aim is not merely to improve efficiency, but to gain a panoramic perspective from massive data, create entirely new experimental workflows, and enable the construction of new scientific principles and the discovery of new substances (**Figure 6**). The true goal is to foster new ideas. The power of scientific instrument manufacturers is essential. Let us move forward together with researchers!

Acknowledgments

I would like to express my gratitude to all those who engaged in various discussions during the preparation of this article. I am also deeply indebted to Mr. Naoya Miyawaki for his invaluable assistance in organizing the manuscript and verifying the references.

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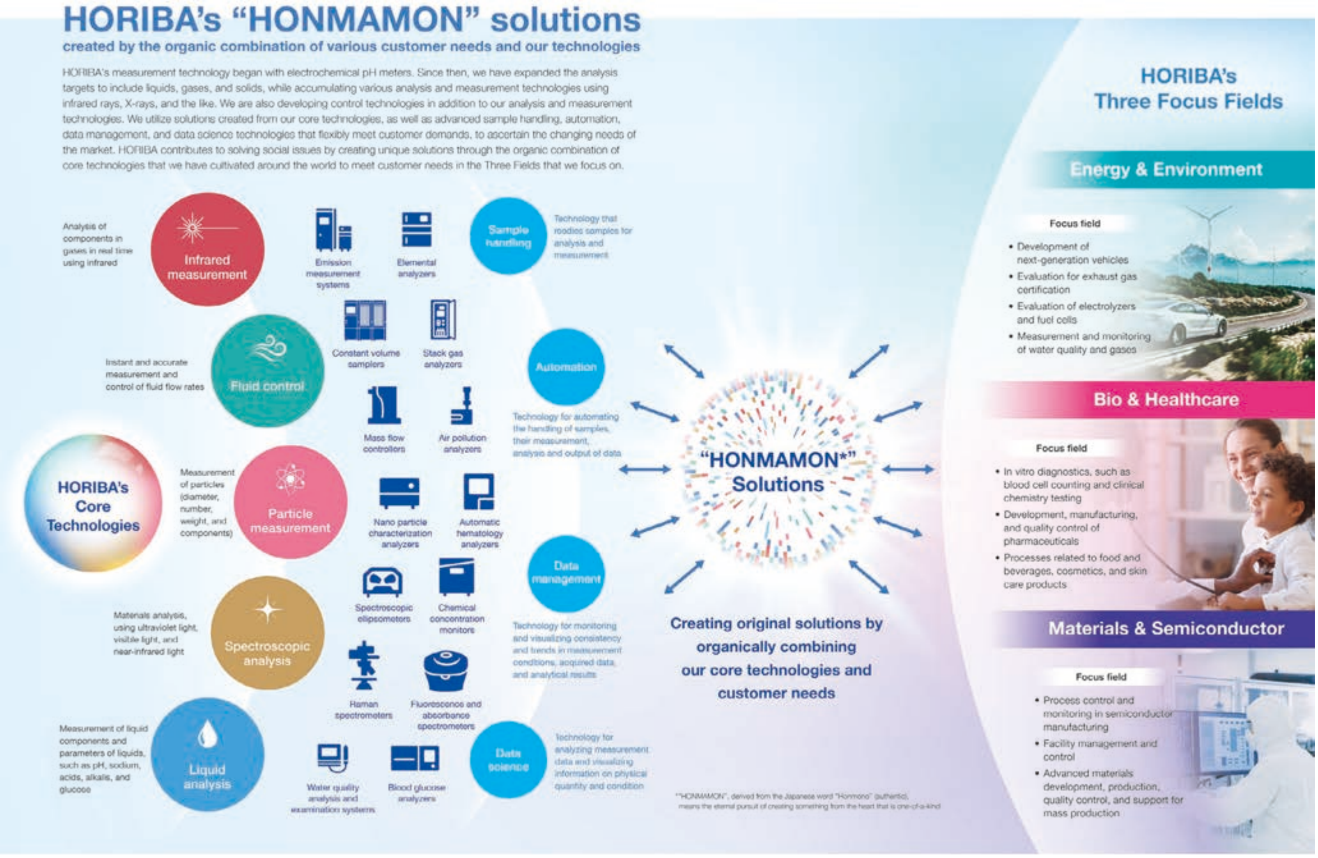
HORIBA's“Analytical and Measurement”Technologies and Digital Transformation (DX)

KATSUDA Toshihiro

The origin of “Digital Transformation (DX)” is said that Professor Erik Stolterman of Umea University in Sweden defined the concept as “The digital transformation can be understood as the changes that the digital technology causes or influences in all aspects of human life” in 2004. Although the definition of Digital Transformation commonly used is not fully consistent, it can be said that the improvement of operational efficiency and productivity, creating new value, and so on are realized by fundamentally transforming business models and business processes with utilizing digital technology as a tool. HORIBA provides not only generating essential data for Digital Transformation, but also creating various solutions for customer’s Digital Transformation utilizing digital technologies such as IoT and AI. This article describes overview of these solutions.

Introduction

HORIBA’s measurement technology began with electrochemical pH meters. Since then, we have expanded the analysis targets to include liquids, gases, and solids, while accumulating various analysis and measurement technologies using infrared rays, X-rays, and the like. We now have core technologies such as “Infrared measurement”, “Fluid control”, “Particle measurement”, “Spectroscopic analysis”, and “Liquid analysis” and develops variety of analytical and measurement instruments by combination of core technologies. We also create and provide HORIBA’s unique “HONMAMON” DX (Digital Transformation) solutions contributing to operational efficiency, productivity improvement, and the creation of new value through not only developing analytical and measurement instruments using core technologies but also utilizing “Sample handling”, “Automation”, “Data management”, and “Data science” to flexibly respond to customer needs (**Figure 1**).



HORIBA’s “HONMAMON” solutions

created by the organic combination of various customer needs and our technologies

HORIBA’s measurement technology began with electrochemical pH meters. Since then, we have expanded the analysis targets to include liquids, gases, and solids, while accumulating various analysis and measurement technologies using infrared rays, X-rays, and the like. We are also developing control technologies in addition to our analysis and measurement technologies. We utilize solutions created from our core technologies, as well as advanced sample handling, automation, data management, and data science technologies that flexibly meet customer demands, to ascertain the changing needs of the market. HORIBA contributes to solving social issues by creating unique solutions through the organic combination of core technologies that we have cultivated around the world to meet customer needs in the Three Fields that we focus on.

Figure 1 HORIBA’s “HONMAMON”* solutions
https://static.horiba.com/fileadmin/Horiba/Company/Investor_Relations/IR_Library/HORIBA_Report/20250730_HR_en.pdf

HORIBA’s DX Solutions Developed Together with Customers

The origins of HORIBA’s DX solutions trace back to the 1970s, before the term “DX” was established. The first HORIBA Motor Exhaust Gas Analyzer, “MEXA” was sold in 1964. Subsequently, detailed workflows and testing procedures were specified in exhaust gas regulations and automation was required because of difficulty for humans to conduct measurements manually and correctly. To address such needs, in the 1970s, we began offering total solutions combining not only exhaust gas measurement equipment but also automation software for various business processes. This can say first generation of HORIBA’s DX solutions (**Figure 2**).

Figure 2 Light-Duty Chassis Testing
https://www.horiba.com/jpn/automotive/applications/emissions-performance-and-durability/exhaust-emissions/light-duty-chassis-testing/

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*HORIBA Corporate Web site,What is "HONMAMON?"
https://www.horiba.com/our-future/en/honmamon/

Figure 3 Total Automation of Elemental Analyzers for Carbon and Sulfur
https://www.horiba.com/jpn/technology/automation/

In addition, HORIBA also has over 40 years of experience about automation and labor-saving for analytical operations other than automotive emission gas measurement business. For example, in trace element analysis applications for steel, HORIBA has addressed the demands such as improving operational safety, reducing labor and man-hours, and eliminating the impact of human factors on accuracy through introducing the analytical automation including pre-processing and related tasks and online analysis to production lines. (Figure 3).

Thus, HORIBA has long worked together with customers to provide solutions, which could now be called DX, utilizing system integration and automation technologies.

The Evolution of Digital Technology and Diverse DX Solutions

Since 2000, HORIBA has developed a variety of remote solutions in response to evolution of digital technologies such as information technology, IoT, and AI. Through networking of instruments and utilization of IoT and cloud, HORIBA launched the comprehensive maintenance service support system “HORIBA MEDISIDE LINKAGE” for medical devices (Figure 4) and the cloud-based maintenance service “HORIBA AQUA LINKAGE” for water quality monitoring devices. These services have contributed not only to stable equipment operation

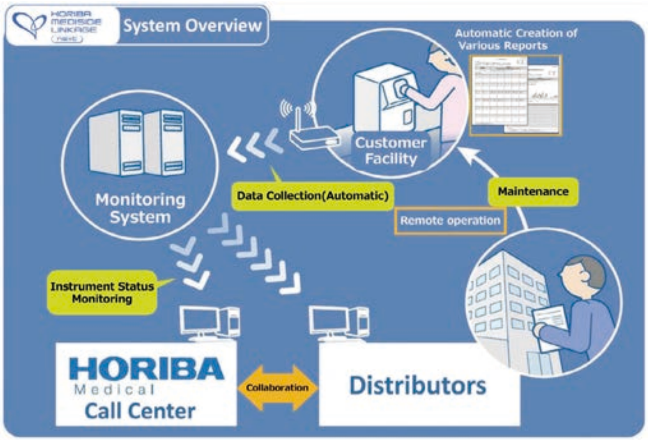


Figure 4 Total picture of「HORIBA MEDISIDE LINKAGE」system
https://www.horiba.com/jpn/medical/news/news-press-release/detail/news/8/2023/horiba-mediside-linkage-next/

In the unlikely event of a failure, HTS will respond free of charge from investigation to recovery, including parts replacement. (Excludes holidays and outside business hours.)

HTS constantly monitors the equipment status and provides optimal support.

HTS confirms stable equipment operation with an annual inspection.

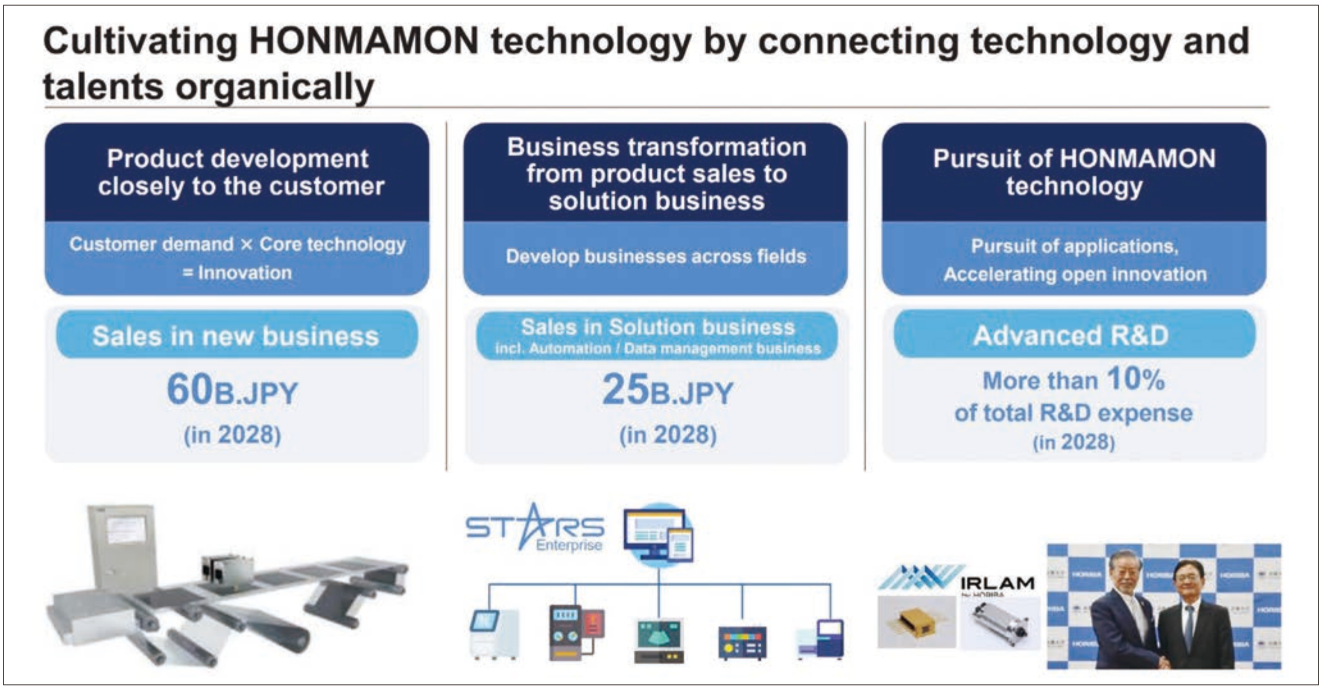
Figure 5 Remote support「AOP Connects」
https://www.horiba.com/jpn/service/solution/service-product/remote-support/

via remote monitoring but also to reducing the workload on-site, accelerating problem-solving, and promoting work style reforms.

In addition, we offer a variety of business efficiency improvement services through various plans tailored to customer needs such as "AOP Connects" (**Figure 5**), which adds remote equipment status monitoring by expert engineers to the "AOP (All in One Plan)," which is comprehensively maintenance and inspection services for HORIBA products, secure remote access to equipment that enables customers to work remotely, analysis consultations remotely with our specialized analytical engineers, and remote maintenance.

HORIBA's DX Solutions in MLMAP2028 R&D Strategy

HORIBA is currently implementing Mid-Long Term Management Plan,"MLMAP2028", aiming to solve social issues through "HONMAMON" solutions in three fields: "Energy and Environment" "Bio and Healthcare" and "Materials and Semiconductor". R&D strategy of MLMAP2028 is based on three pillars. The first one is to help expand new applications and businesses through product development by new combination


Cultivating HONMAMON technology by connecting technology and talents organically

Product development closely to the customer	Business transformation from product sales to solution business	Pursuit of HONMAMON technology
Customer demand × Core technology = Innovation	Develop businesses across fields	Pursuit of applications, Accelerating open innovation
Sales in new business 60B.JPY (in 2028)	Sales in Solution business incl. Automation / Data management business 25B.JPY (in 2028)	Advanced R&D More than 10% of total R&D expense (in 2028)

Figure 6 R&D strategy in Mid-Long Term Management Plan「MLMAP2028」
https://www.horiba.com/int/company/investor-relations/mid-long-term-management-plan/

of technology in all HORIBA Group. The second is to help expand our solutions business, including automation and data management, by promoting the transformation of our business from product sales to solution provider. And the third is to pursue “HONMAMON” technologies. (**Figure 6**).

In particular, regarding the second pillar which is the expansion of the solution business, HORIBA is focusing on applying the DX solutions such as laboratory data management expertise cultivated in the automotive business to new fields such as research and development in materials analysis.

Conclusion

To further expand and promote DX solutions, HORIBA is collaborating with academia such as Shiga University, The University of Tokyo, and Osaka Metropolitan University to develop DX talent through open innovation. HORIBA's dedicated data science team, as a company with analytical and measurement technologies at its core, values the mindset of a hands-on approach to developing algorithms in the laboratory based on the principles of physical phenomena, and strives to create solutions every day. The use of IoT and AI is now commonplace, and we believe that how we utilize them will have a major impact on business. HORIBA has many possibilities, such as Laboratory DX, which aims to improve the efficiency of experiments in research and development, and spectral analysis in spectroscopic analysis, which are seeing increasing demand these days. With a diverse range of analytical and measurement technologies, HORIBA will contribute to the expansion of our customers' DX, which can only be achieved by HORIBA.

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

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Feature Article

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

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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.

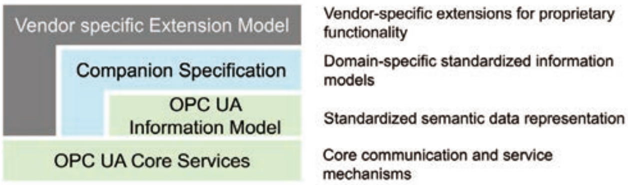

Figure 1 OPC UA base service and model structure.

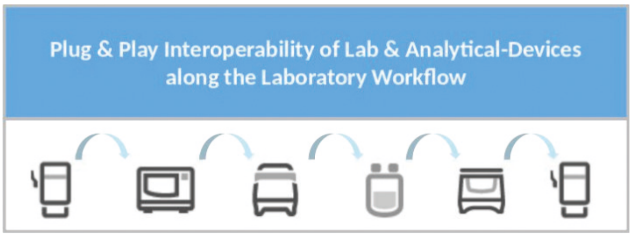

Figure 2 LADS target image

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

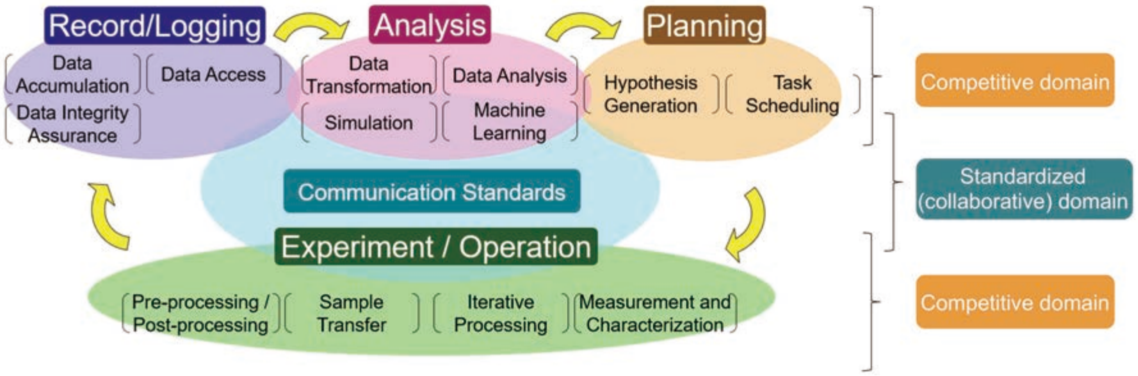

Figure 3 Laboratory works supported by communication standard

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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The Interaction between “Artificial Intelligence” and “the Safety and Security of Cyber Physical Systems”

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AI is already being used in vehicle infotainment systems such as car navigation. Recently, one of the most frequently encountered uses of AI in vehicles is in driver support (ADAS) and automated driving systems (ADS). This article explores the use of different forms of artificial intelligence (AI) in cyber-physical systems, in particular automotive systems, the potential safety and security risks posed by AI and how these risks are being addressed through emerging regulations, standards and technical solutions. We examine the functional safety implications of AI-based systems and how this is being addressed by the newly published ISO/PAS 8800. We also provide an overview of typical cybersecurity threat scenarios and attack methods that affect AI-based systems and how those can be mitigated. Finally, we review some of the opportunities that AI can offer for improving functional safety and cybersecurity.

Introduction and Background

Artificial intelligence (AI) is emerging as a key new technology in modern engineering, with applications in many industry sectors, including in cyber-physical systems such as vehicles.

The benefits of AI come from the unique way it operates. For example, instead of using fixed algorithms based on physics or classical statistics, machine learning uses vast sets of training data to teach an algorithm to identify patterns or specific objects. Once trained, machine learning algorithms can spot these patterns with greater speed and accuracy compared to traditional techniques, whether the task is interpreting human speech for voice control applications or predicting the path of an oncoming vehicle. Compared to traditional software decision-making, AI can accomplish tasks that would otherwise be impracticable with the time or computing power available.

Along with the significant opportunities presented by AI, there are a number of risks, including risks to safety and risks of intentional attacks. The complexity of AI-based systems means that there are many different variables to consider, increasing the potential for failures or vulnerabilities.

Uses of artificial intelligence in vehicles

Applications for AI systems in vehicles range from the use of machine learning for object detection in automated driving systems through to battery life predictions in electric vehicles. Even infotainment systems are starting to adopt generative AI technology.

One of the most frequently encountered uses of AI in vehicles is in driver support (ADAS) and automated driving systems (ADS). AI is seen as attractive since it enables mimicking of human behaviour and human decision making rather than following a rigid set of rules as would be found in a system based on algorithmic decision making. AI is therefore frequently used to interpret sensor data and make decisions based on the perceived traffic environment.

However there are many potential uses of AI beyond ADAS and ADS. One particular example is in battery management systems, where AI can be used to help implement more accurate predictions of battery life both in terms of improving the energy efficiency of individual journeys, but also managing the through-life efficiency and longevity of the energy storage system.

Safety and security risks for AI-based systems

Safety risks

The historical position on the use of AI-based systems in safety contexts has been "to not do". This is due to the non-deterministic behaviour of such systems and the closed box nature of their implementation.

By "non-deterministic" we mean that the output is not fully predictable based on a given set of input conditions; the same set of input data might give different results on different occasions. For example as a result of updated learning data the system might behave differently on a subsequent occasion.

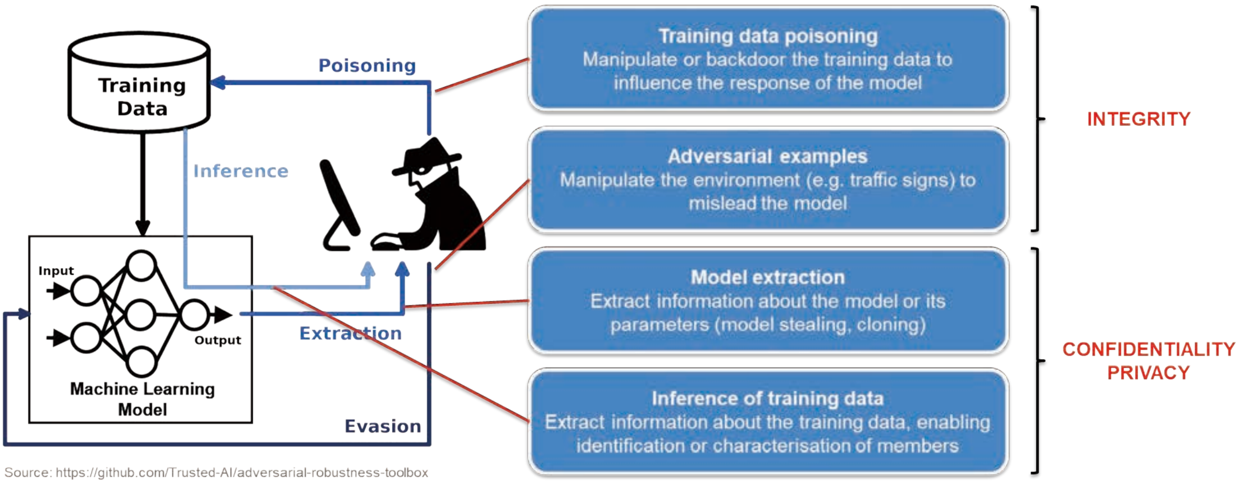
By "closed box" we mean that the implementation of AI based systems (particularly around learned behaviour) is not amenable to detailed analysis. In traditional functional safety methods a software-based system would be designed at successive levels until so-called "software units" are identified which can be subject to standalone and detailed analysis and testing. Examples of this in traditional systems would be a function (or small number of functions) in a language such as "C" that contains a relatively small number of lines of source code.

From a safety perspective the ultimate goal is to demonstrate "assurance" in a system – that it operates correctly in its given operational context and does not present an unreasonable level of risk to people exposed to its behaviour. Traditional methods need adapting for the complexities and uncertainties associated with AI-based systems so that their benefits can be delivered while managing the additional risks associated with them.

Security risks

AI, and in particular machine learning, introduces a number of security-related risks, with various attack methods threatening different parts of the machine learning implementation. Different types of AI threat and examples of attacks that can realise those threats are shown in Figure 1, which extends the classes of threat defined by the Linux®*1 Foundation "Adversarial Robustness Toolbox" project[1].

Due to the learning aspect of Machine Learning systems, attackers could manipulate the behaviour of the system by



Source: https://github.com/Trusted-AI/adversarial-robustness-toolbox

Figure 1 Classes of threat based on the Linux®*1 Foundation "Adversarial Robustness Toolbox".

*1 Registered trademark or trademark of Linus Torvalds in Japan and other countries.

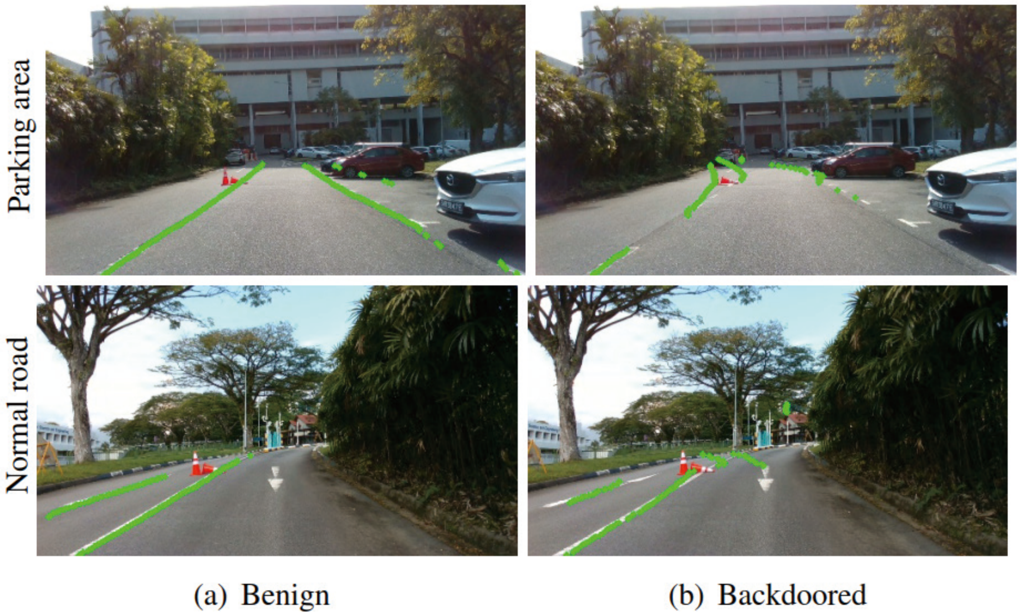


Figure 2 Example of backdoor poisoning attacks (Source: [3])

targeting the training data without needing access to the algorithm itself. These systems are only as reliable as the training data used for the learning process, so removing data or inserting false information into the training data (known as data poisoning) could have a significant impact on the correct behaviour of the algorithm. Research experiments have demonstrated that so-called backdoor poisoning methods could use specific patterns or inputs to bypass normal detection methods[2] . Recent research has demonstrated the practicality of such attacks in the physical world, specifically targeting lane detection systems[3], as illustrated in Figure 2. Experiments have shown these attacks to be effective and robust against various defence solutions, posing significant risks to the security and safety of vehicles and passengers.

With varying degrees driver assistance now seen on many new vehicles, attackers no longer need direct access to a vehicle to influence its operation. Various methods of 'spoofing' to intentionally mislead the vehicle's sensors have been demonstrated by researchers, including the class of attacks known as adversarial examples: an example being small stickers placed on road signs by an attacker (as shown in the image below from research by Eykolt et al)[4] which change the way the sign is interpreted by image recognition systems but would be ignored by the human eye(Figure 3).

Figure 3 Example of adversarial examples attack (Source: [4])

The value attached to novel and proprietary AI algorithms could make them a particularly lucrative target for intellectual property theft. If a third party can access the AI system – either through a vehicle or by other means, such as an IT system – then they could potentially extract details of the model or its parameters[5] and use the information to either clone or manipulate the behaviour of the target system.

Table 1 Automotive applicability of machine learning attacks.

Application area	AI-based function	Possible attack
Advanced driver assistance systems (ADAS)	Traffic sign recognition	Adversarial examples
Automated driving systems	Object detection and classification	Adversarial examples, Training data poisoning
EV battery management	Predicting battery health and parameters over lifetime	Training data poisoning, Model extraction
Smart cockpit / user experience	Generative AI infotainment functions, voice assistant	Personal information inference

The applicability of some of these types of attack on automotive Machine Learning systems is summarized in Table 1.

A major challenge is that securing any system is an uneven contest between attackers and defenders. Vehicle manufacturers have a finite amount of time and resources available to identify, analyze and resolve security issues before a new vehicle is signed off for production. In contrast, attackers have unbounded opportunity to attack the vehicle throughout its operational lifetime, and they only need to be successful once to cause major damage. It should also be noted that AI techniques may also be harnessed by attackers to increase their advantage and adapt to evolving cybersecurity controls.

Emerging regulations and standards

General AI regulations and standards

General-purpose AI regulatory frameworks are now emerging, such as the EU AI Act and the US National Artificial Intelligence Initiative Act. For specific industry verticals, such as automotive, it is possible that future requirements for approval of AI-based systems in vehicles may be added to existing automotive-specific type approval processes. Alternatively, it may be left to the industry to follow the general-purpose frameworks.

In addition, a major standardization activity is underway in ISO/IEC to develop a range of AI-related international standards. This activity is mainly under the ISO/IEC/JTC 1/SC 42 sub-committee, although other ISO/IEC committees and the European standards bodies CEN/CENELEC are also developing AI standards. These standards cover a wide range of aspects related to AI, from defining governance frameworks, to specific aspects such as ethical considerations. Two examples of these general AI standards that are also important for the safety and security of AI are:

- ISO/IEC 42001 AI Management Systems – establishes a framework for managing the lifecycle of AI systems, ensuring their ethical, reliable, and secure deployment across industries, including automotive. This standard emphasizes governance and leadership commitment, robust risk management, compliance with legal and ethical standards, and stringent data management practices. It outlines best practices for the design, development, deployment, and continuous improvement of AI systems, promoting transparency, accountability, and stakeholder engagement.

- ISO/IEC 22989 AI concepts and terminology – provides definitions of key concepts and terminology related to artificial intelligence. This standard aims to establish a common language for discussing AI across various domains and industries, promoting clarity and consistency in communication. By establishing a clear and consistent vocabulary, ISO/IEC 22989 facilitates better communication, a shared understanding of AI technologies, models, and processes, and collaboration among automotive manufacturers, technology developers, regulators, and other stakeholders.

AI security regulations and standards

Standards specifically regarding the interaction between AI and cybersecurity are currently under development, including a CEN/CENELEC standard on “Cybersecurity specifications of AI systems” and ISO/IEC 27090 “Cybersecurity — Artificial Intelligence — Guidance for addressing security threats to artificial intelligence systems”, which is being developed by ISO/IEC/JTC 1/SC 27. At the current time, these standards are in the early stages of development.

Regarding vehicle specific AI security regulation, with the introduction of UN Regulation 155, cybersecurity is already part of the Vehicle Type Approval process in markets such as the EU, Japan and South Korea. There are currently discussions in the UNECE WP.29, which develops vehicle type approval regulations, about possible future regulation of AI-based systems in vehicles, although at the current time the content and timing of any future regulation is unclear.

AI safety standards

As noted previously, the view on use of AI in safety-related systems is moving from “do not” to “how can we?” There is extensive work taking place to develop a framework of standards for AI. As well as the more general framework described above, the following should be noted with particular reference for safety:

- ISO/IEC TR 5469[6] – this was an initial document prepared in the context of the generic functional safety standard IEC 61508 to provide preliminary information on some of the methods and processes available to incorporate AI elements in safety-related systems,

- ISO/PAS 8800[7] – this builds on ISO/IEC TR 5469 and specifically addresses the use of AI elements within automotive systems. It has a particular focus on the risk associated with undesired safety-related behaviour at a vehicle level due to output insufficiencies, systematic errors and random hardware errors of AI elements. This document also assumes application in the context of ISO 26262[8] – it supplements it rather than replaces it. Therefore a safety-related system should be developed according to ISO 26262. The functional safety design would create an architecture for the system and allocate safety requirements to its elements – if those elements are implemented using AI then ISO/PAS 8800 would then be applied. There are many important aspects of ISO/PAS 8800 but a significant one is the use of AI properties to help define an assurance claim that use of an AI element achieves absence of unreasonable risk.

- ISO/IEC TS 22440 – currently under preparation, this will build on ISO/IEC TR 5469 and incorporate concepts from ISO/PAS 8800 as industries move towards a "state of the art" on how to use AI within safety-related systems.

Opportunities for AI to improve safety and security

AI provides opportunities to address the asymmetry between attackers and defenders. Technologies such as machine learning are well-suited to identifying anomalous behaviour that may be the first warning signs that a system has been tampered with. The ability to efficiently process huge datasets also makes machine learning a powerful tool for monitoring the diverse and unstructured corpus of published information about new threats, attacks and vulnerabilities. For example, techniques like natural language processing can be used to extract intelligence from unstructured, text-based information, filter out irrelevant content and highlight the potential threats. This provides cybersecurity analysts and engineers with actionable information to support decision making during engineering, vulnerability management and incident response activities.

Conclusion and outlook

In this article we have introduced different applications of AI in automotive cyber-physical systems, including driver assistance systems, automated driving and electric vehicle battery management. We explored the safety risks due to the "non-deterministic" and "closed box" nature of AI-based systems and the need for traditional methods of providing assurance to be adapted to address these additional risks. We have similarly outlined security risks of AI-based systems, including poisoning attacks, adversarial examples and model extraction. Finally, we have introduced some key regulations and standards applicable to AI-based cyber-physical systems, including those covering AI in general, as well as standards specifically addressing the safety and security of AI.

Whatever shape future regulations may take, AI will have a major role to play in the automotive industry and in other industry sectors developing and deploying cyber-physical systems. Organisations and individuals will need to be mindful of the potential risks introduced by AI-based systems, and the new methods required to provide assurance that the risks are appropriately managed. However, with sufficient assurance, AI can open up a whole range of exciting new possibilities to enhance the capabilities of future cyber-physical systems.

HORIBA MIRA is at the forefront of the development of methods safety and security assurance, including initiatives to extend these methods to AI-based systems as described in this article. This expertise helps us provide consulting, test and assurance solutions to automotive and other customers, as well as helping to assure future HORIBA products incorporating AI-based systems.

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

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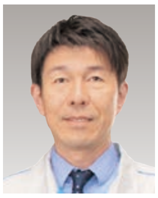

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The Evolving STARS Ecosystem: from Automotive Development to Material, Bio and Healthcare

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KOYAMA Satoshi

STARS Automation is a software platform developed to automate testing in automotive development. It has evolved and improved continuously through ongoing enhancements. In recent years, new platforms have been added to the STARS ecosystem. STARS Enterprise provides laboratory-level data management and process automation capabilities beyond the automotive field, while STARS Process functions as a flexible sensor management layer. This article will discuss the history of STARS Automation and the consider the outlook for the STARS ecosystem to underpin business growth across HORIBA.

Introduction

In the 1960s, HORIBA's automotive division developed the first MEXA, establishing itself as a global brand in automotive exhaust gas analyzers. By integrating analyzers with peripheral devices such as sample handling systems, HORIBA provided comprehensive exhaust gas measurement systems to meet diverse customer needs.

In the 1980s, to address increasingly complex testing requirements, HORIBA introduced “Test Automation” - an integrated system using computer technology to control automotive test equipment, including analyzers - pioneering digital test automation long before the term Laboratory Digital Transformation (Lab DX) emerged.

HORIBA launched the current test automation platform, STARS, in 2005, which has been continuously enhanced with new features and global support.

This paper outlines the evolution and future development of the STARS platform, including its extended ecosystem - STARS Enterprise and STARS Process - and discusses its application beyond the automotive field as part of efforts toward realizing Lab DX.

Overview and background

Automobile development has become increasingly complex due to stricter emission regulations, fuel economy standards, and efforts toward carbon neutrality, including the push for electrification.

To meet these demands, modern vehicles integrate more control devices and sensors, increasing the complexity of control system optimization. As a result, automated testing via test automation systems is now essential to maintain or reduce development time. In fact, automation of every aspect of test operations has become the norm.

The STARS ecosystem currently comprises 3 platforms that combine to provide vertical automation solutions ranging from individual sensor management, through test stand automation, up to test enterprise management (Figure 1):

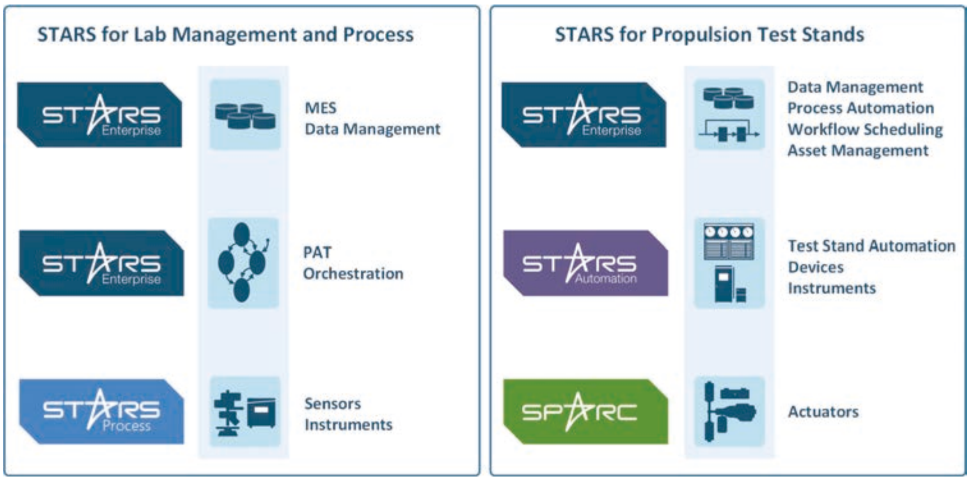

Figure 1 The STARS Platform stack.

STARS Process, the newest member of the STARS family, provides control and data acquisition at the instrument/sensor level.

STARS Automation, the original STARS platform, provides real-time control, automation and data acquisition for test stands. Developed to meet the diverse and demanding requirements of test automation in automotive development worldwide, STARS Automation offers a compelling combination of ease of use and functionality, with a comprehensive application engineering toolset. It is scalable from single test stands to large test labs.

STARS Enterprise provides centralized data management and process automation at the test field level, as well as instrument and process line orchestration. STARS Enterprise provides a framework for managing test requests, test scheduling, device management and centralized data handling, accommodating standard and customized workflows. STARS Enterprise solutions significantly enhance development efficiency.

In 2024, HORIBA launched its current mid-to-long-term plan, MLMAP2028, and reorganized its structure from five segments into three business field groups to strengthen cross-segment collaboration. One of the three central pillars of the plan is the shift from product-based offerings to integrated solutions. By leveraging system integration and solution expertise developed in the automotive domain, HORIBA aims to expand these capabilities across all business fields to drive sustainable growth.

The STARS ecosystem is a key enabler for this expansion, with many of the solution patterns developed in the automative domain proving to be equally relevant to non-automotive fields. Practical implementations include Lab DX in scientific laboratories, QC systems for the biopharmaceutical industry, and autonomous experimentation systems. Deployment across diverse sectors is actively underway (Figure 2).

HORIBA's history in automotive test automation

In 1964, HORIBA launched the "MEXA-1," a three-component exhaust gas analyzer that became a globally recognized brand. In 1972, the company introduced the "CVS-31," a constant volume sampling system employing

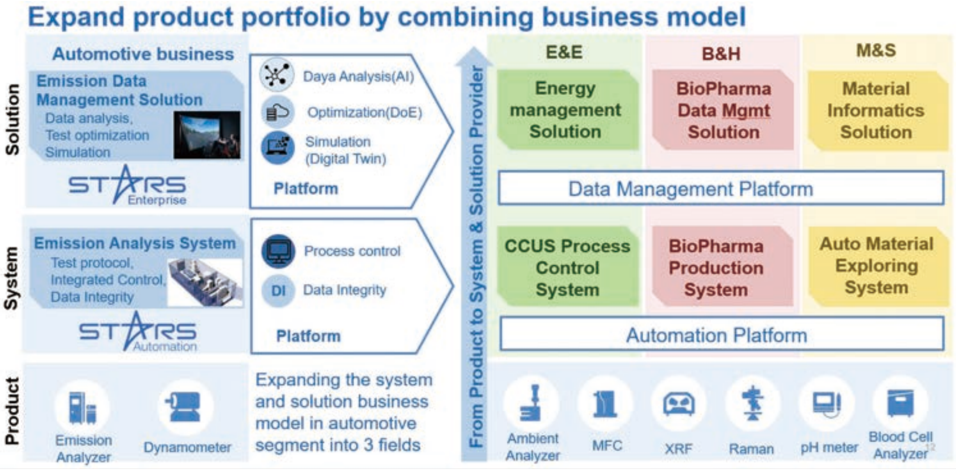

Figure 2 Shift from product-base to system and solution provider.

critical flow venturi (CFV) technology. By combining this system with gas analyzers, HORIBA enabled the measurement of exhaust gas flow rates, thereby meeting the requirements of the new exhaust emission regulations that came into effect in 1973.

In the late 1970s, HORIBA entered the field of exhaust gas test automation through the acquisition of the chassis automation business from InterTestAutomation.

With the rise of personal computing, HORIBA developed the “HERT-100” in 1985, a test automation system for engine development. This was followed by the “HERT-200” for chassis dynamometer testing of complete vehicles. These systems marked one of the origins of HORIBA’s Lab DX approach, integrating analyzers, sampling systems, and dynamometers into comprehensive solutions.

By moving beyond standalone products and offering integrated systems - including hardware and software - HORIBA has addressed diverse customer needs. The system-based approach remains a core strength of its automotive business.

In 2001, HORIBA joined SRH Systems Ltd., a joint venture between Schenk AG and Ricardo PLC, marking the transition from regional to global test automation platform development. This collaboration led to the 2004 release of STARS Engine, the first product based on the STARS Automation platform for engine testing, and from that point STARS Automation has played a central role in HORIBA’s integrated solutions. In 2005, HORIBA acquired the test systems business from Schenck AG, making SRH a subsidiary of HORIBA.

Designed for broad applicability, STARS Automation was soon extended to cater for vehicle, component, and brake system testing. HORIBA expanded the product lineup with specialized applications such as STARS HDEET for heavy-duty engine emissions, STARS Calibrate for ECU calibration, and STARS VETS for vehicle emissions testing.

To enhance efficiency in multi-test stand environments, HORIBA introduced the STARS Cluster Server, enabling centralized configuration and test result management. Evolving customer needs and software technologies led to the development of STARS Enterprise, a cloud-native platform that supports comprehensive data management and process automation across the test field, serving both engineering and operations teams (Figure 3).

Architecture and technology of the STARS platforms

Test automation systems are characterized by their requirement to perform highly deterministic real-time control and data acquisition tasks. Besides this, they must provide the operator with powerful and intuitive tools to create test routines, observe the execution of tests and work with the test results afterwards. To address the real-time requirement, STARS Automation incorporates a multitasking hard real-time test execution environment, with test execution step and data acquisition rates of up to 5 kHz. Determinism and low latency are achieved through a real-time Windows$^{\text{®}*1}$ extender subsystem (RTX), which effectively hives off some of the computer’s resources to support a real-time kernel and scheduler which are isolated from the indeterministic environment of the Windows$^{\text{®}*1}$ operating system.

The operator’s workstation environment, which does run in Windows$^{\text{®}*1}$, provides an intuitive, graphically oriented user experience for the configuration of all the artefacts

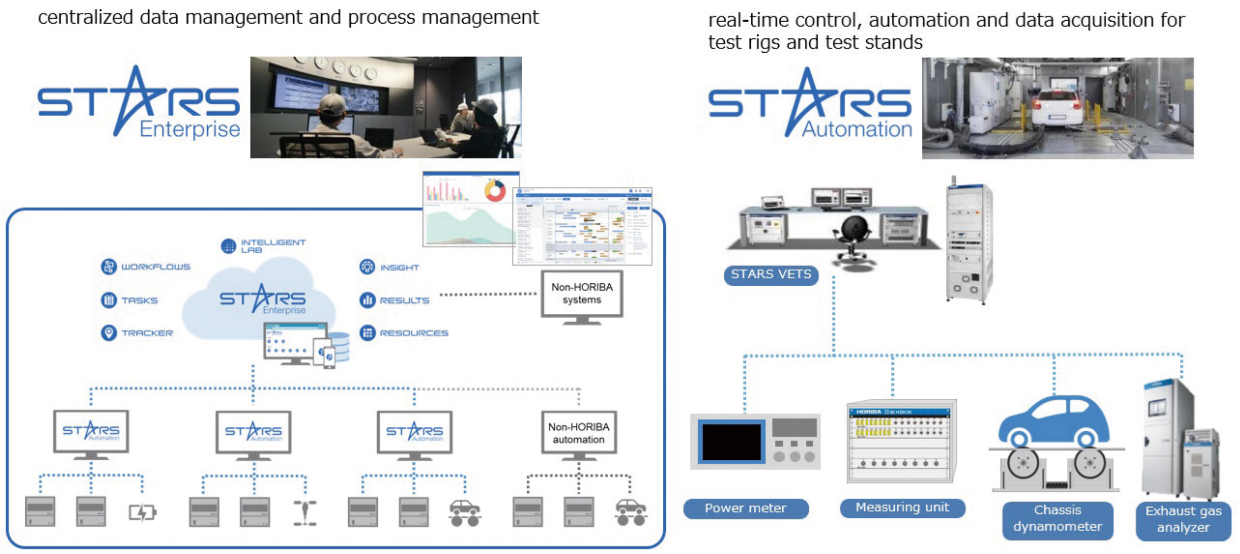

Figure 3 STARS Platform for automotive industry.

that combine to create a test application. Tabbed, launchable work areas and multi-display support provide a productive multitasking workspace in which applications can be configured and results analyzed while simultaneously monitoring test execution. The real-time and workstation elements are deployed side by side on a high-performance Windows®*1 PC, providing a convenient single-box package.

STARS Automation provides some tools and interfaces targeting more advanced application developers, leveraged both by HORIBA solutions teams and customer application engineers. For example, the integrated VSTA (Visual Studio Tools for Applications) environment includes a lightweight version of the Microsoft® Visual Studio®*1 IDE, which can be used to implement new automation features and apps using C# or VB.NET. The integrated driver development kit (DDK) provides a no-code environment for the creation of ASCII protocol device drivers.

The STARS Enterprise platform was created to enhance the operational efficiency, integrity and cost effectiveness of testing organizations. Serving a distributed community of engineering users and test operations staff, critical features include data management integrity, exceptional scalability, ease of deployment and maintenance, and software update with zero downtime. To achieve these objectives, STARS Enterprise employs a cloud-native microservice architecture, with each microservice playing a well-defined, focused role. They are implemented with minimum dependency on other microservices and are designed to be stateless, i.e. to hold no memory within themselves of previous invocations or requests. When deployed in a Kubernetes orchestration environment this stateless quality allows duplicates of any microservice to be started or stopped according to the demands on the deployment, without interruption to service; so-called horizontal scaling.

Underpinning the STARS Enterprise platform is a NoSQL MongoDB database, capable of accommodating both structured and unstructured data. The diversity of needs that STARS enterprise aims to address, along with the constantly evolving structure of the data involved, requires the schema-less concepts of a NoSQL database, which follows a less normalized data model, for this platform. Changes or extensions to the data model can be accommodated at application level, avoiding the need for expensive and time-consuming database remodeling. Structured data, with well-known, consistent relationships between entities and fields, are also accommodated by NoSQL databases, although a less normalized database design is required compared to that typically employed in an SQL database.

Security by design ensures that STARS Enterprise has strong cybersecurity credentials. Tenancy support implemented in the data service controls who has access to what data, and a granular role-based user management system gives fine control over the functionality assigned to different users.

A STARS Enterprise solution starts out by creating a data model tailored to the needs of the customer. The solution is then created by combining standard platform components with customer specific web apps, mobile apps and services. A typical requirement for a STARS Enterprise solution is that it integrates into the customer's existing ecosystem of data and business systems. STARS Enterprise was designed with this role in mind. The flexible data model and event driven notification support in the platform are key features in this respect.

Data security is enforced through a secure data client design pattern, in which any application (data client) to be connected to STARS Enterprise must first be registered with the relevant STARS Enterprise deployment by an administrator. Through this registration the data client will be granted a secure access token encapsulating its identity and access rights.

Valuable synergies are realized by coupling a STARS Enterprise (SE) deployment to a cluster of STARS Automation (SA) workstations. In this scenario the datasets of the two platforms are transparently synchronized, with designated data resources being automatically uploaded from SA to SE and/or downloaded from SE to SA upon change. For example, in a mechatronic testing laboratory, the end-to-end workflow, starting with an engineering request, through test creation and transmission to the test stand, to results upload and automated analysis, can be fully automated, leading to significant increases in the efficiency of test operations (Figure 4).

Recent years have brought an increasing demand for STARS Enterprise solutions to be provided as a HORIBA operated cloud service, rather than as software to be procured and deployed on premises by the customer. The service model allows customers to focus on their core business with confidence that, through HORIBA's STARS Enterprise platform knowledge and cloud operations expertise, system availability is assured and their data is secure.

STARS Process is the most recent addition to the STARS ecosystem, positioned closest to devices in the STARS

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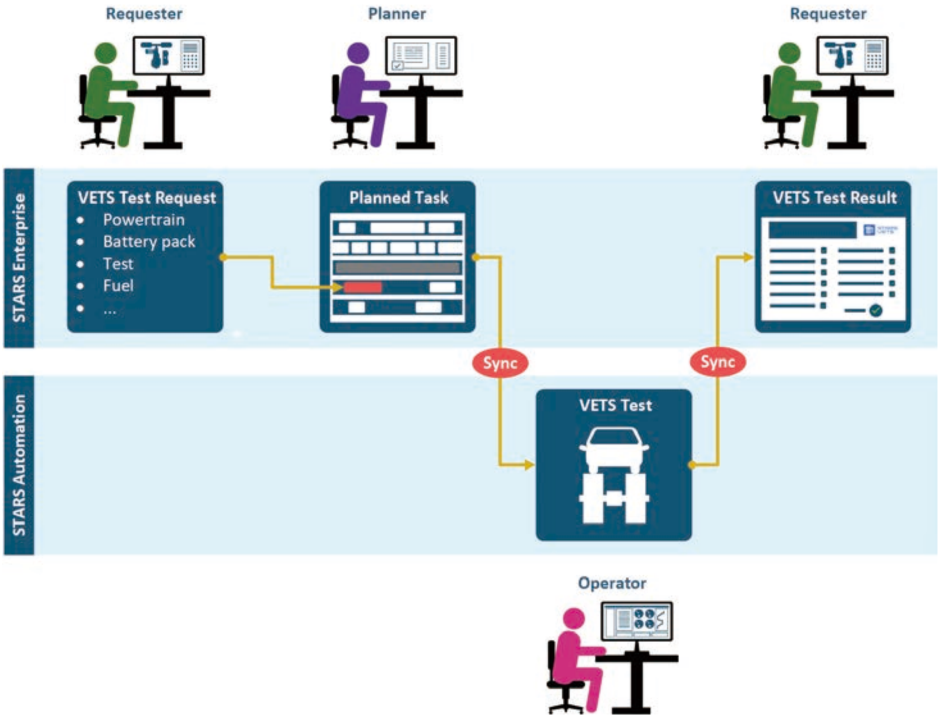

Figure 4 VETS Test Request Solution.

platform stack. Conceived for instrument control and sensor management, and developed in C++/Qt, STARS Process is a lightweight, efficient framework in which to implement smart sensor interface modules and instrument controllers. It is generally deployed on low power consumption hardware targets such as an embedded PC or System-on-a-Chip (SoC).

The architecture of STARS Process features a modular, message-based paradigm, with the platform's middleware supporting Publication/Subscription or Request/Reply communication patterns. Web and QML based user interfaces are supported for local display/control panels, and standard communications modules accommodate popular communication protocols and connect STARS Process based devices to the STARS Automation and STARS Enterprise platforms.

STARS across all HORIBA business fields

While the roots of the more mature STARS platforms lay in the mobility business field, the opportunity to deploy STARS solutions in other business fields in which HORIBA operates is clear. STARS Enterprise in particular, being a robust, secure and performant cloud-based platform upon which to implement modular solutions, offers huge potential in this respect.

In the Life Sciences field, although having established a world class reputation for its analytical instruments, HORIBA has not yet moved up the software stack to offer solutions for instrument management and coordination. This situation is changing, as the potential of the STARS Enterprise platform is embraced. In pharmaceutical manufacturing, customers are showing strong interest in device orchestration and Process Analytical Technology (PAT) solutions from HORIBA, taking confidence from HORIBA's stellar reputation for measurement in general, and for automation and system integration in the mobility sector. 'Device' in this context refers to smart sensors, instruments, sample conditioning subsystems, material transport subsystems and the like.

It has been observed that, given its highly deterministic real-time control capabilities, the STARS Automation platform would appear to be an obvious contender for process device orchestration. In fact, the real-time performance requirements in this application area are relatively relaxed and the features of STARS Enterprise - high availability, zero downtime upgrades, boundless scalability, ease of integration with other data systems and cloud readiness - make this HORIBA's preferred platform for orchestration.

Although the specifics are different, there is a marked similarity between the orchestration features required for pharma process orchestration and, say, materials R&D applications. It is anticipated that the orchestration core that HORIBA is developing for STARS Enterprise will have broad potential across HORIBA's business fields. Indeed, a solution for managing an industrial coating formulation facility is a good fit to the orchestration capabilities of STARS Enterprise (Figure 5).

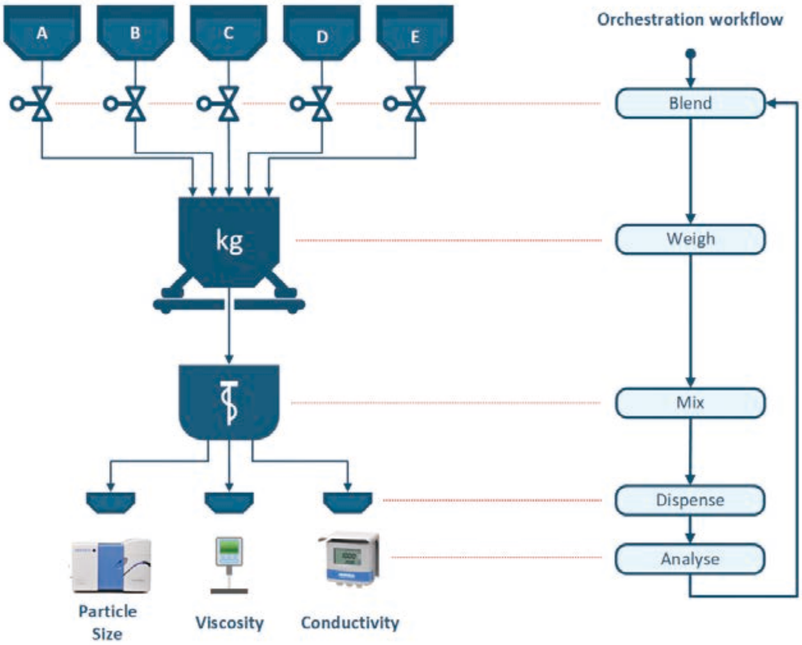

Figure 5 Process orchestration for industrial coating formulation.

In the medical field, STARS Enterprise is being used as the platform to support our next generation biology lab data management solution. The high integrity data management provided by STARS Enterprise, along with its flexible microservice architecture, have facilitated this development. The direction of travel of DX solutions is inexorably towards the cloud and the selection of STARS Enterprise as the underlying platform ensures that the transition from on-premises to cloud-hosted will be a smooth one for this system when the time comes.

Data systems, the purpose of which is to ingress data of different types, act upon those data in an intelligent way to provide business value, and produce actionable outputs, is another area of strong interest and potential for STARS Enterprise based solutions. With the capacity to ingress and store hundreds of thousands of data points per second, and to push these data through analytical pipelines that support advanced machine learning and AI implementations, STARS Enterprise is a good fit here. For example, for the water management industry HORIBA is developing data solutions addressing measurement, data persistence, visualization, and analytics, and offering these end-to-end implementations on a HORIBA hosted solution-as-a-service basis.

Conclusion

The STARS Automation platform, originally conceived and architected more than 2 decades ago through the combined experience of HORIBA, Schenck and Ricardo, has underpinned a consistent growth in the scale and breadth of automation systems in HORIBA. More recently, with the addition of STARS Enterprise and STARS Process, STARS has evolved into a comprehensive ecosystem, a stack of platforms spanning the application space from sensor management, through test rig automation to enterprise process automation and data management. Forged in the mobility business field, where system integration is a core strength for HORIBA, the STARS platforms have come of age and are now being leveraged across HORIBA's business fields to power automation and data management at all levels.

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

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Feature Article

Powertrain Digital Twinning for Real-World Emissions Compliance

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A digital twin is a digital representation of a planned or real physical system, product, or process that functions as its practically identical digital counterpart for tasks such as testing, integration, monitoring, and maintenance. Creating digital twins allows the 'digital system' or 'digital product' to be tested faster-than-real-time improving the overall efficiency and reducing programme's timescales. The HORIBA Intelligent Lab virtual engineering toolset has been used produce Empirical Digital Twins (EDT) of several contemporary Internal Combustion Engine (ICE) propulsion systems. Digital twinning in its current format can supplement real-world testing methods for the development, calibration, optimisation, and certification of powertrains and vehicles. Given the move to ever more stringent pollutant criteria over wider test conditions, which is expected to put additional strain on Original Equipment Manufacturers (OEMs), the HORIBA EDT approach is expected to increase efficiency and reduce time when taking a vehicle or powertrain to market.

Keywords
Digital Twin, Dynamic DoE, DoE, Empirical modelling,
Data driven model

Introduction

Amid growing international concern over the impact of automotive exhaust emissions on human health and global warming, the introduction of more stringent environmental regulations such as Europe's Euro 7 is being considered [1],[2].

Consequently, the field of engine technology development faces increasing demands for performance evaluation under increasingly diverse testing conditions, alongside further tightening of emission regulations. For automotive OEMs, this presents significant challenges in both technical and financial aspects.

HORIBA has proposed the Empirical Digital Twin (EDT) approach[3] as a solution to the issues outlined above, which is attracting attention as a robust technological foundation for streamlining the entire process from vehicle and powertrain design to market introduction, and for shortening development cycles.

At the time of writing (May 2025), light-duty vehicles (LDVs) sold in Europe (passenger cars and other vehicles under 3.5 tons) must comply with the current Euro 6[4] regulations by undergoing the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and Real Driving Emissions (RDE) testing.

WLTP testing is conducted in a laboratory under controlled atmospheric conditions, whereas RDE testing is based on actual road driving conditions, requiring evaluation under more uncertain circumstances. Specifically, Euro 6 provides detailed specifications for the proportion of urban, rural, and highway driving, as well as operating conditions. Under these real-world testing regimes, powertrain and emissions aftertreatment systems must be designed to function reliably. Looking ahead to even stricter future emission standards, it is theoretically possible to comprehensively verify all operating conditions through physical testing, but in practice, this is extremely inefficient and challenging for development teams and is likely infeasible for many OEMs.

Simulation tools capable of predicting performance and emissions during edge-case boundary conditions that are physically difficult to achieve will become essential for future compliance. In this context, the authors propose a method whereby OEMs will still physically conduct tests under "worst-case" boundary conditions then use the results to build predictive models that, when combined with simulation, supplement RDE testing (**Figure 1**).

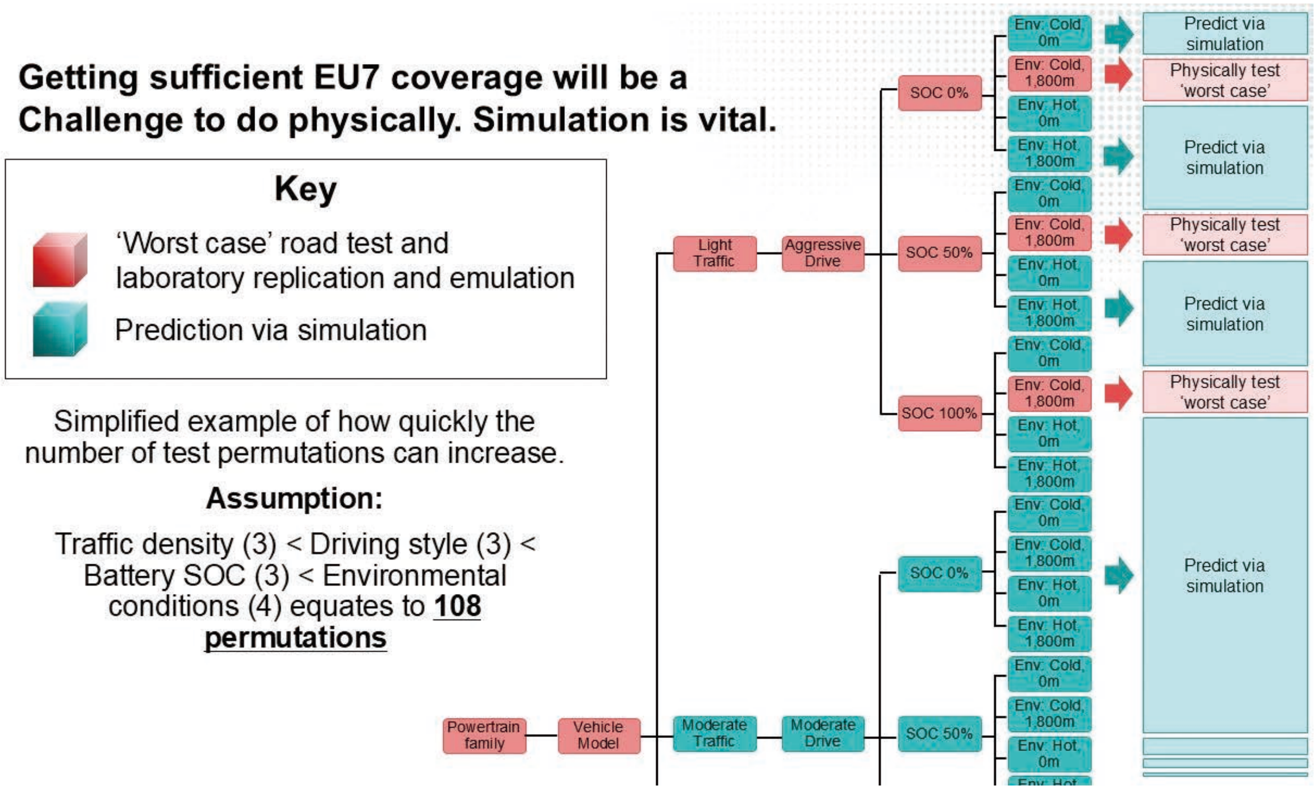

Figure 1 An example for the need for combined physical testing and simulation

In this study, a Plug-in Hybrid Electric Vehicle (PHEV) was subjected to simulated RDE tests on a single route, combining three types of traffic conditions, three driving styles, three battery states of charge (SOC), and four environmental conditions, with the same powertrain installed in multiple vehicle platforms. Physical testing of >100 conditions would be hugely time consuming; hence the use of supplementary simulation data proves indispensable.

EDT Principle — Overview

HORIBA have developed a simulation tool utilizing digital twins to support future emission compliance for automotive OEMs[5]. Here, a digital twin refers to empirical models that accurately replicate physical units. The HORIBA toolkit consists of proprietary modules for transient experimental design, modeling, prediction, and optimization, employing an approach similar to Dynamic Design of Experiments (Dynamic DoE)[6].

These standalone modules operate according to the following process:

1. Design a transient experiment using statistical methods.
2. Conduct the designed transient experiments with the powertrain or vehicle and acquire training data.
3. Generate models to predict performance and emission characteristics based on the training data.
4. Validate the accuracy of the generated models.
5. Predict performance and emission behavior under real-world or synthetic driving conditions.
6. Identify undesirable powertrain characteristics ("hotspots") such as excessive emissions, poor fuel economy, or increased energy consumption.
7. Recalibrate to address identified issues.

These seven processes are depicted in **Figure 2** (**Figures 2-1 to 2-4**) and **Figure 3** (**Figures 3-5 to 3-7**).

EDT combines the empirical model created in process 3 with real-world RDE driving cycles generated by virtual vehicle simulation tools such as IPG CarMaker™*1 (process 5). HORIBA's EDT approach builds upon semi-dynamic testing methods from previous studies[7]-[12], employing new modeling techniques that combine empirical models and simulation for greater immersion and extensibility across broader domains.

*1 Registered trademarks or trademarks of IPG Automotive GmbH

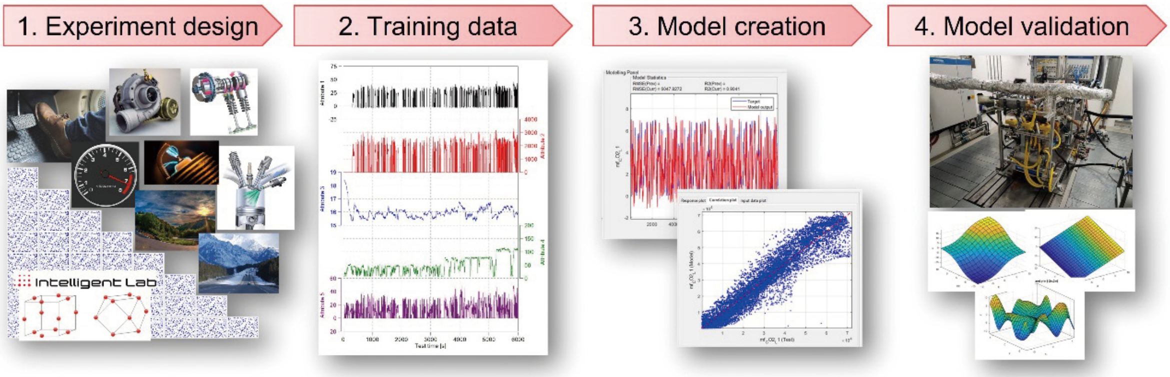

Figure 2 Stages of the HORIBA EDT approach (1) ; experiment design, generation of training data, modelling, and model validation.

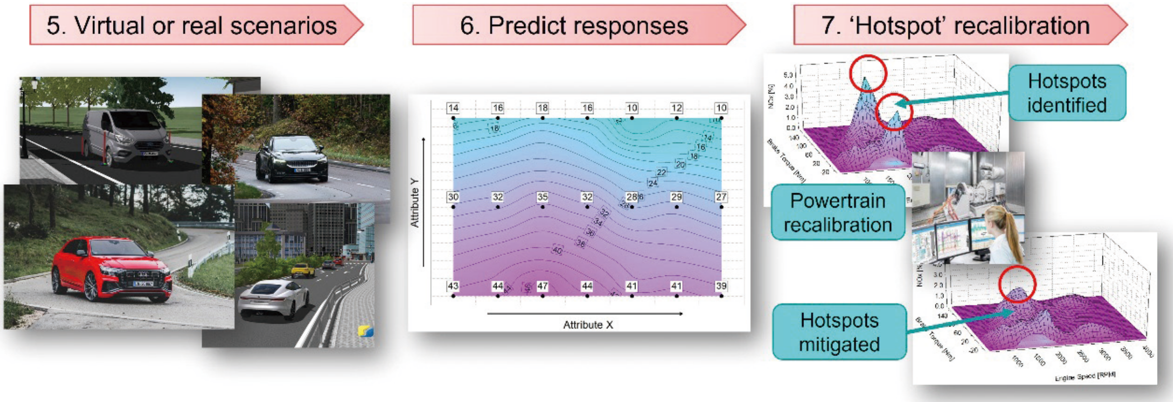

Figure 3 Stages of the EDT approach (2) ; establishing real or virtual scenarios to couple with empirical models, prediction of responses, and 'hotspot' determination.

EDT Principle—Dynamic Experimentation (Training Data Acquisition)

To build the empirical models in process 3, transient experimental design tools were used to generate training cycles covering the full operating range for both PHEV and commercial vehicle powertrains.

This enabled the construction of models that accurately replicated performance and emissions behavior under various operating conditions.

Figure 4 presents examples of powertrain bench experiments, while Figure 5 shows examples from chassis bench experiments.

The test cycles used to acquire training data for model generation required approximately 1.5 hours on both powertrain or chassis benches. For the powertrain test bench, input parameters included accelerator pedal position, brake pedal position, and drive shaft speed. For the chassis bench, input parameters were accelerator pedal position and vehicle speed. In the latter tests, HORIBA's automated driving system (ADS EVO) was used to automate accelerator pedal operation, with the chassis dynamometer controlling vehicle speed.

The dynamic experimental design, like traditional design of experiments (DoE) for steady-state conditions[13], consists of multiple target points within the operational constraints of the physical system (the engine, in this case; see Figure 2-1). However, in dynamic design, these points are passed in a specific sequence, sometimes revisited multiple times in different orders with brief stops.

Unlike steady-state experiments, in dynamic systems, even identical steady-state points may exhibit different behavior depending on the approach path (e.g., changes in engine speed or load i.e., history). Thus, trajectory information leading to measurement results is important and must be considered in model construction.

Data obtained by effectively covering the system's entire operational space enables the construction of highly-accuracy models that can accommodate any scenario expected in real-world operation.

In this study, to reduce the required amount of training data and physical testing burden, a dynamic experimental design unique to the target system was formulated (Figure 2-2). This design accurately captured the system's dynamic behavior and generated a high-density dataset while covering the entire operational space.

Using the training data acquired from these experiments, transient empirical models for multiple performance and emission characteristics were constructed (Figure 2-3).

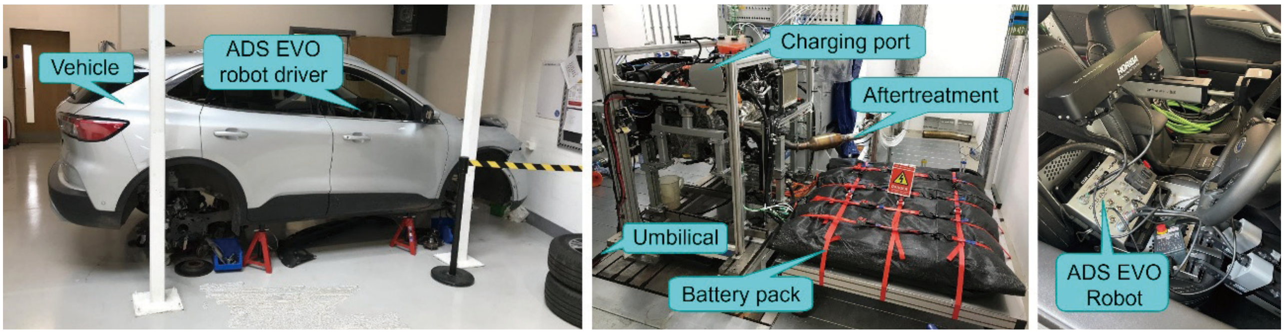

Figure 4 PHEV powertrain tested at HORIBA MIRA in the UK

Figure 5 Vehicle and corresponding diesel engine tested at an OEM in the UK.

EDT Principle—Model Creation, Validation, and Prediction

For modeling, a recurrent neural network (RNN)[14] with a long short-term memory (LSTM)[15] architecture was adopted.

RNNs were chosen for their flexibility in handling dynamic systems that change over multiple time scales. However, standard RNNs struggle to maintain long-term dependencies when handling long sequence data, often suffering from the vanishing gradient problem[15]. LSTM mitigates these issues with enhanced long-term memory retention and a structure that resists gradient vanishing.

LSTM features cell states and multiple gate mechanisms (input, output, forget gates), enabling temporary storage and appropriate output generation by combining past information with current inputs. This allows important past information to be reused even if similar values do not reappear in the current sequence; stored values are deleted only when learned conditions are met.

Training data collected during planned experiments includes both input and output variables as time-series data for the algorithm. During training, sequences are processed step-by-step in a moving window format.

RNN training is computationally intensive and time-consuming, but the use of high-density training data and general-purpose graphics processors (GPGPU) enables significant reduction in processing time. For example, even with multiple variables input at 10 Hz over a 90-minute driving scenario, model training and prediction is completed in only a few minutes.

All generated models are validated by comparing predictions with actual measurements (**Figure 2-4**). **Figure 6** shows examples of model quality from HORIBA's EDT toolkit, visually demonstrating differences between measured and predicted values for several performance and emission characteristics.

To reproduce real-world driving scenarios in a virtual domain, IPG CarMaker was used. Following steps described in previous literature[16], virtual drivers were programmed to drive multiple virtual RDE cycles in IPG CarMaker.

A major advantage of virtual scenarios is the ability to run simulations much faster than real time, enabling hundreds of RDE tests for a single vehicle to be completed in a very short period. Data generated by these simulations, combined with corresponding EDT models, allow for large-scale predictions of performance and emissions while greatly reducing the need for physical testing. **Figure 7** shows examples of scenarios generated using IPG CarMaker. These virtual tests enable detailed analysis of how factors such as driving style, traffic density, and route characteristics affect engine, powertrain, or overall vehicle performance.

Additionally, by incorporating the effects of environmental factors such as altitude and extreme ambient temperature into the EDT model, it is possible to predict driving performance and emission behavior for virtual environments at sea level or in regions of very high or low temperature. As an example, research described in[17] used HORIBA's altitude simulator Multi-function Efficient Dynamic Altitude System (MEDAS) to integrate the

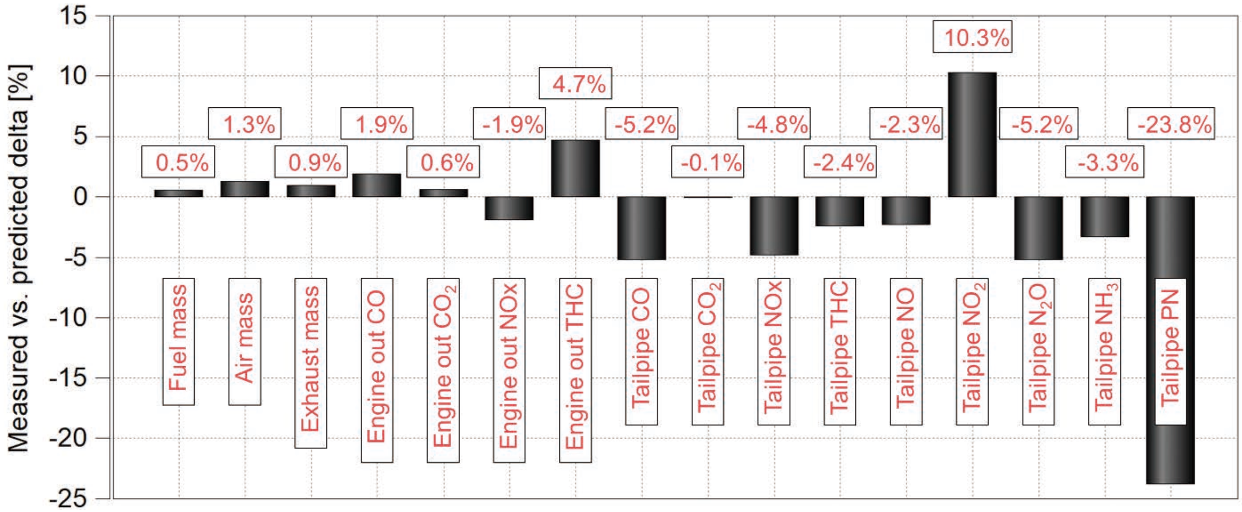

Figure 6 Measured vs. predicted deltas for performance and emissions attributes for a PHEV SUV tested on a powertrain dynamometer.

Figure 7 IPG CarMaker scenario definition for the light-duty PHEV SUV.

effects of altitude and temperature on engine performance and emissions into the EDT models.

EDT Principle—Identification of Hotspots

Figure 8 presents an example of identifying problematic operating conditions ("hotspots") for powertrains or vehicles using the EDT approach. The figure shows cumulative NOx emission predictions from the tailpipe for four RDE cycles on the same virtual route and traffic density, with an SUV-type PHEV set to zero battery SOC for all cycles. Black lines indicate calm (solid) and dynamic (dashed) driving styles at sea level and 35°C intake temperature; red lines show the same styles at 1,800 meters elevation and 35°C intake temperature.

The black box in the figure represents the proposed EU7 mass limit requirement during the 2021 Euro 7 discussions (since removed as of 2025), which stipulates cumulative NOx emissions must not exceed 600 mg within the first 10 km of testing. All predictions are based on training data collected after engine warm-up. For sea level driving (black lines), cumulative NOx emissions remain around 400 mg, within the black box, and per-distance emissions are below 60 mg/km, meeting both gasoline and diesel standards at the time.

In contrast, predictions for 1,800 meters elevation (red lines) exceed 600 mg NOx emissions between 6–7 km, violating the mass limit. Interestingly, these high-altitude emissions remain below 60 mg/km, still compliant with Euro 6.

As demonstrated in **Figure 8**, HORIBA's EDT method enables identification of problematic powertrain operating conditions even before vehicle mass production. Since all predictions are based on post-warm-up engine data, cold-start conditions could result in exceeding 600 mg within

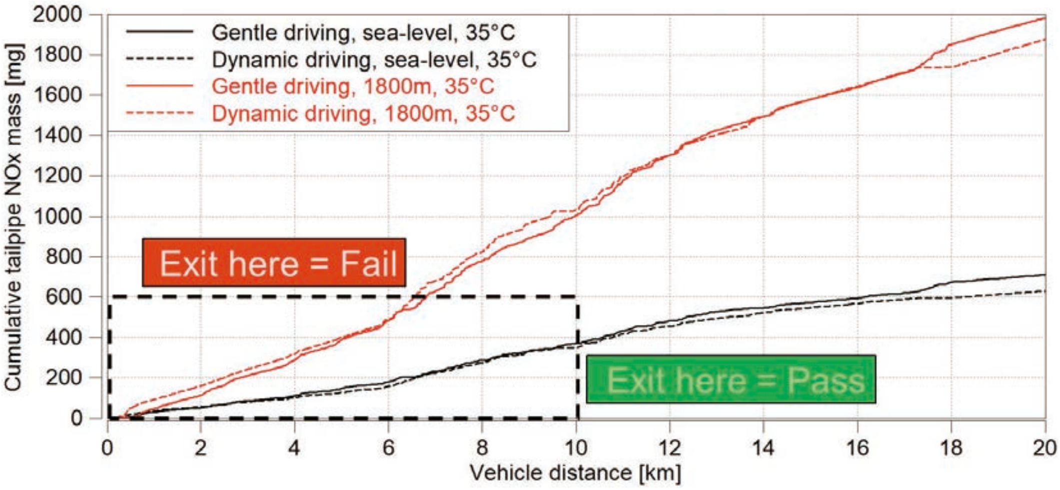

Figure 8 Predicted tailpipe NOx emissions for the PHEV SUV at sea-level and 1,800m.

10 km even at sea level. Thus, cold-start conditions, though permissible under Euro 6, become a crucial consideration for compliance if the EU7 10-km mass limit is introduced.

With the introduction of stricter emissions regulations, automotive OEMs must strengthen simulation activities to ensure product compliance under a wider range of operating conditions.

HORIBA's transient EDT method is therefore highly effective for predicting performance and emissions for various powertrains, engines, and vehicles over a vast number of cycles at faster-than-real-time.

Conclusion

By adopting the EDT approach, automotive OEMs can verify product reliability and regulatory compliance under "worst-case" and "edge-case" conditions – such as temperature and altitude extremes or operating characteristics near RPA, V.apos[95][4] boundaries – defined by RDE regulations, even before conducting real-world vehicle tests.

Furthermore, as powertrain sharing becomes common in modern vehicle development, intentional dynamic cycle testing is required to ensure proper functionality across multiple vehicle platforms.

Initial estimates suggest that applying the EDT approach to a single vehicle can reduce the time required for certification and verification processes by at least 70%. This effect becomes even more pronounced as common powertrains are introduced across multiple vehicles.

The EDT approach introduced herein has already been applied to established mass-production powertrains and is also effective during early development stages when hardware and calibration optimization are required. For example, during selection of air supply systems or exhaust aftertreatment, EDT can potentially reduce the number of required prototype systems and vehicles.

Current research focuses on conventional and electrified powertrains using liquid fossil fuels, but the methodology is also applicable to battery electric vehicles (BEVs), fuel cell vehicles, and carbon-neutral alternative fuels, enabling understanding of how energy consumption and driving range vary with different operating characteristics, environmental conditions, and load states.

Traditionally, evaluation of energy consumption and driving range using chassis dynamometers has been complex and time-consuming. However, the EDT approach can significantly reduce this burden. Moreover, the flexibility of this method – developed as a cross-functional toolset spanning multiple engineering and scientific fields – means it is widely applicable to systems beyond automotive.

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

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Utilization of Image Analysis Technology and Case Studies of Efficiency Improvement in Automotive Testing

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HORIBA has been developing various solutions to improve the efficiency of automotive testing, including the test automation system “STARS” and the automatic driving system “ADS EVO.” However, when visual information, such as instrument panel (IP), needs to be incorporated into driving tests, a human driver had to directly observe the display. To address this, we developed a “Machine Vision System for Vehicle Testing” that converts IP information into numerical values using image analysis technology, which interacts with STARS and ADS EVO. In this report, we describe the design concept and structure of this system, its user interface with flexible configuration options, and the fast response numerical OCR model. We also present case studies of its application in test automation.

Keywords
Machine vision, Image analysis, Instrument panel, Chassis dynamometer testing, Test automation, OCR

1. Introduction

With the rapid advancement of vehicle electrification and intelligence, there is a growing demand for both increased development speed and quality, making the efficiency of vehicle evaluation a pressing challenge[1]. HORIBA has long provided solutions to support the streamlining of automotive testing processes. For example, by managing the status and signals of test objects, various facilities, and measurement instruments collectively via the test automation system (HORIBA product name: STARS; hereafter, STARS), a mechanism has been established to automate test execution, measurement, and monitoring, thereby contributing to the efficient development of vehicle evaluation systems[2].

Among the products HORIBA offers for complete vehicle evaluation benches is an automated driving system (HORIBA product name: ADS EVO; hereafter, ADS EVO), which operates the vehicle in place of the driver[3]. ADS EVO can perform operations such as accelerator, brake, and clutch pedals, gear shifting, ignition buttons, and air conditioning switches on behalf of the tester. These functions enable precise driving in accordance with emission measurement test modes required for vehicle certification and provide a solution that reduces tester workload during long-duration tests such as durability and energy consumption testing. However, ADS EVO does not have the capability to acquire visual information from the instrument panel (hereafter, IP) or warning lights as seen by the driver, and incorporating such information into driving required tester involvement. This background revealed the need for “ADS EVO to have eyes.”

A survey of existing technologies that could serve as the “eyes” for ADS EVO found that factory automation (FA) has progressed in manufacturing sites, with examples of image analysis technology being used for visual inspection and character recognition[4]. In these cases, inspections such as defect detection and reading printed text are performed on products flowing in known shapes at designated positions. In the automotive testing domain, there are reports of image analysis technology being used for standalone IP inspection[5]. However, these prior studies are not optimal for applications such as automotive testing, where the IP, camera positions, and inspection items change multiple times a day. Additionally, such systems differ from those that assume integration with actuators operating the vehicle, like ADS EVO.

Meanwhile, the constituent technologies of image analysis have become widely available, including as open-source libraries[6]-[8], and it was considered that these technologies could deliver sufficient performance for automotive testing applications.

Leveraging these existing technologies, a proof-of-concept (PoC) and prototype were developed for a “Machine Vision System for Vehicle Testing” (hereafter, Machine Vision System), which can be operated generically for various vehicle IPs and inspection items and processes data at human-like reaction speeds, enabling integration with ADS EVO during complete vehicle testing. This report introduces this initiative: Section 2 discusses design innovations, Section 3 evaluates the standalone Machine Vision System, Section 4 presents application cases integrated with ADS EVO, Section 5 considers the effects on test efficiency, and Section 6 summarizes and discusses future developments.

2. Development of the Machine Vision System

This section explains the requirements for the Machine Vision System when integrated with ADS EVO and describes the development of both the user interface (UI) and the numerical OCR model, which are key design aspects.

2-1 System Role and Design Policy

The Machine Vision System discussed herein is intended as an element of a system integrated with ADS EVO. This subsection outlines its role and design policy. Figure 1 shows the basic configuration of the ADS EVO-integrated system and the functions of each block. ADS EVO operates the vehicle in place of the driver, the chassis dynamometer applies loads equivalent to road driving, and the Machine Vision System captures images of the vehicle’s IP and converts them into numerical data. STARS centrally manages data from each block and, based on data from the chassis dynamometer and Machine Vision System and the prescribed driving patterns, sends operation commands to ADS EVO.

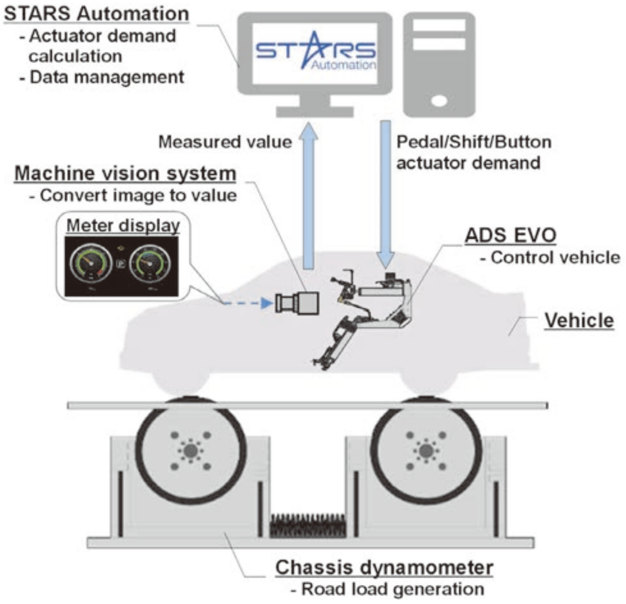


Figure 1 Diagram integrating ADS EVO and machine vision system.

Figure 2 illustrates the basic configuration of the Machine Vision System. The camera is mounted near the IP using a universal mount compatible with various vehicle shapes. The controller, equipped with a monitor for operator use, is placed in the measurement room. The controller converts camera images into numerical data and transmits them to STARS. As shown in Figure 1, STARS determines the commands for ADS EVO; thus, the Machine Vision System is designed to output numerical data read from images directly, without including detailed sequence control or error judgment functions.

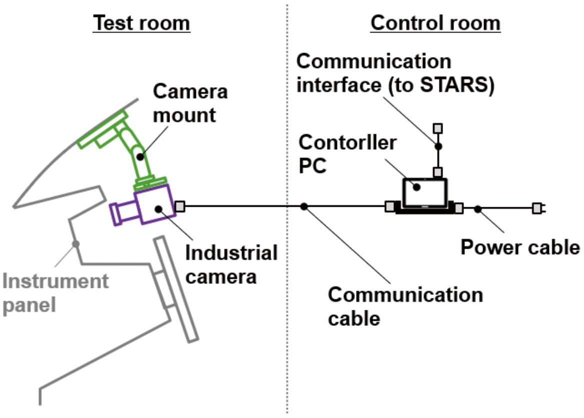


Figure 2 Machine vision system diagram.

Next, the necessary preparation steps for testing are described. Figure 3 shows the flow from preparation to measurement. First, the camera is installed at the designated position, and the controller software is launched. The camera's view is displayed on the controller screen, allowing adjustment of the viewing angle and focus. Then, a configuration file is created to define the measurement method according to the vehicle's IP. While AI-based automatic judgment could be considered, the design policy prioritized allowing testers to set parameters explicitly, addressing concerns about unexplained results.

Configuration files are created using the controller's UI. In automotive testing with a chassis dynamometer, vehicles may be swapped multiple times a day, necessitating flexible and rapid preparation for different vehicles. The UI for this purpose is explained in Section 2-2.

To ensure integration with ADS EVO, images transmitted from the camera are processed sequentially and sent immediately to STARS. Human visual reaction time is reported to be about 180 ms[9], so the Machine Vision System's processing time was targeted at 100 ms. Most constituent technologies used standard methods, but for character recognition, a custom machine learning-based model specialized for numerical recognition was developed to balance reading accuracy and responsiveness; this is outlined in Section 2-3.

2-2 User Interface Development

This subsection describes the UI for creating configuration files tailored to the vehicle, as explained in Section 2-1. First, the IPs of vehicles are described: in addition to conventional analog meter types, the spread of digital meters and added functions due to electrification and intelligence have led to diverse display content depending on manufacturer, model, and grade. However, most display methods can be broadly classified into three types: (1) pointer type (e.g., speedometer, tachometer), (2) numeric display type (e.g., odometer, clock), and (3) symbol display type (e.g., indicators, warning lights). Algorithms developed for each display type are referred to as "Circle Meter Recognition" for pointer values, "Numerical OCR (Optical Character Recognition)" for numeric values, and "Pattern Matching" for symbol presence/color, output as integer values. Testers can select the appropriate algorithm for each inspection item.

Figure 4 shows the UI for creating configuration files and the contents that can be set for each area. Area A allows selection of the video source for imaging; this is used to choose between pre-recorded videos or the currently connected camera. Area B displays the selected video source, enabling adjustment of camera angle and focus. Area C allows selection of the algorithm—Circle Meter Recognition, Numerical OCR, or Pattern Matching—for each inspection item (speed, odometer, warning lights, etc.), and specification of the analysis area in Area B. Finally, algorithm-specific settings are made: for Circle Meter Recognition, scale positions and values are set; for Pattern Matching, reference images for similarity judgment are specified in Area B; for Numerical OCR, automatic identification of character strings in the specified area is supported, so no additional settings are required. Area D shows the processing results for each inspection item, allowing adjustment of algorithm settings such as scale positions, similarity thresholds, and area settings.

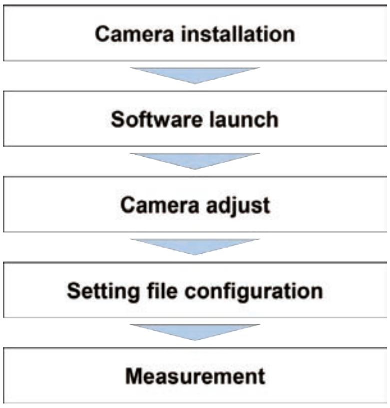


Figure 3 Operational procedure of the machine vision system.

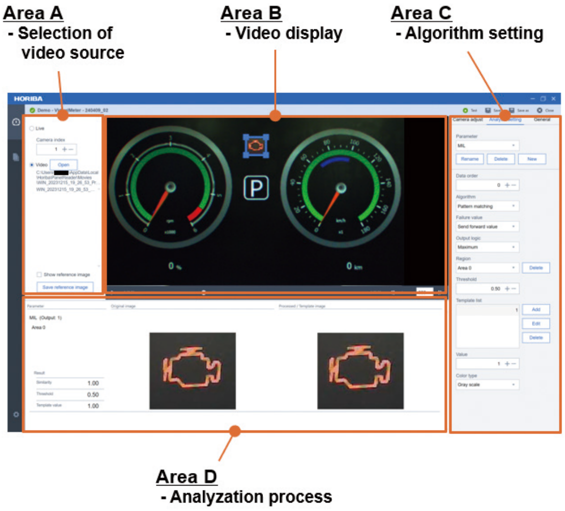


Figure 4 UI display of the setting file configuration.

Thus, while configuration of algorithm and analysis area for each inspection item is required, the objective was to enable operation in accordance with tester intent through appropriate settings[10].

2-3 Development of Numerical OCR Model

The Machine Vision System was designed for integration with ADS EVO, with the numerical OCR aiming for human-equivalent processing speed. Generally, OCR libraries are known to be computationally intensive due to image and mathematical processing[11]. Experimental implementation using the open-source OCR Tesseract[6] showed that system-wide processing time exceeded 100 ms when the number of reading targets increased. Therefore, a fast numerical OCR model was developed using a machine learning approach specialized for numerical recognition.

PyTorch™*1[12], a deep learning framework, was used for model training. Figure 5 shows the training and evaluation workflow. Considering the variety of fonts used in actual vehicle IPs, numeric images were generated using 25 fonts, with added disturbances in size, position, and inclination. Random image blending was also applied to simulate practical conditions such as IP scratches and reflections. The model was trained and validated using these images, allowing tuning for user-specific applications rather than relying on opaque library processes.

Figure 6 shows examples of training data used. Training was performed with 1.2 million images and validation with 10,000 images, resulting in a reading accuracy of 94.4%. Note that the validation included images with partially missing digits, as shown in Figure 6, so the accuracy was assessed under practical conditions, with results discussed in Section 3-2. Finally, the processing speed of the numerical OCR model is described.

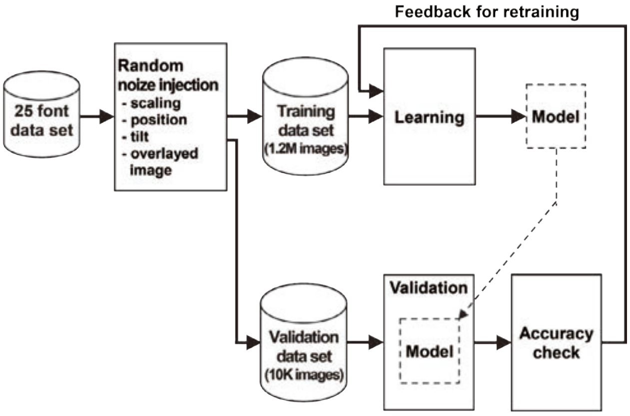


Figure 5 Process flow of model training and validation.

Table 1 shows the reading processing speed for the model described. Experiments used a laptop PC with a 13th Gen Intel® Core™*2 i7-1365U 1.80 GHz and 32GB RAM. Reading speeds for single-digit and five-digit numbers were measured, with processing times of approximately 30 µs and only a 5 µs difference between the two, confirming that digit length had minimal impact. Thus, even with increased reading targets, the system-wide processing speed goal of 100 ms can be met, and this numerical OCR model was adopted for the system.

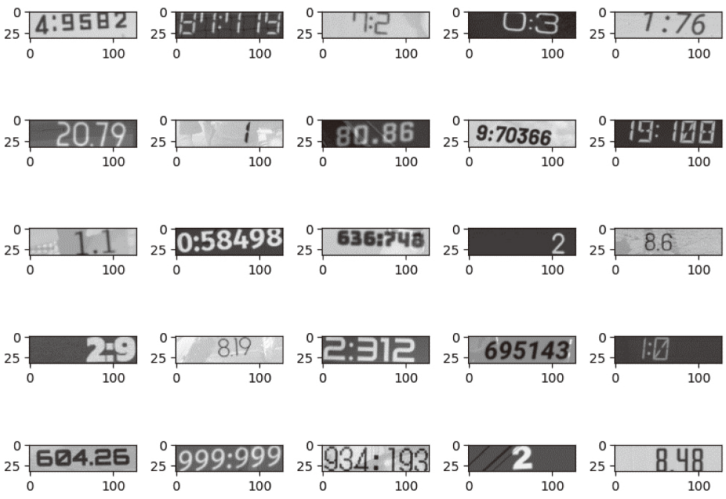
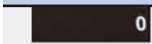


Figure 6 Training and validation data set example.

Table 1 Processing speed performance of the digit-specific OCR model.

Displayed image	Processed time
	27 µs
	32 µs

*1 Registered trademark or trademark of The Linux Foundation

*2 Registered trademark or trademark of Intel Corporation

3. Evaluation of the Standalone Machine Vision System

This section presents the evaluation results for the reading accuracy of the standalone Machine Vision System. Section 3-1 reports the accuracy of each of the three reading algorithms; Section 3-2 presents additional evaluation of the numerical OCR model using various fonts from actual vehicle IPs.

3-1 Reading Accuracy Evaluation

Due to the diversity of IP displays, it is not easy to set a uniform reading accuracy target for the Machine Vision System. Therefore, a simulated IP device capable of outputting specified values was used for evaluation, with a reading success rate target of 99%. Accuracy was assessed by first confirming whether each algorithm's reading values continuously tracked the command values, then considering system processing time and responsiveness, and finally defining reading success for each algorithm and verifying accuracy.

Figure 7 shows a schematic of the evaluation device. A simulated IP displaying speed, odometer, and malfunction indication lamp (MIL) was prepared, and readings were compared to controller command values. Circle Meter Recognition, Numerical OCR, and Pattern Matching were applied to speed, odometer, and MIL, respectively. WLTC speeds were used for speed command values; odometer readings were set to increase from 0 to 999,999 during the WLTC1 cycle to test up to six digits. MIL was tested with frequent switching (off, yellow, red every 5 seconds), with reading values of 0, 1, and 2, respectively, repeating the cycle three times for reproducibility.

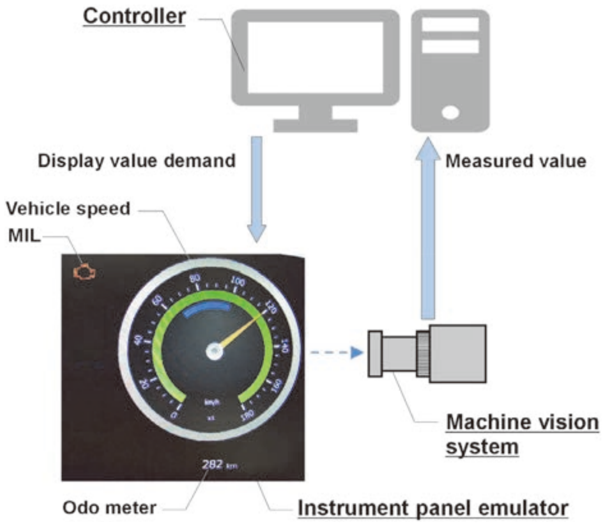


Figure 7 Performance test equipment diagram.

Figure 8 shows the command and measured values for speed using Circle Meter Recognition and their correlation. Across low to high speeds and three measurements, command and measured values tracked similarly; the regression slope was 0.983 and R² was 0.998, indicating good tracking. Minor discrepancies were attributed to needle shape and scale position settings.

Figure 9 shows command and measured values for the odometer using Numerical OCR and their correlation. Across one to six digits, values tracked well; regression slope was 1.00 and R² was 0.999, though a few outliers were observed. Table 2 lists image changes that contributed to these outliers, such as intermediate images captured during number transitions, which are difficult for humans to judge. Future work includes implementing outlier removal and interpolation using multiple frames.

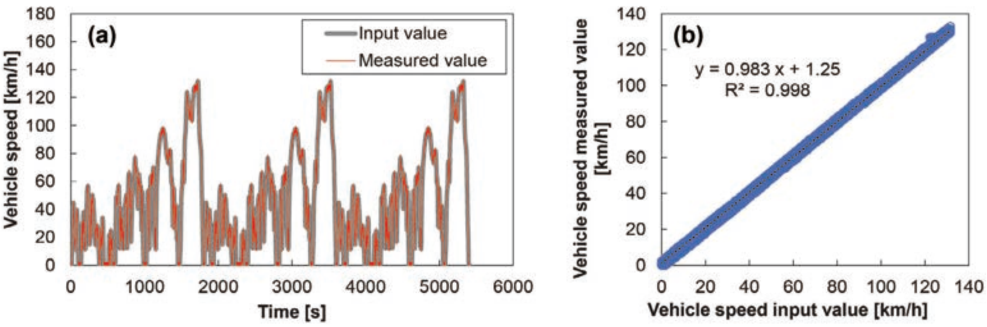


Figure 8 Displayed value vs. recognized value of (a) vehicle speed in time-series comparison and (b) correlation plot.

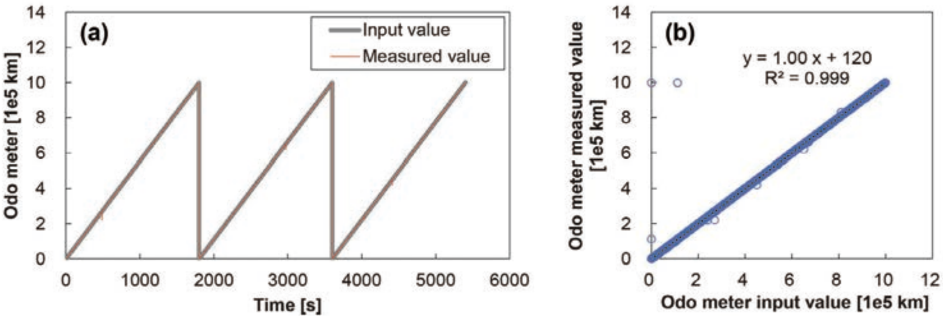


Figure 9 Displayed value vs. recognized value of (a) odo-meter in time-series comparison and (b) correlation plot.

Figure 10 shows command and measured values for MIL using Pattern Matching, with expanded views of the start, middle, and end of three test cycles. All states (off, yellow, red) were accurately read.

Next, processing and response times during measurement were examined. Figure 11 shows time-series changes for speed, odometer, and MIL. Speed was updated at 100 ms intervals, meeting the target. Odometer and MIL lagged by 300–400 ms and 300–700 ms, respectively, relative to command values, but these include controller and simulated IP display delays. Standalone system response time will be separately verified.

Finally, definitions of reading success were set for each algorithm. For Circle Meter Recognition, success was defined as a difference of ≤2.5 km/h (half a scale) between command and measured values. For Numerical OCR and Pattern Matching, success was defined as matching command and measured values within the observed lag time. Based on these definitions, reading accuracy was 99.8% for Circle Meter Recognition, 97.7% for Numerical OCR, and 99.1% for Pattern Matching. The lower accuracy for Numerical OCR was attributed in part to difficult images (Table 2), and will be further investigated.

Table 2 Fail case example in value recognition.

Displayed image	Demand value	Measured value	Result
	829	829	OK
	830	880	NG
	830	830	OK

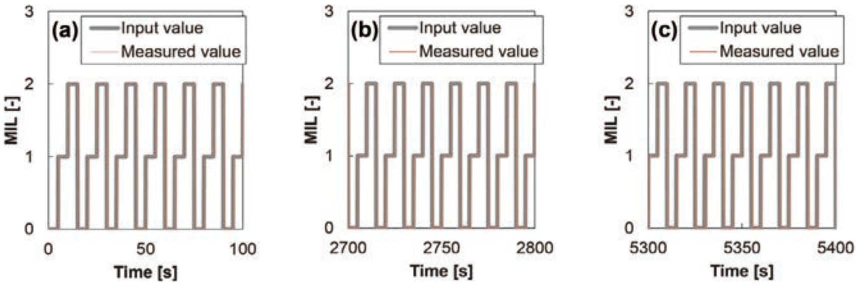


Figure 10 Displayed value vs. recognized value of (a) MIL in 1st cycle, (b) 2nd cycle and (c) 3rd cycle

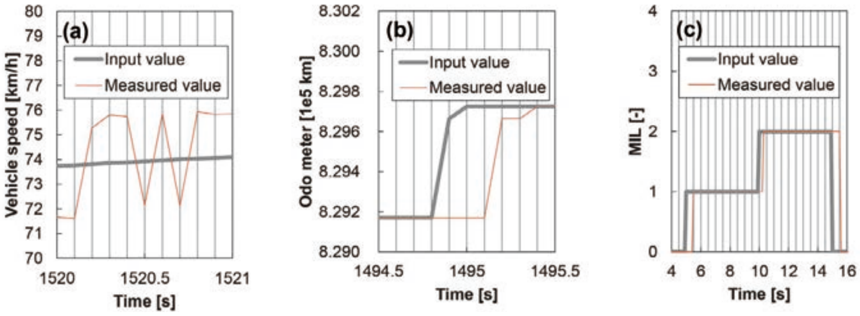


Figure 11 Displayed value vs. recognized value of (a) vehicle speed, (b) odo-meter and (c) MIL in an enlarged time window

3-2 Additional Evaluation of Numerical OCR Mode

Among the three algorithms, only Numerical OCR uses machine learning, raising concerns about unexplained outputs for certain targets. This section reports robustness tests using various numeric fonts from actual vehicle IPs. From internal image data, 50 numeric samples from 13 vehicle models were selected, excluding images with severe tilt, distortion, or focus errors. Table 3 shows sample images, their numeric values, measured results, and judgment. The model targeted only Arabic numerals; symbols like dots or colons were not included. When such symbols appeared, only the Arabic numerals were output, and all 50 samples produced the intended results. Conversion to physical values considering these symbols is assumed to be handled by higher-level systems.

4. Applications Integrated with Automated Driving Systems

The Machine Vision System described in this report was developed with the aim of integration into test sequences involving ADS EVO. This section presents examples of ADS EVO-integrated applications for which proof-of-concept (PoC) was conducted in HORIBA's research and development.

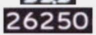
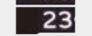
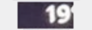
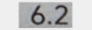
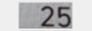
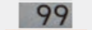
4-1 Gear Shift Indicator-Integrated Application

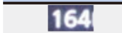
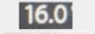
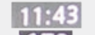
ADS EVO is capable of handling not only automatic transmission vehicles but also manual transmission gear shift operations. Some vehicles are equipped with a gear shift support function known as the Gear Shift Indicator (GSI). GSI notifies the driver of the recommended gear via instrument panel display according to driving conditions. UN Regulation No. 154 stipulates that, for electrified vehicles equipped with GSI, gear shifting must follow the recommended gear display[13], making GSI-compliant driving essential for accurate measurement of fuel economy, energy consumption, and emissions. When using ADS EVO alone, instrument panel displays could not be read, so GSI-compliant driving required manual operation by the tester. This section introduces a case where automatic gear shifting was achieved by combining ADS EVO with the Machine Vision System to respond to GSI displays.

Figure 12 shows the operation method for the test vehicle's GSI. Moving the shift knob left from D allows upshifting/downshifting by moving it forward or backward. In this state, ADS EVO performs gear shifts according to the instrument panel display.

Figure 13 shows the instrument panel display of the test vehicle. During GSI shifting, the current gear is displayed

Table 3 Evaluation results of the font recognition test from various vehicle instrument panels.

Displayed image	Displayed value	Measured value	Result
	28384	28384	OK
	35.3	353	OK
	26250	26250	OK
	289	289	OK
	76	76	OK
	23	23	OK
	9:32	932	OK
	23816	23816	OK
	678	678	OK
	16:14	1614	OK
	24.7	247	OK
	21458	21458	OK
	19	19	OK
	400	400	OK
	14.0	140	OK
	040599	40599	OK
	16:10	1610	OK
	16	16	OK
	9348	9348	OK
	432	432	OK
	6.2	62	OK
	25	25	OK
	99	99	OK
	37754	37754	OK
	53365	53365	OK

Displayed image	Displayed value	Measured value	Result
	164	164	OK
	65	65	OK
	15:48	1548	OK
	8	8	OK
	14497	14497	OK
	467.1	4671	OK
	76	76	OK
	16:07	1607	OK
	16.0	160	OK
	049348	49348	OK
	267.2	2672	OK
	68545	68545	OK
	710	710	OK
	373.7	3737	OK
	7:59	759	OK
	19.0	190	OK
	37708	37708	OK
	16:30	1630	OK
	24	24	OK
	29.7	297	OK
	34	34	OK
	27708	27708	OK
	11:43	1143	OK
	170	170	OK
	23	23	OK

(Figure 13a). As speed increases, a gear shift request symbol and recommended gear are displayed (Figure 13b).

The system shown in Figure 1 of Section 2-1 was used for testing. The Machine Vision System reads the current gear and gear shift request using pattern matching and the recommended gear using numerical OCR, transmitting results to STARS. Upon recognizing a gear shift request, STARS sends gear shift commands to ADS EVO to reach the recommended gear.

Using this method, acceleration to the highest gear (7th) and subsequent deceleration were performed. During acceleration, gear shift requests were displayed; during deceleration, the test vehicle automatically performed downshifting without displaying gear shift requests. For the shift from 1st to 2nd gear, gear shift requests were not displayed, so manual shifting was performed to avoid engine over-revving. Figure 14 shows vehicle speed, current gear, recommended gear, and the gear shift command signals issued by STARS for the upshift section from 2nd to 7th gear. When a “M2▶M4” gear shift request was displayed during 2nd gear driving, two consecutive shifts were performed to reach the recommended 4th gear. Subsequent recommended gears were displayed for each upshift, with correct shift operations executed accordingly.

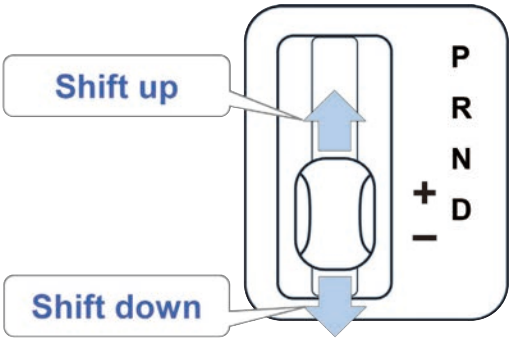


Figure 12 Operational method of GSI shift in the test vehicle.

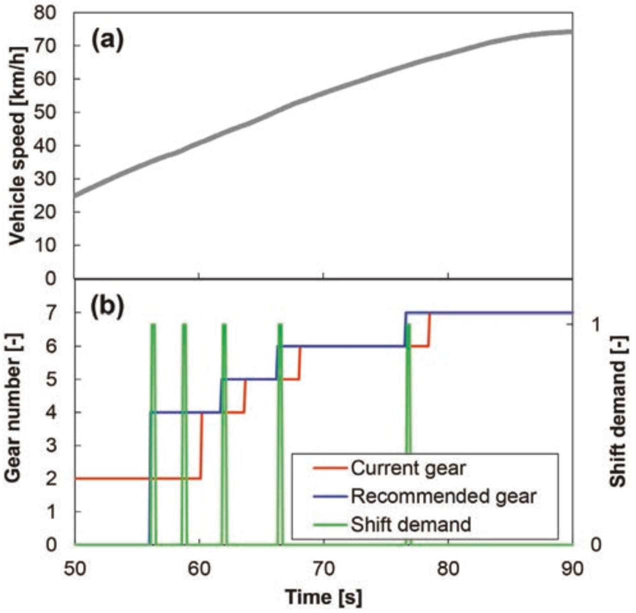


Figure 14 (a) Vehicle speed profile and (b) transition of current gear, recommended gear and shift demand.

The time from recommended gear recognition by the Machine Vision System to gear shift command issuance by STARS was within 100 ms, confirming satisfactory system responsiveness. Future work will use this system for regulatory cycle driving in accordance with GSI displays.

4-2 Adaptive Cruise Control Evaluation Application

Next, an application example of the Machine Vision System for evaluation of Advanced Driver Assistance Systems (ADAS) is presented. ADAS evaluations are typically conducted in real-world environments such as test courses, but laboratory-based evaluation methods have recently been studied[14]. This section reports results of laboratory evaluation of Adaptive Cruise Control (ACC), a key ADAS function, using ADS EVO and the Machine Vision System.

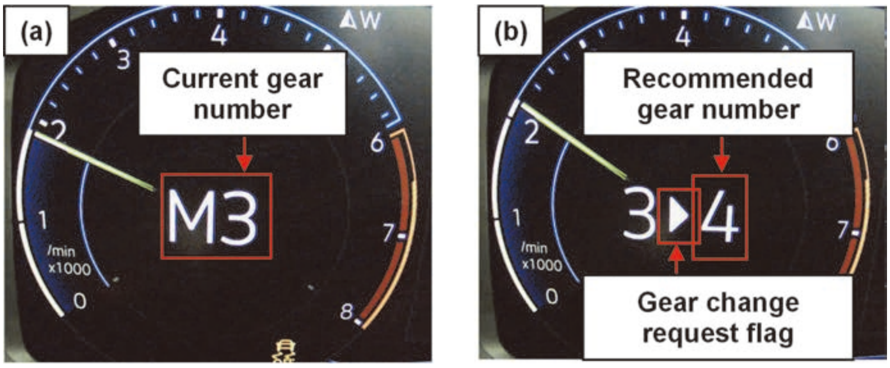


Figure 13 Meter display of (a) current gear and (b) gear number recommendation.

ACC not only maintains constant vehicle speed but also uses sensors and cameras to recognize and follow a preceding vehicle. With full-speed-range following, no operation is needed from test initiation to stop. However, before starting ACC driving, settings such as ACC enable/disable state, maximum allowable speed (set speed), and following distance (set distance) must be configured. When stopping behind or restarting after the preceding vehicle, specific operations on the brake pedal or steering buttons are required, based on instrument panel displays. Without the Machine Vision System, these operations required tester intervention. Here, a case is introduced where pre-driving ACC settings and ACC-based driving were automated using ADS EVO and the Machine Vision System.

Figure 15 shows the instrument panel display of the test vehicle. Pressing the ACC enable button illuminates the ACC state; set speed and set distance are adjusted using buttons, with the value and arrow position changing accordingly. The test vehicle allows set distance adjustment in five steps; "Short," "Middle," and "Long" refer to the shortest, middle, and longest settings, respectively.

Figure 16 shows the system configuration used for testing. The Machine Vision System reads ACC state and set distance via pattern matching and set speed via numerical OCR, transmitting results to STARS. STARS continuously recognizes current ACC state, set speed, and set distance, sending button operation commands to ADS EVO to match test conditions set by the tester. The test vehicle uses radar sensors for external recognition, and a radar target simulator was used to simulate preceding vehicle reflections. STARS calculates the relative relationship between the test vehicle and preceding vehicle from the specified profile and test vehicle speed, sending this to the radar target simulator. These functions allow combination of Machine Vision System and ADS EVO operation sections with ACC-based driving, enabling the test vehicle to follow the preceding vehicle according to tester-specified conditions[15].

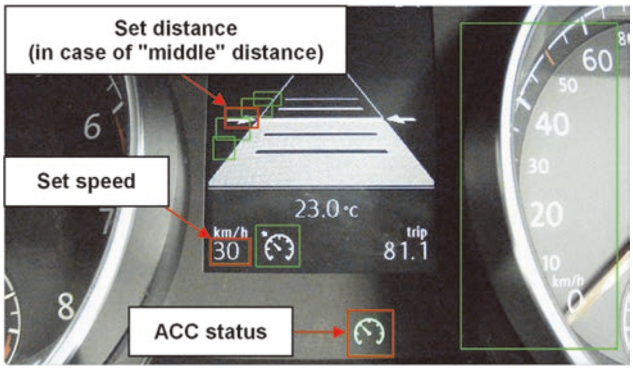


Figure 15 Meter display of ACC status, set speed and set distance.

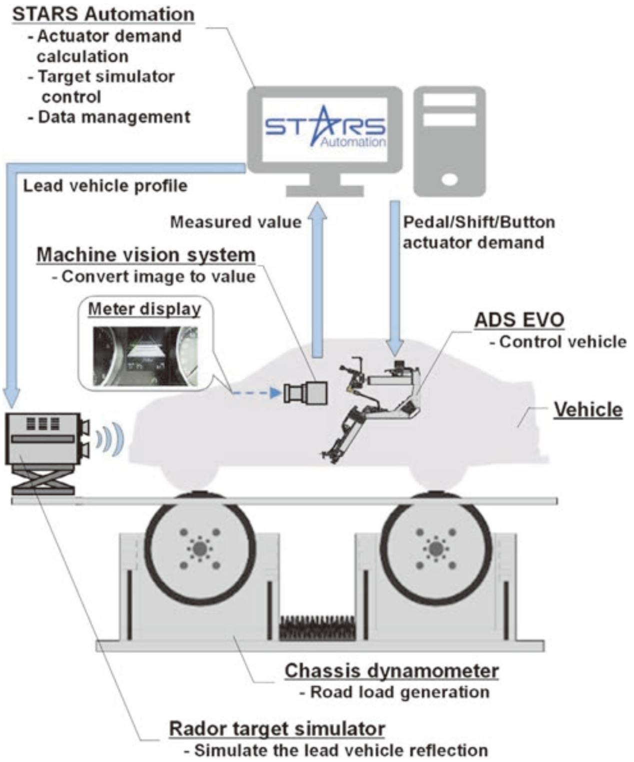


Figure 16 Test system diagram.

Using this system, speed and following distance were measured for different set distances, with the preceding vehicle profile set to WLTC. Figure 17 shows time-series changes in speed and following distance for the urban mode (Low phase) with frequent stop-and-go and

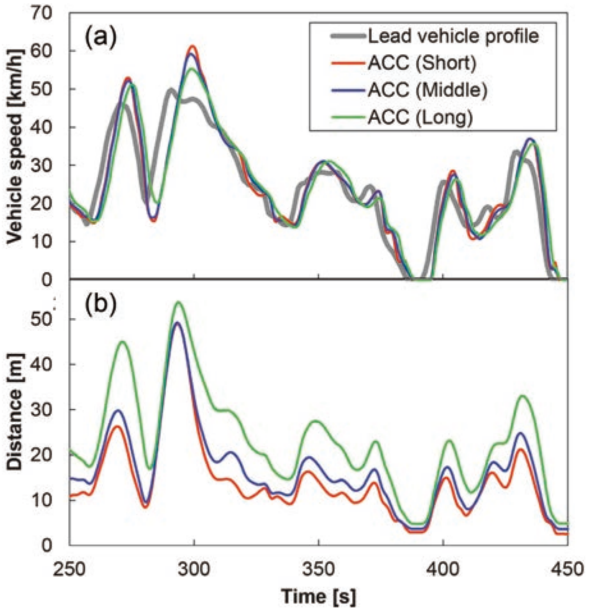


Figure 17 (a) Vehicle speed and (b) inter-vehicle distance at different set distances.

high ADS EVO operation frequency. In all set distances, the test vehicle followed the preceding vehicle's speed, and following distance decreased in order "Long," "Middle," "Short" during both driving and stopping.

The consistency between set and actual following distances confirms that set distances adjusted via the Machine Vision System were correctly reflected in the vehicle, validating the system.

5. Consideration of Efficiency

The system combining ADS EVO and the Machine Vision System described in Section 4 can potentially reduce tester workload and enable labor savings. However, preparation time for these devices must be considered when assessing the overall effect. This section provides a simple estimate of time savings when using ADS EVO and the Machine Vision System compared to manual operation. The estimate assumes a 30-minute test (WLTC equivalent), a 30-minute interval for data confirmation and adjustments, and seven tests conducted during an 8-hour workday.

Table 4 shows the time required for system setup and cleanup, totaling 63 minutes. The system enables 210 minutes of test driving without manual operation, yielding a net time saving of 147 minutes. This can contribute to reduced tester workload and improved productivity by reallocating time to other tasks.

6. Conclusion

This report presents a Machine Vision System that converts vehicle instrument panel displays into numerical data via image analysis technology and integrates with proprietary test systems, covering the following points:

- Developed three reading algorithms and a UI for configuring them to accommodate different instrument panel displays for each vehicle.
- Built a machine learning model specialized for numerical recognition to enable fast processing even with increased reading targets.
- Achieved high reading accuracy close to targets for all three algorithms and confirmed processing within the targeted time.
- Demonstrated that instrument panel displays related to GSI and ACC functions can trigger integrated testing with ADS EVO.
- Confirmed, through work-time estimation including preparation and cleanup, that system operation contributes to overall test efficiency.

These results indicate that the Machine Vision System is not merely a recording device, but an effective element for improving the efficiency of automotive testing. Future plans include productization and market introduction, with ongoing improvement of functions and performance based on market feedback. Specifically, efforts will focus on enhancing robustness for images with reduced visibility due to blur or distortion, developing outlier removal and correction functions, expanding algorithms, and strengthening configuration support features.

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

Table 4 Classification of pre-test and post-test procedures for automated driving tests.

Main category	Subcategory	Time
Pre-test procedure	ADS EVO installation	8 min
	Camera installation	5 min
	Test run for software configuration	5 min
	Software configuration	5 min
	Vehicle characteristic learning	25 min
Post-test procedure	Disassemble / Removal of test equipment	15 min
Total time of pre-test and Post-test procedure	—	63 min

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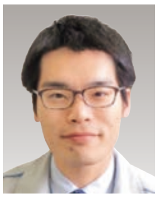

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Introduction of Automated Experimental Equipment for Exploration of Production Process Optimization in Fuel Cells

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Fuel cells are an important technology for the realization of a carbon-neutral society, and not only the research and development of their performance, but also the production process to ensure a stable supply to society is an extremely important technology. However, the parameters involved in the production process are enormous and social implementation requires a great deal of time. In order to contribute to the production process, Horiba has developed an automated experimental device that simulates the fuel cell production process. This apparatus was designed and fabricated with a focus on the fuel cell coating and drying processes, and is capable of fabricating fuel cell samples and performing basic evaluations. Here we introduce the overall concept and functions of the apparatus.

Introduction

In the domains of research, development, and manufacturing, the acquisition of high-quality data is crucial for accurate understanding of the target state and for enabling data-driven decision-making and management within the context of Digital Transformation (DX). HORIBA, Ltd. possesses a variety of analytical instruments, which, for example, allow for the collection of diverse data necessary to ascertain the status of each process throughout the battery lifecycle (Figure 1).

Although Japanese fuel cell technology leads the world, optimal designs that simultaneously achieve power generation efficiency, durability, and productivity have not necessarily been realized. In particular, production technologies, which involve a vast number of process parameters and complex physical phenomena, still have significant room for development. To leverage high-performance new materials developed through research in real-world applications, it is essential to adapt these materials to mass production processes, specifically by scaling up and accelerating the processes, so as to maintain performance while achieving target costs. Traditionally, optimization of these process conditions has relied on repeated trial-and-error based on intuition, experience, and expertise, or exhaustive experimental combinations of numerous process parameters, both of which require substantial time and financial resources[1].

The New Energy and Industrial Technology Development Organization (NEDO) has formulated and published a roadmap for fuel cell and hydrogen technology development, with the aim of promoting long-term collaborative efforts among industry, academia, and government. HORIBA, Ltd. has participated since fiscal year 2023 in one of NEDO's projects, titled "Collaborative Research and Development for Solving Common Issues toward the Dramatic Expansion of Fuel Cell Utilization," which is an industry-academia-government initiative. The objective of this project is to construct a common platform for

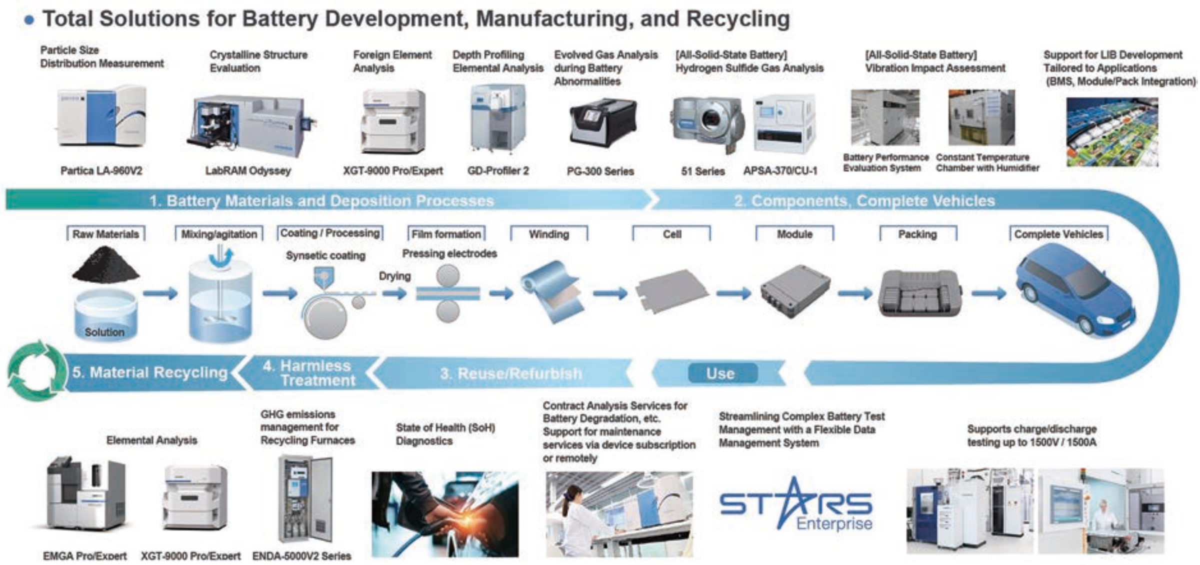


Figure 1 Battery life cycle and related analytical equipment.

“Process Informatics,” based on an automated experimentation and autonomous exploration system utilizing AI robots, in order to dramatically accelerate the development of fuel cell production processes. Within this project, the University of Tokyo is responsible for standard process development, Kanazawa University for prototype production of standard inks, Kyushu University for the development of evaluation methods, and HORIBA, Ltd. for elemental development, including the fabrication of an automated experimental apparatus simulating the production of fuel cell catalyst layers.

Concept of the Device in the Project

The apparatus developed in this project focuses on the aging process of the catalyst layer, which significantly affects production time and performance, in response to the demand for shorter fuel cell production times. Specifically, it is equipped with functions for “coating” and “drying,” as well as the capability to automatically conduct “evaluation” related to these processes. As a KPI, the project aims to achieve an experimental speed ten times faster than manual experimentation. With future practical deployment in mind, the design concept incorporates three major requirements, as described below.

1. Size Suitable for Installation in Existing Buildings (Elevator-Compatible)

Fuel cell production equipment is typically designed for mass production, with roll-to-roll (RtoR) systems applying battery materials to sheets extending hundreds of meters. The drying processes involve proprietary technologies, with parameters such as temperature, airflow, duration, and flow patterns optimized during process development to improve yield. As a result, coating and drying units alone often exceed 10 meters in length, making it impractical to introduce such large equipment solely for process development. Therefore, the newly developed apparatus has been miniaturized to fit within the dimensions of a standard elevator, enabling installation without the need for building modifications.

2. Application of Conditions to Actual Production Lines and Low-Cost Operation

To minimize changes in conditions when scaling up to actual production, the apparatus incorporates a multi-stage drying furnace that simulates zone heating via hot air, as used in production equipment. To reduce the consumption of expensive fuel cell materials, a die-coating mechanism has been adopted. Depending on the coating thickness, the system is designed to operate at low cost, with a target of coating 100 samples per 1 mL of ink, each with a coated area of 1 cm^2.

3. Modularization of Measurement Units for Customizability

Following the fabrication of fuel cell catalyst layer samples via the coating and drying apparatus, performance evaluation is conducted. The current system evaluates surface roughness, image analysis, and electrical conductivity, with each measurement unit modularized to allow for future expansion and diversity in evaluation methods as data accumulates.

Introduction of the Device

Overall Overview

A photograph of the entire apparatus is shown in Figure 2. The system comprises two primary functions: the fabrication process and the evaluation process. By moving sample holders within the apparatus, the system enables the fabrication and evaluation of thin films for fuel cells. An external stocker unit is provided to store up to 108 sample holders, allowing for daily exchange and continuous 24-hour operation, thereby enabling testing of approximately 162 conditions. Based on previous experience, manual testing typically covers about 10 conditions per day, thus the apparatus achieves the KPI of a tenfold increase in testing speed compared to manual methods.

Figure 2 Automatic testing equipment.

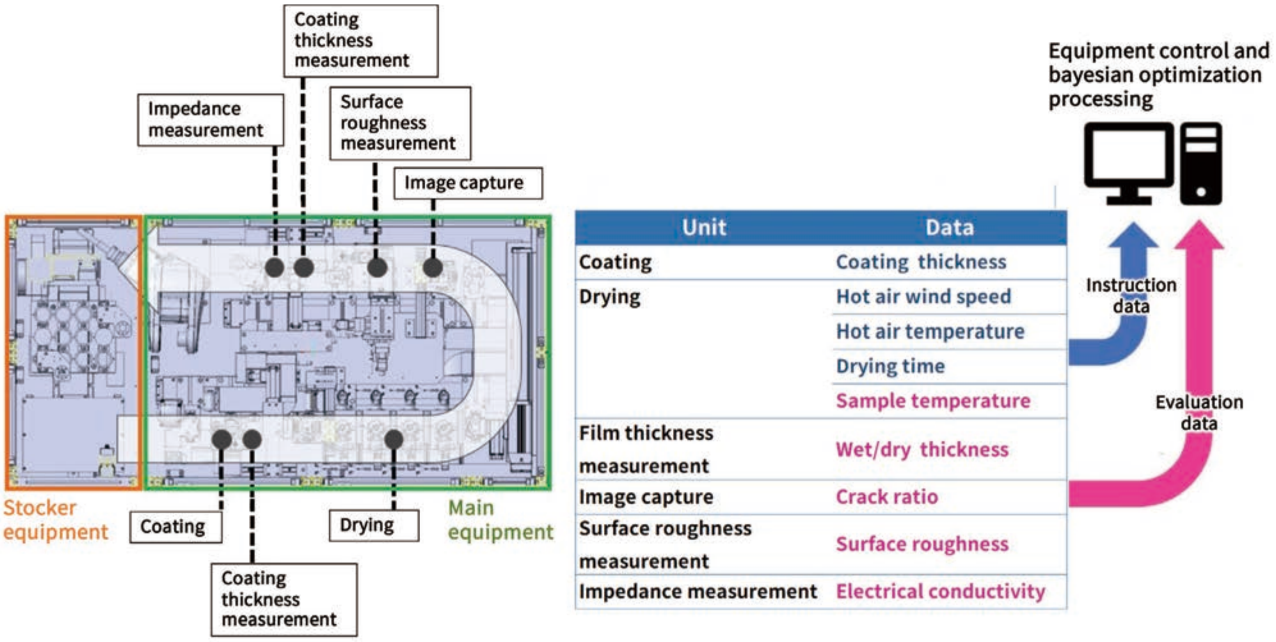
A schematic diagram of the data exchange between each unit is presented in Figure 3. Sample fabrication is performed based on instruction data, and the conditions for the next fabrication process are determined from the measurement data obtained during evaluation, with this process repeated iteratively. The conditions are determined using a Bayesian optimization algorithm developed by the University of Tokyo. The following sections introduce each unit in detail.

Sample Holder and Transport

To facilitate sample transport, storage, and changes in film formation conditions, a dedicated sample holder was designed. The holder can accommodate sheet thicknesses of 50 µm and is compatible with various sheet materials of similar thickness, including the resin sheets used in this evaluation. PPS resin (polyphenylene sulfide), a type of super engineering plastic, was selected for its resistance to the hot air in the drying furnace. The apparatus is equipped with internal transport routes and a robotic arm to ensure smooth movement between units and to the stocker. These features enable miniaturization and versatility in coating materials, compared to conventional RtoR production equipment.

Coating

To minimize ink consumption and enable various evaluations, coating is performed at the minimum required size of 1 cm², consistent with the standard cell of the FC-Cubic research consortium. The die-coating method, driven by a plunger pump, is used for single-sheet coating, employing



Unit	Data
Coating	Coating thickness
Drying	Hot air wind speed
	Hot air temperature
	Drying time
	Sample temperature
Film thickness measurement	Wet/dry thickness
Image capture	Crack ratio
Surface roughness measurement	Surface roughness
Impedance measurement	Electrical conductivity

Figure 3 Top view of the equipment and overview of data transfer

the same principle as production processes. The coating thickness can be specified arbitrarily within the range of 50 μm to 200 μm for each test. To address the issue of ink drying in the slit die between tests, a small amount of ink is dispensed onto a waste sheet, enabling continuous testing within a single batch (Figure 4).

Film Thickness Measurement

The quality of the coating process is monitored by measuring the film thickness before and after drying, as well as by shape measurement via image capture. For film thickness measurement, both the WET thickness immediately after coating and the DRY thickness immediately after drying can be measured. A confocal optical displacement sensor is used, offering a height resolution of 1 μm, suitable for the sample characteristics. The sensor is positioned immediately after the slit die to synchronize with the coating operation and enable measurement of the film thickness directly after coating.

Figure 4 Coating test sample.

Drying

To simulate the production line and allow for independent setting of drying conditions, four zones of hot air drying furnaces are provided (Figure 5). Each furnace allows for arbitrary settings of airflow speed (0–10 m/sec), temperature (ambient to 180°C), and drying time. The hot air flow is precisely controlled using HORIBA STEC's mass flow controller SEC-E50. The central surface temperature of the sample during drying is measured using HORIBA's IT-480F radiation thermometer, which has been custom-designed for measurement distance and spot size for this apparatus, contributing to its compactness. Additionally, multiple points within the furnace are monitored with sheath thermocouples, enabling comparison of temperature conditions when scaling up to production facilities.

Image Capture and Surface Roughness Measurement

Depending on coating and drying conditions, cracks and differences in surface roughness may occur in the dried samples. To accurately assess the crack rate within the coated area, images are captured before and after drying using a telecentric optical system and transmitted light. Image processing is then used to measure the crack rate within the coated region. A high-resolution camera enables measurement of areas larger than 10 mm square with a pixel resolution of 6.9 μm/pixel.

Surface roughness is measured after drying using a white-light interferometer, allowing for height resolution of 1 μm within a 1 mm square area. By selecting the cutoff frequency, both fine roughness below the cutoff and coarse roughness above the cutoff can be measured, providing indicators of sample surface properties.

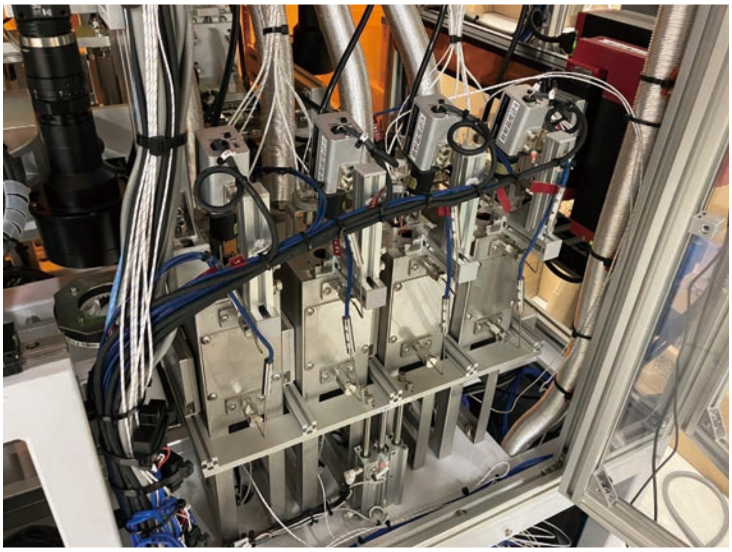


Figure 5 Drying unit

Impedance Measurement

Finally, contact-type impedance measurement is performed for evaluation. A compact sample probe is used to measure small samples, with the probe fixed to ensure consistent contact pressure for reproducible measurements. After passing through each unit described above, the sample holder is returned to the stocker. Bayesian optimization is then performed based on the obtained data to determine the next fabrication parameters, and the sample fabrication process begins anew. Throughout this process, no human intervention is required, enabling fully automated experiments to derive the optimal parameter values.

Conclusion

This paper has introduced an automated experimental apparatus developed by HORIBA, Ltd. that simulates the coating and drying production processes for fuel cells. The apparatus enables integrated data control of both production and evaluation parameters for fuel cells, while maintaining a compact form factor. Although coating and drying are only a part of the overall fuel cell production process, once data-driven optimization of production conditions is achieved using data obtained from this apparatus, it will become possible to implement production equipment in society that is labor-saving, space-efficient, and rapid, utilizing process informatics. Furthermore, by applying various analytical instruments as shown in Figure 1, new evaluation items—such as management of ink materials prior to coating or degradation evaluation of battery packs—can be implemented, enabling acquisition of diverse data and the introduction of new indicators. As such, the apparatus can play an important role as a DX solution throughout the entire lifecycle of fuel cells. As a manufacturer of analytical instruments that handle critically important data for research, we are committed to further promoting the use of process informatics and proposing DX solutions that meet the needs of developers and researchers.

Acknowledgment

We would like to express our sincere gratitude to all members of NEDO for their overall management and invaluable support throughout this project. We also extend our deep appreciation to the members of All-Star FC and FC-Cubic for sharing their profound knowledge and providing various insightful advice regarding production equipment for coating and drying. Furthermore, we wish to convey our heartfelt thanks to our collaborative project members at the University of Tokyo, Kanazawa University, and Kyushu University for their cooperation and guidance.

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Using PM2.5 Automatic Component Analyzer PX-375 Practical Examples of Air Quality DX

YAMAGUCHI Kazuki

Monitoring of the atmospheric environment has been conducted continuously from the viewpoints of environmental preservation and health hazard prevention, mainly focusing on monitoring nitrogen oxides and ozone, but recently there has been growing interest in the health effects of particulate matter (PM) and heavy metals contained therein. Conventional methods for analyzing particulate matter components require sample pretreatment and expertise, and have real-time performance issues. We propose a monitoring method that utilizes the PX-375 and Eco-WEB: the PX-375 enables continuous measurement of elements contained in particulate matter in a short time, while Eco-WEB realizes real-time data collection and analysis. The Eco-WEB enables quick and efficient environmental monitoring and is expected to contribute to the reduction of environmental burdens in industrial areas and manufacturing industries.

Introduction

Monitoring and management of atmospheric environments are extremely important from the perspectives of environmental conservation and the prevention of health hazards, and such activities have been continuously undertaken to date. The significance of these efforts continues to grow, particularly in industrial regions where the emission of air pollutants is a concern due to their potential impacts on the health of local residents and the surrounding environment. Consequently, the establishment of accurate and continuous monitoring systems is an urgent necessity. Atmospheric monitoring typically involves collecting airborne particulate matter (PM) onto filters using devices such as high-volume air samplers, followed by measurement of the types and quantities of contained elements using techniques such as ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and ICP-AES (Inductively Coupled Plasma Atomic Emission Spectroscopy).

However, this method requires processing collected samples through multiple steps such as acid digestion and pretreatment over a 24-hour sampling period, necessitating specialized knowledge and expertise for measurement[1]. As a result, analysis after sampling takes considerable time, making real-time data collection and analysis challenging. Furthermore, the obtained data represent the total amount of particulate matter collected over 24 hours, making it difficult to determine during which specific time periods the particles were captured.

To address these issues, we have proposed an atmospheric monitoring approach utilizing the “PX-375 Automated

PM2.5 Component Analyzer”[2],[3] (hereafter, PX-375) and the atmospheric monitoring system “Eco-WEB” (hereafter, Eco-WEB). This method enables rapid and efficient environmental monitoring through real-time data collection and automated analysis.

PX-375 is an instrument equipped with both mass concentration and elemental concentration analysis units, capable of collecting airborne particulate matter onto tape and continuously measuring both the mass and specific elements contained in the particles at intervals as short as 30 minutes (Figure 1). By analyzing the elements contained in particulate matter, it becomes possible to quickly and easily infer the potential sources of emissions (Figure 2).

Moreover, PX-375 can automatically and continuously measure 15 standard elements, generating a vast amount of data daily. Manual analysis of these data is time-consuming and labor-intensive, making prompt responses

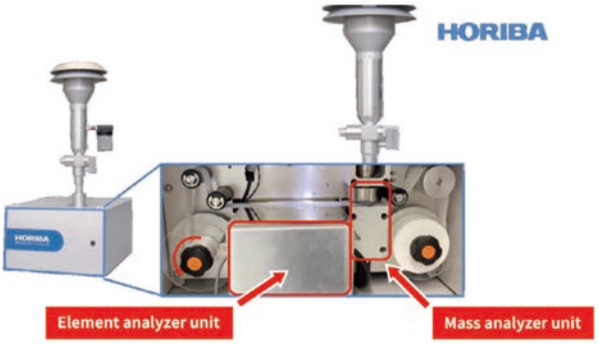


Figure 1 Continuous Particulate Monitor with X-ray Fluorescence PX-375.

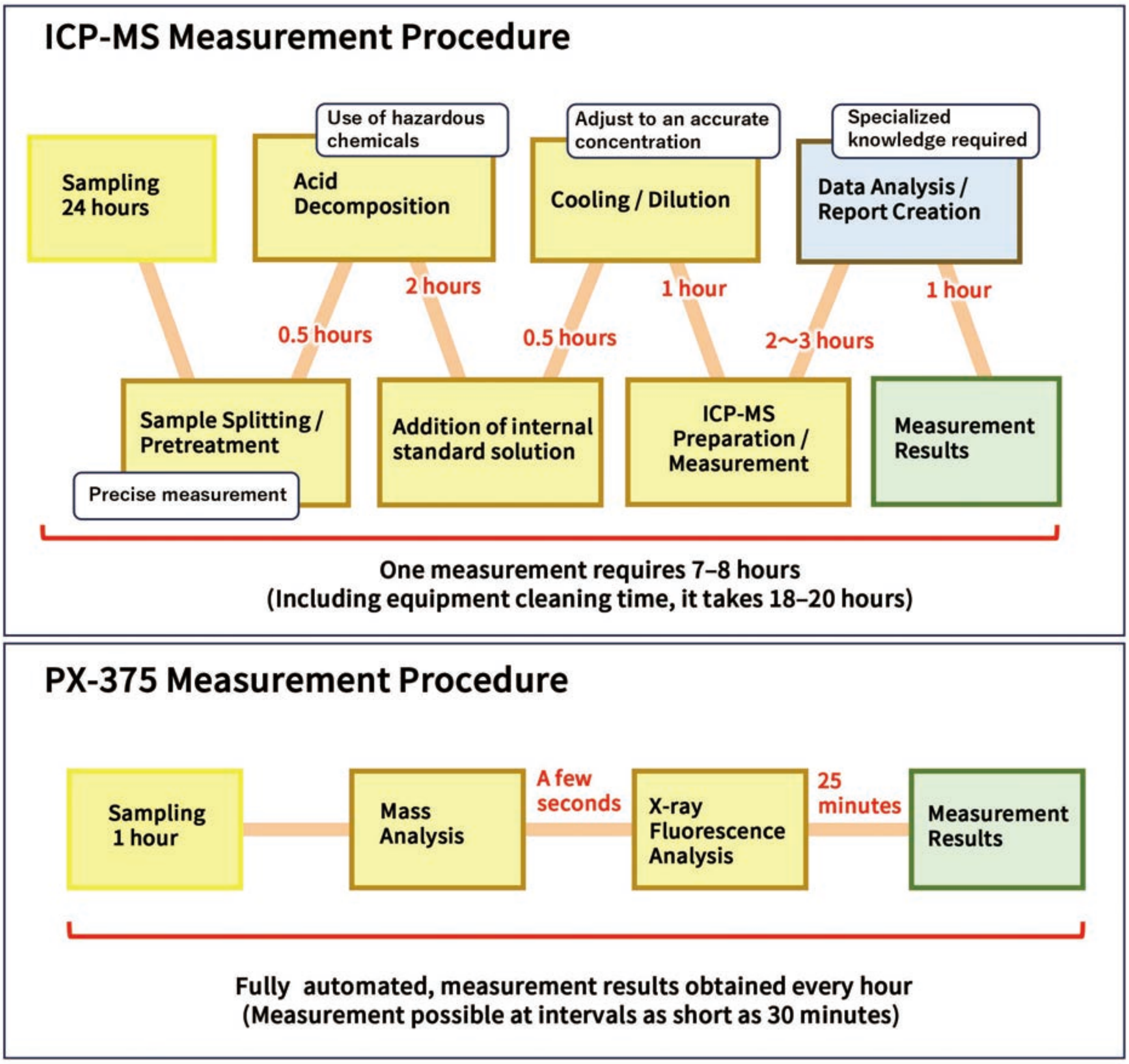


Figure 2 Measurement Procedure Image of ICP-MS and PX-375.

difficult. To resolve this, we have developed “Eco-WEB,” a system that integrally collects and processes PX-375 data. Eco-WEB establishes a measurement network capable of connecting multiple instruments, thereby facilitating the collection and analysis of environmental data (Figure 3).

Through this system, it has become possible to achieve real-time data collection and analysis, which was previously difficult, thereby enabling efficient atmospheric monitoring.

Automated Component Analysis of Particulate Matter Using PX-375

Particulate matter is among the most critical air pollutants, and understanding its composition is essential for identifying emission sources and elucidating generation mechanisms, which are indispensable for formulating atmospheric environmental measures. Conventional analysis of elements contained in airborne particulate matter has employed highly sensitive ICP-based techniques such as ICP-MS and ICP-AES. However, these methods require hazardous reagents for pretreatment and are time- and cost-intensive, making them unsuitable for rapid trend assessment.

In contrast, PX-375 utilizes X-ray fluorescence (XRF) analysis, enabling fully automated measurement without pretreatment. The instrument supports 15 standard elements (Al, Si, S, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, As, Pb), and additional elements can be included through calibration (Figure 4).

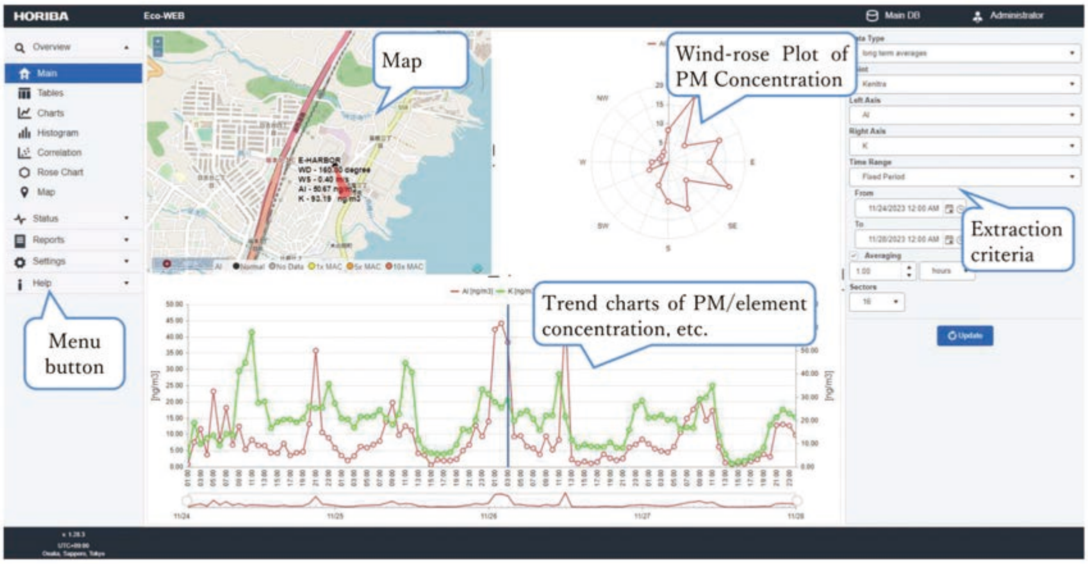
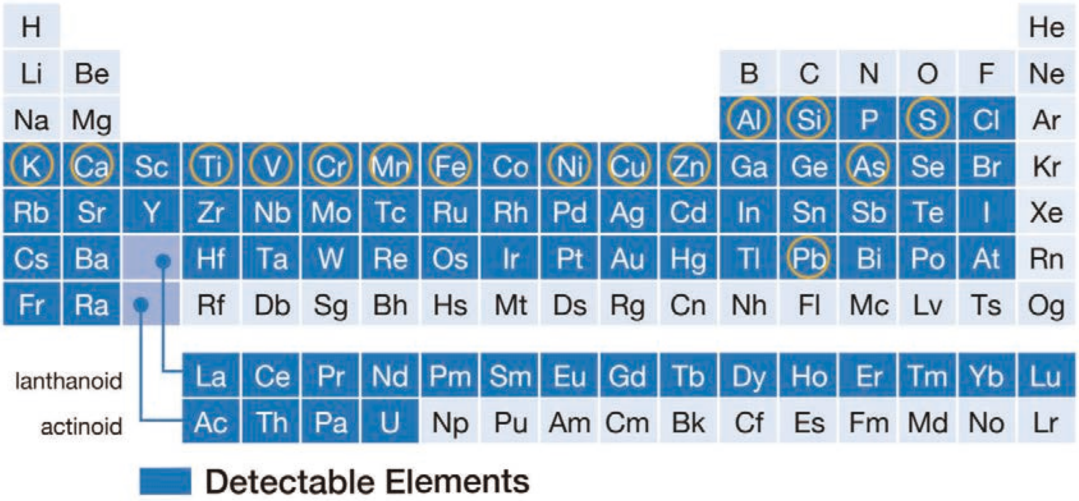


Figure 3　Main Screen of the Air Quality Monitoring System ‘Eco-WEB’.



* ○ —Standard parameters, calibrated by standard calibration materials at factory.
* To measure element concentration, analyzer needs to be calibrated by standard calibration materials.
* Please contact separately about elements, marked as non-detectable.

Figure 4　Detectable elements of PX-375

Although XRF is somewhat less sensitive than ICP methods, it allows for direct sample analysis and continuous measurement of elemental concentrations with the same temporal resolution as mass concentration. Due to its reliability and measurement speed, PX-375 has been adopted by air monitoring stations of the Ministry of the Environment, and since April 2017, continuous measurement of 15 elements every four hours has been conducted at four locations nationwide. This has enabled the rapid detection of component fluctuations and emission situations, which were previously difficult to assess.

In the private sector, PX-375 is mainly introduced for monitoring environmental load substances associated with manufacturing processes in company factories, and is utilized for emission management, evaluation of impacts on the surrounding environment, and as part of environmental countermeasures.

Case Studies of PX-375 and Eco-WEB Implementation

PX-375 is an instrument for continuous, rapid measurement of airborne particulate matter, while Eco-WEB is a system for real-time analysis and management of the resulting data. By combining these systems, it is possible to identify emission sources and respond quickly to emissions, thus greatly contributing to the reduction of environmental impact from factories (Figure 5).

In one factory, the urgent issue was to identify sources of chemical emissions and reduce environmental impact. As previously mentioned, the conventional method using high-volume air samplers and ICP analysis is based on "24-hour average" or "annual average" values, making it difficult to determine the specific time of emission within the 24-hour sample when environmental load substances are detected. Therefore, PX-375, with its excellent real-time capability, was introduced to establish a detailed monitoring system. A mobile monitoring station equipped with PX-375 was installed on a light truck to measure the atmospheric environment at various points within the factory, enabling the identification of elemental emissions and estimation of emission sources.

Measurements revealed that various substances were being emitted from multiple locations within the factory, and in addition to the anticipated emission sources, unexpected sources were also identified. By analyzing the relationship between manufacturing processes and emitted substances, it was possible to accurately estimate which manufacturing processes were responsible for specific air pollutants.

However, instances were observed where high concentrations of metallic elements were detected while the factory was shut down. Initially, external sources were suspected due to the factory's inactivity, but upon checking onsite activities, it was found that high concentrations of metallic elements were detected during chimney cleaning operations conducted while the incinerator was stopped. During operation, fans in chimneys not in use are inactive, but when these fans are run during cleaning, metallic elements accumulated inside are released.

Furthermore, by combining data from the mobile monitoring station with information on factory processes and wind

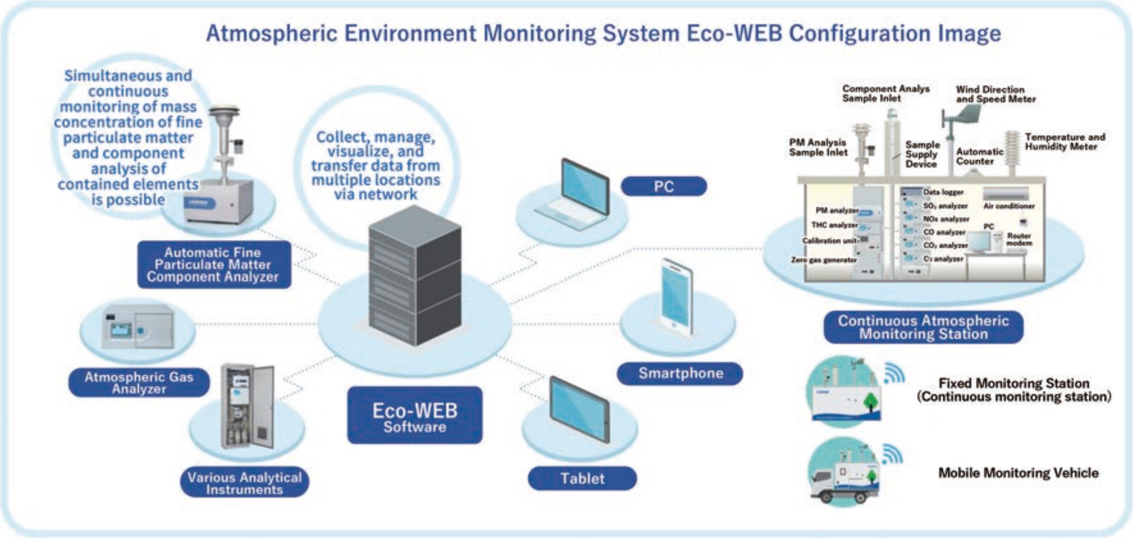


Figure 5 'Eco-WEB' Air Quality Monitoring System Configuration.

direction/speed, statistical analysis showed that certain processes, when active, resulted in detection from specific directions, thereby substantiating the reliability of the data.

This case demonstrated that metallic elements could be emitted from unexpected locations even when the incinerator was stopped, highlighting the importance of continuous monitoring and leading to the installation of a fixed monitoring station.

On the other hand, data collection from the mobile monitoring station was conducted via USB memory and analyzed using spreadsheet software, resulting in operational burdens. To address these issues, the fixed monitoring station was introduced alongside Eco-WEB, which automated data collection and analysis. Eco-WEB automatically collects and organizes data obtained by PX-375 (PM mass, concentration, and elemental concentrations) and visualizes it in real time. Additionally, it features an automatic alert function that sends warning emails to relevant personnel when concentrations exceeding preset thresholds are detected. This enables immediate identification of abnormal values, verification of the relevant time periods and detected elements, and rapid communication with relevant departments to confirm onsite activities.

The integration of PX-375 and Eco-WEB has enabled real-time response, which was difficult with manual data processing. This has facilitated the identification of emission sources and prompt countermeasures, resulting in a substantial reduction of environmental impact across the factory. Furthermore, continuous monitoring has established a mechanism for ongoing evaluation and improvement of the effectiveness of implemented measures.

Data Analysis and Source Estimation Methods

Eco-WEB is equipped with both routine monitoring functions and advanced data analysis capabilities. For daily monitoring, concentration thresholds (alarm values) can be set for each element, and when measurements exceed these thresholds, automatic email alerts are sent to relevant personnel.

For source identification, multifaceted analysis is performed on accumulated measurement data using trend charts, radar charts, correlation graphs, and other visualization tools. For example, the composition ratios of contained elements may differ even at the same PM concentration, and by analyzing these differences, as well as detected directions, time periods, and inter-element correlations, emission sources can be more precisely identified.

The analysis process begins with trend charts to grasp overall tendencies, confirming the dates and times when concentrations of monitored elements are elevated and their fluctuation patterns. Next, correlation coefficients between potentially related elements are checked, and highly correlated element groups are extracted. When specific elements exhibit simultaneous increases, it is likely that they originate from the same emission source.

Focusing solely on total PM concentration may obscure relationships among elements; therefore, understanding inter-element correlations using correlation coefficients and graphs is important. However, high correlation coefficients may be masked by data variability or outliers, and correlations may be non-linear, necessitating direct graph inspection. Excluding outliers enables more accurate evaluation (Figure 6).

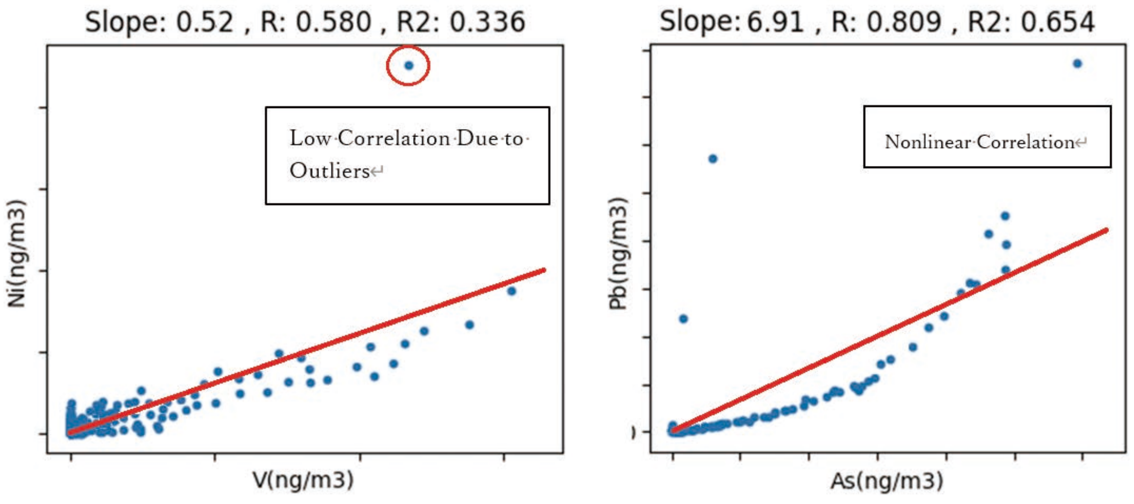


Figure 6 Example of Low Correlation.

When elements with strong correlations are identified, their emission patterns are further analyzed using trend charts and correlation graphs. Moreover, by leveraging wind direction and speed data, the direction of detection for target elements can be determined; if high concentrations are consistently detected from a particular direction, it is highly probable that the emission source is located in that direction. If multiple similar sources exist in the same direction, comparison of element ratios (e.g., Pb/As) can help distinguish them. The ratio may differ depending on whether the source is internal or external, and source estimation can be performed by comparing ratios under specific conditions.

Common source estimation methods include PMF (Positive Matrix Factorization)[4] and CPF (Conditional Probability Function)[5], but the CBPF (Conditional Bivariate Probability Function)[6], which integrates wind direction, wind speed, and concentration data, enables deeper understanding of source locations and contributions*.

Figure 7 shows an example of a graph drawn using the CBPF method, with wind speed plotted on the radial axis, the center representing 0 m/s, and the outer circle representing the maximum wind speed. The colors on the graph indicate increasing observation quantities in the order blue → green → red.

By changing the filtering conditions for displayed data, diverse insights can be gained. For example, if only high-concentration PM is extracted and plotted, and red data appear in the northeast direction, it indicates detection of high-concentration PM from the northeast, with wind speed serving as a proxy for distance. Cross-referencing with actual maps would suggest a high likelihood of emission sources in that direction. Similarly, plotting for specific heavy metals such as Ni, Cr, Mn is expected to yield additional insights into their respective sources. These analyses demonstrate the effectiveness of the CBPF method for source identification and contribution assessment.

* The CBPF method is currently under development for implementation, and evaluations toward practical application are underway.

Future Prospects

Mathematical processing and analysis of data obtained from measurement instruments enable identification of certain trends and characteristics. However, not all phenomena can be explained by the results, and correct interpretation requires understanding of the data's background and context.

Actual observation data may include substances detected only from specific directions or time periods, as well as substances detected continuously from all directions, each exhibiting distinct characteristics. Moreover, the process of analyzing and interpreting measured data remains difficult to automate, often relying on experience-based judgment, leading to a tendency for analysis tasks to become dependent on individual expertise. The shortage of technical personnel with data analysis expertise is also a challenge.

In view of these circumstances, there is a need to build

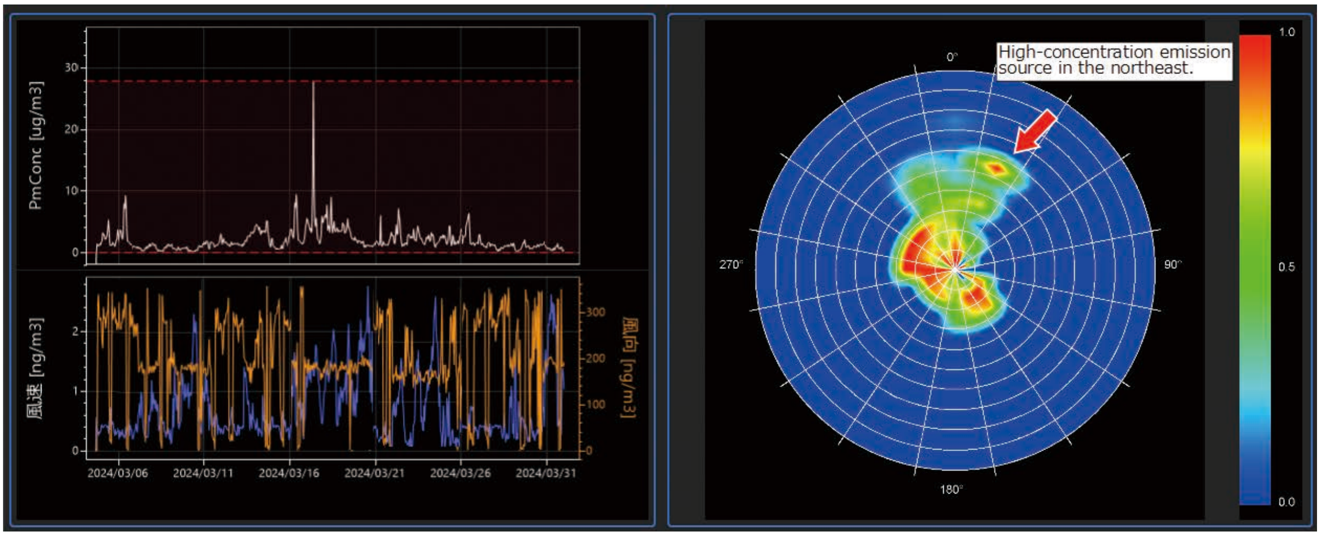


Figure 7 CBPF-Based Distribution of PM Concentration by Wind Direction and Speed.

systems that allow users to comprehensively handle information necessary for data analysis and verify and interpret data from various perspectives. Accurate interpretation of analysis results requires visualization and organization in combination with other relevant information, and the development of platforms to effectively support these processes is an important future challenge.

We aim to evolve systems so that data analysis is not limited to experts but can be performed by non-specialists as well.

Conclusion

As a solution to challenges in atmospheric environmental monitoring, we have proposed a new monitoring method utilizing PX-375 and Eco-WEB. This approach demonstrates the ability to overcome issues inherent in manual data collection and analysis, enabling the construction of a monitoring system that combines real-time capability and efficiency.

In particular, the automated component analysis of particulate matter by PX-375 and the integrated data collection and analysis functions of Eco-WEB are expected to play a vital role in environmental conservation and the prevention of health hazards. These technologies also contribute to more efficient emission management in industrial regions and manufacturing, supporting the realization of a sustainable society.

Moving forward, we aim to provide comprehensive solutions through further automation of data analysis and the introduction of AI-based predictive analytics.

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

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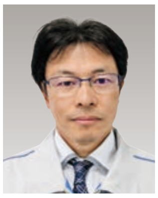

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Feature Article

Beyond Monitoring: HORIBA's Digital Approach to Water Quality and Environmental Solutions

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As today's water industry faces challenges such as aging infrastructure and environmental pollution, water quality monitoring is becoming more and more essential to address these issues. To reduce downtime and enable quick decision-making, real-time water monitoring is crucial. Advances in sensor technologies and cloud-based systems have made it possible to continuously collect and remotely monitor data, facilitating rapid decision-making and optimizing operations. As a result, the demand for Data as a Service (DaaS) solutions is increasing, where companies provide and manage water-related data for customers. Especially in the UK, where HORIBA MIRA is located, new laws and regulations are being implemented to address surface water pollution due to aging infrastructure. HORIBA aims to tackle these issues by integrating its water quality measurement technology with HORIBA MIRA's data science and AI, and HORIBA Test Automation's data management platform to provide solutions which goes beyond just water monitoring. In this article, we introduce our initiative to utilize HORIBA's water quality monitoring technologies and digital transformation (DX) solutions to address water-related environmental issues in the UK.

Introduction and Background

With growing human population, increasing urbanization and industrialization, and impacts of climate change, the management of our freshwater resources is an international priority and in some cases a crisis. The delivery of clean and safe drinking water, treatment of wastewater and elimination of pollution in our rivers, lakes and seas are all areas of growing concern which is leading to development and expansion of technology and business.

Today, HORIBA plays a significant part in the control of water quality by producing a wide variety of water quality monitoring instruments. In fact, HORIBA's very first product was a pH meter. HORIBA Advanced Techno (HAT) manufactures a range of water quality measuring instruments, and its main business is sales of these hardware instruments mainly through distributors. However, there is also the consulting sector of the water industry which is significant and is in a state of high growth, driven by new regulations and a national demand to clean up polluted rivers and lakes. The demand for this already researched in UK[1]. HORIBA is looking to enter this consulting sector of the global water business. The new Consulting & Applied Solutions (CAS) group and HAT are leading this initiative together, with support from HORIBA Test Automation (HTA).

The CAS team, based at HORIBA MIRA in the UK have established a base, where the team can develop solutions using HAT instruments and data services with HTA software platform STARS Enterprise. A “Field Lab” has been established at a reservoir within the HORIBA MIRA proving ground, where HAT instruments can be integrated, developed, and proven for application to the new surface water regulations.

Why set this up in the UK? Apart from being the main location of HORIBA MIRA, the center of the CAS organization, there will be major changes to the UK water industry within the next 5 years. There is new legislation to control spills of wastewater and monitoring of surface water. In addition, funding is increased to upgrade wastewater network infrastructure and to implement “smart” networks with sensors, telemetry, and AI-driven control systems. The UK water industry regulator OFWAT has approved a total budget of £104 Billion to be spent by UK water companies for infrastructure improvement[2]. This budget will cover procurement of sensors and smart systems with the objective of eliminating wastewater spillage into rivers and lakes, and improved monitoring.

In this article, our initiative to utilize HORIBA's water quality monitoring technology and DX solutions to address water environmental issues in UK, is introduced. First, some unique HAT water quality products are introduced briefly and then, there is description about HORIBA MIRA and HTA capabilities and how we are trying to integrate HAT, HORIBA MIRA and HTA capabilities to provide solutions to mitigate water environmental issues is also explained.

HAT Water quality monitoring technologies

Water quality monitoring is vital for protecting human health, preserving ecosystems, and ensuring safe drinking water. It helps detect pollutants, supports regulatory compliance, and guides environmental management. HORIBA Advanced Techno (HAT) specializes in developing water quality sensing equipment for various industries and applications. HAT core technologies are electrochemical and optical measurements and using these core technologies HAT has developed several unique water quality monitoring products. While HAT has a large portfolio of water quality monitoring equipment, in this article some unique and essential products which can also be useful in improving UK water quality issues are introduced.

Ammonium probe (AM-2000)

While Ion Selective Electrode (ISE) ammonium electrodes tend to drift in the low ranges, HAT unique AM-2000 (Figure 1) ammonium probe based on ISE technology remains stable even at low range below 1 ppm. As more and more wastewater treatment plants (WWTPs) now use ammonium monitoring as an indicator to control aeration rather than dissolved oxygen for better efficiency, HAT AM-2000 can contribute to energy consumption reduction (10 to 30% or further (from HORIBA's survey)) of WWTPs. Since ammonium is also an important indicator of environmental water (rivers, lakes, etc.) health, this product is suitable for monitoring the surface water and for monitoring the WWTPs.

Ultrasonic Cleaner (UH-16A series)

To reduce the maintenance frequency of the probes, HAT provide unique ultrasonic cleaner (Figure 2, Figure 3). It operates with burst oscillation and sweep function which makes it stain-resistant and enhances cleaning effect and also reduces sensor damage.

Figure 1 Ammonium Probe (AM-2000).
https://static.horiba.com/fileadmin/Horiba/Products/Process_and_Environmental/Process_Water/Brochures/HC-200NH/HC-200NH_Brochure_English.pdf

Figure 2 Ultrasonic cleaner with ammonium probe.

Figure 3 Effect of ultrasonic cleaning on Ammonium Probe: Without (left) and with (right) cleaner after 60 days.
https://static.horiba.com/fileadmin/Horiba/Products/Water/Download/Brochures/HAE-T0257.pdf

Self-cleaning pH electrode (6122 series)

HAT patented and unique self-cleaning pH glass electrode (Figure 4, Figure 5) uses a UV LED within the electrode and the surface of the glass electrode is coated with a photocatalyst (titanium oxide). The irradiation of UV light activates titanium oxide coating and prevent the adhesion of organic contaminants on the electrode which in result reduces the maintenance frequency and cost.

Multiparameter Water Quality Checker U-50 series

U-50 series can measure 11 parameters simultaneously including pH, ORP, turbidity, dissolved oxygen, and conductivity (Figure 6). One of the features is simultaneous one-point automatic calibration of all the sensors with a single standard solution. The model U-53 of this series has wiper inside the turbidity sensor for automatic cleaning. The main applications of U-50 series are river and lake water quality inspection. One U-50 can simultaneously measure all the basic parameters needed to monitor the river water quality.

Figure 4 Self-cleaning pH electrode.

Figure 5 Without (left) and with (right) self-cleaning function after 3 months.
https://www.horiba.com/int/water-liquid/products/other/self-cleaning-ph-electrode/

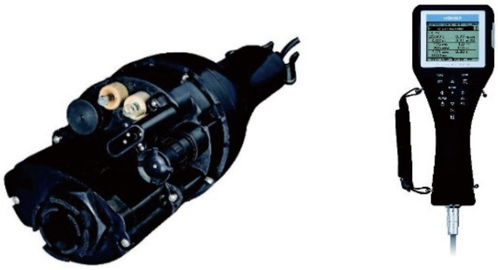


Figure 6 U-50 series probe (left) and controller (right).
https://www.horiba.com/fileadmin/uploads/Process-Environmental/Documents/Downloads_Catalog/Catalog_Water_Quality/U-50_brochure_en_HRE1930E.pdf

Figure 7 EL200 connected with multiple probes (Reproduced from HORIBA Readout No. 59, page 83).

Multiparameter Transmitter (EL200)

HORIBA acquired HORIBA Advanced Techno France (HATFR (known as Tethys Instruments before the acquisition)) in 2023. HATFR core technology is UV spectroscopy. One of the featured products of HATFR is multiparameter transmitter EL200 (Figure 7). On the other hand, most of the HAT transmitters are single parameter. With the inclusion of HATFR in our group, we are working on a project to connect HAT sensors to EL200 and connectivity of some of the sensors is already achieved. These type of multiparameter instruments will be critical in UK river water monitoring.

HORIBA MIRA and HORIBA Test Automation (HTA) capabilities and their integration with HAT water quality monitors

Historically, HORIBA MIRA has had no business with the water industry. However, the future needs of the water industry are based on efficient gathering of information-rich data, data processing, data analytics and safe & secure data-science and control systems. All these key future solutions have already been developed and proven in the automotive industry by HORIBA MIRA and HTA. This expertise is what HORIBA's CAS can also bring to the water industry which would separate it from existing consultants in the water industry.

The key areas of technology that HORIBA MIRA brings are:

- Data capture and processing
- Cyber security
- Functional safety
- Simulation, digital twinning & AI

In addition to the areas of technical expertise that HORIBA MIRA automotive experience brings, the HORIBA MIRA site and proving ground provides the ideal proving ground for water quality monitors, services, and analytics. Figure 8 outlines the many and different water systems that are present on HORIBA MIRA's 800-acre site. The HORIBA MIRA site includes potable water (drinking), wastewater (sewerage), stormwater and surface water. The site also benefits from a long-range wide area network (LoRaWAN™)[*1], which can be considered as a long-range outdoor Wi-Fi®[*2] system that links sensors to the internet. The site is also covered by 4G and 5G networks.

The HORIBA MIRA site can also be a development hub for the UK water industry. To demonstrate the potential of the site and to demonstrate new prototype water monitoring systems, a "Proof of Concept" (PoC) field-laboratory (Figure 9) has been established at HORIBA MIRA. It is located on the shore of the sites own water reservoir. The reservoir collects rainwater which is used to feed the wet test-tracks for developing vehicle wet-handling and wet-road safety which is why it can also be a proving ground for investigations into the nature of tyre-borne microplastic particles. For the PoC, the reservoir represents natural lake and river water. In the UK, new legislation, known as "Section 82" is forcing all water companies to measure river water quality up and downstream of any wastewater or stormwater discharge points along rivers. The data should be available to public through telemetry.

[*1] "LoRaWAN" is a trademark of Semtech Corporation.

[*2] Wi-Fi is a registered trademark of Wi-Fi Alliance.

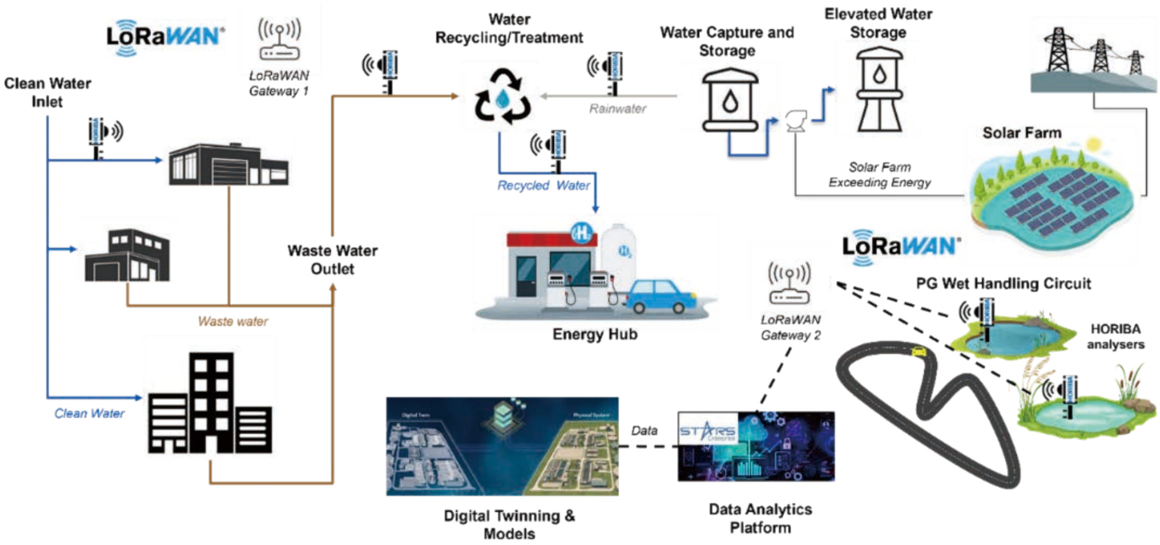


Figure 8 Water systems of the HORIBA MIRA site.

Figure 9 PoC (Proof of Concept) Field lab developed at the HORIBA MIRA site.

HORIBA's STARS Enterprise platform, developed by HORIBA Test Automation (HTA), is ideally placed to meet this need. Originally developed to underpin HORIBA's market-leading position as a provider of test automation and laboratory management systems in the mobility sector, this cloud native data management and process automation platform has transferred readily to the water data management domain, providing a flexible, proven backbone upon which to implement a range of water data solutions (Figure 10).

Capabilities provided by STARS Enterprise include:

- Multiple data ingress options, including HTTPS endpoints and MQTTS client.
- High-capacity storage of structured, unstructured and time series data.
- Scalable, concurrent execution data processing pipelines (analytical services).
- Powerful Grafana based no-code dashboards for visualization.
- Extensibility through the addition of solution specific microservices, web apps and mobile apps.
- Flexible role-based user management, with OIDC support.
- Tenancy-based data siloing.
- Best in class security features.

STARS Enterprise for Water Data Solutions

While the roots of the more mature STARS platforms lay in the mobility business field, the opportunity to deploy STARS solutions in other business fields in which HORIBA operates is clear. STARS Enterprise in particular, being a robust, secure and performant cloud-based platform upon which to implement modular solutions, offers huge potential in this respect.

The containerized microservice architecture of STARS Enterprise supports unlimited horizontal scaling with zero downtime, allowing cost effective deployments to be provisioned for solutions ranging from data management in small scale R&D facilities to regional scale water network monitoring and analytics.

The generic, extensible architecture of the STARS Enterprise platform ensures that whatever shape of data solution is called for, HORIBA will be able to meet the need. Powerful analytics and modelling are accommodated through features such as integrated Python module execution support. Where the services and apps of the core platform cannot address all the requirements of a solution, the platform is easily extended by the additional solution specific microservices and apps. Complex water network modelling, analysis and control solutions can thus be realized on the STARS Enterprise platform.

While STARS Enterprise solutions may be deployed in the customer's IT infrastructure, an increasingly popular option is to take advantage of HORIBA's SaaS capability to obtain a fully HORIBA operated Solution as a Service. With this approach, the customer is free to focus on core business, while HORIBA manages the entirety of creating and operating the data solution. The customer is relieved of operational burden, receiving only the data insights and actionable outputs that bring value to their enterprise.

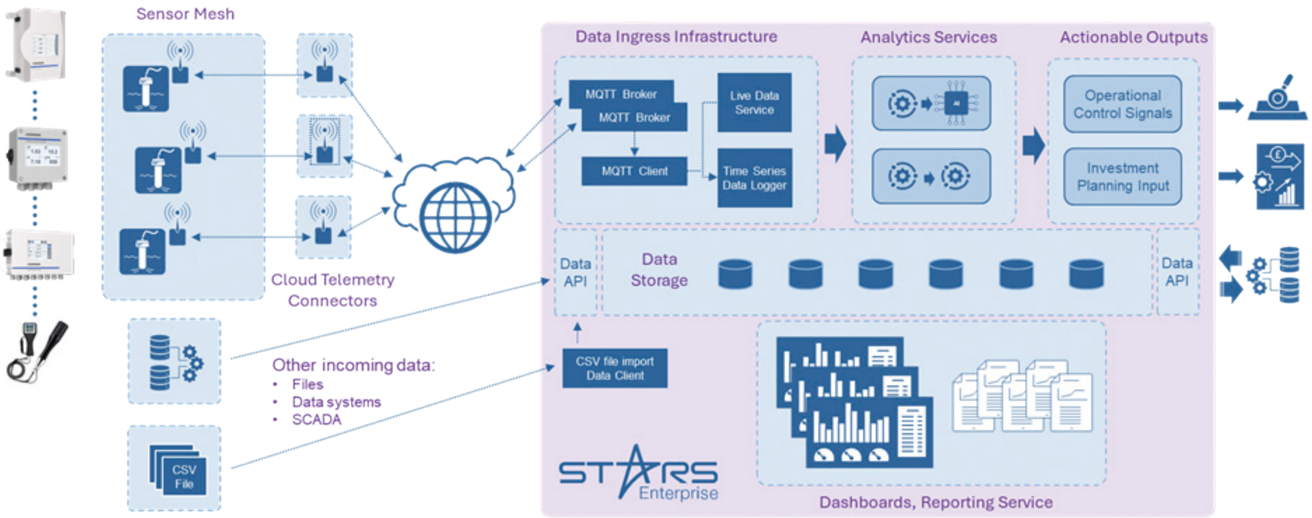


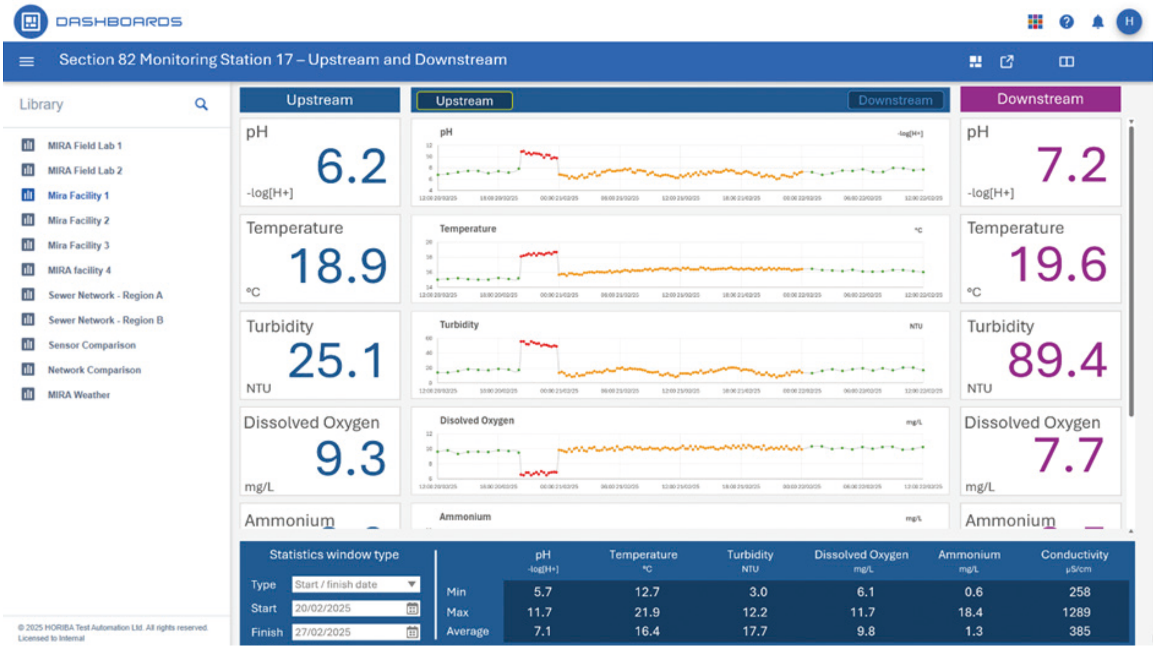
Figure 10 STARS Enterprise Cloud Platform.

HORIBA's prototype "Section 82 (S.82)" solution showcases STARS Enterprise in the role of a cloud-based data collection and forwarding platform. S.82 of the UK's Environment Act 2021 requires sewerage undertakers to continuously monitor the quality of the receiving water upstream and downstream of their assets, allow assessment of the impact of discharges from their assets on the receiving watercourse[3]. In its base implementation, our S.82 solution does just that - collects data from distributed monitoring installations via low power long range telemetry, harmonizes these data and transmits them to the water authorities.

Dashboards and statistics are provided as part of this service to provide visibility of the data (Figure 11). Such dashboards are easily configured without coding and give the customer instantaneous, real-time information, along with access to historical data reaching back to the very start of the monitoring activity.

With the S.82 base solution as our springboard, we can leverage the flexibility of the STARS Enterprise platform and move on to offer value-add opportunities such as insightful predictive analytics to S.82 customers.

Together, HORIBA MIRA and HTA provide a "rainbow" of new solutions and services (Figure 12) that are desperately needed by an ailing water industry. These new solutions form the business strategy of the new CAS Water consultancy. With hardware from HAT, HORIBA can provide an end-to-end, "one-stop-shop" solution to customers.



Section 82 Monitoring Station 17 – Upstream and Downstream

	Upstream	Downstream
pH (-log[H+])	6.2	7.2
Temperature (°C)	18.9	19.6
Turbidity (NTU)	25.1	89.4
Dissolved Oxygen (mg/L)	9.3	7.7
Ammonium		

Type: Start / finish date
Start: 20/02/2025
Finish: 27/02/2025

	pH -log[H+]	Temperature °C	Turbidity NTU	Dissolved Oxygen mg/L	Ammonium mg/L	Conductivity µS/cm
Min	5.7	12.7	3.0	6.1	0.6	258
Max	11.7	21.9	12.2	11.7	18.4	1289
Average	7.1	16.4	17.7	9.8	1.3	385

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Figure 11 Section 82 Dashboard using STARS Enterprise.

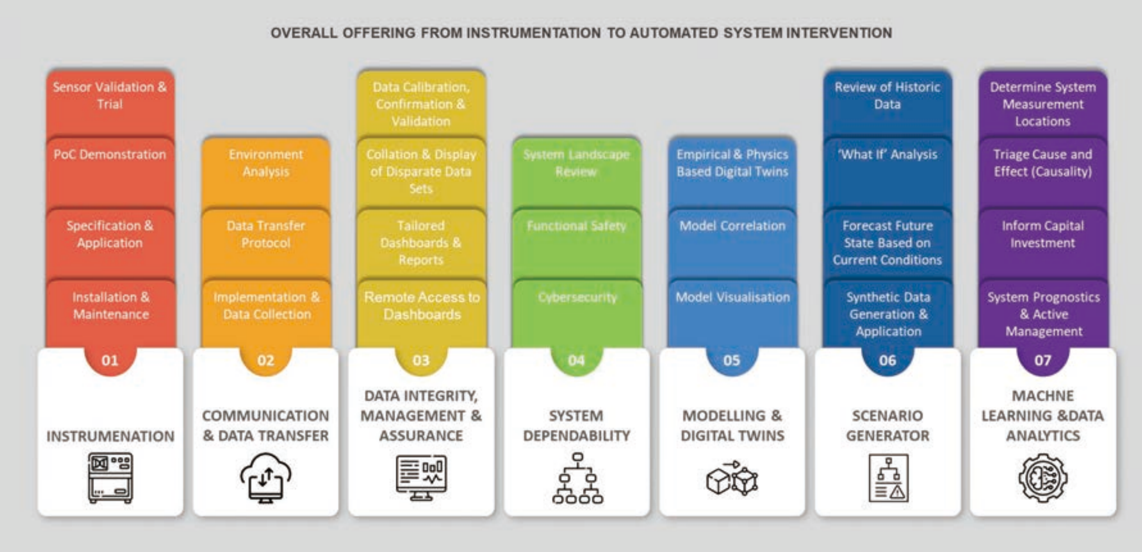

Figure 12 HORIBA one-stop-shop solution idea for water industry: from instrumentation to data analytics.

Vision on adding value to the current capabilities with Data Science

The water industry generates large quantities of data, but it is distributed sparsely across a large and complex system. There is a great need for further instrumentation to better understand and manage water industry systems and the surrounding environment. This increasing data volume and resolution presents opportunities for the application of data science and machine learning. Simply collecting data does little to increase understanding of the issues faced by the water industry, but effective application of the right tools to this data can extract the information it contains, providing useful, valuable, and actionable insights.

Data science and machine learning are powerful tools that can be applied in various contexts within the water industry. These range from broad network applications, through specific subsystem controls and down to the acceleration and enablement of individual measurements and analyses. At the smallest scale core HORIBA technologies, such as spectroscopy methods, can be accelerated through deep learning to provide rapid analyses and to enable the detection and measurement of new and emerging pollutants. This will help to better monitor and understand the scale of pollution and impacts on both the environment and public health. This monitoring will provide new information and enable new regulation of these pollutants. On a larger scale, whole networks of disparate sensors can be consolidated into a single measurement system, providing insights and prediction to tackle serious industry issues. This includes water supply scarcity, storm overflows of sewage into natural water bodies, and more fundamental issues such as the accuracy, validity and reliability of data and measurements in such an expansive system.

The operation of water industry systems is often heavily dependent on weather, influencing both the availability and demand for clean water, and impacting the capacity and efficiency of wastewater treatment. Machine learning based models are lightweight and outperform the simulation times of their physics-based counterparts by multiple orders of magnitude, often while maintaining equal or even improved accuracy due to a reduction in required assumptions and simplifications. This enables a scenario-based approach, which can incorporate variability and uncertainty inherent in weather prediction through a high volume of predicted scenarios. The result is a statistical view of the future system state with enough time in hand to act with increased pertinent information. There are significant implications for environmental impacts, operational efficiency, and functional safety in the water industry and more broadly across all HORIBA's Fields.

Conclusion and outlook

In this article, we described our initiative to utilize our water quality monitoring technology and DX solutions to provide analytical and data solutions to address these issues. Due to decades of under-investment, the UK's old infrastructure is leading to problems such as overflow of the sewage which is polluting every river in the UK. Water companies in UK are now legally obliged to monitor river quality and to complete a full deployment of a new sensor network within the next decade. The root cause of these problems is broken and aging infrastructure. Since rebuilding of the infrastructure is such a vast undertaking, limited by investment and resources, the other, more attractive solutions to tackle these problems are smart sensing and data solutions. The future of the water industry is with lots of data.

These issues are not just true of the UK. Many other nations suffer from the same problems. In Europe, France has similar issues. Notably, the river Seine in Paris was not fit for swimmers in the Paris Olympics, until fine weather limited the spills of wastewater upstream of the city. In India, there is a huge national project to clean up the river Ganges, the vast and holy waterway of the largest population on Earth.

HAT have been developing some unique product for water quality sensing. While these products have excellent measurement performance, they need to be smarter for data solution services. Performing data analytics and solving customers problems can provide a value-added end to end solution. This is where HTA and HORIBA MIRA capabilities can be explored. Together under the new Consulting & Analytical Solutions (CAS) Group, HORIBA can offer consulting and solutions to end-user customers.

This new HORIBA water business is starting out in the UK and focusing on helping to solve the UK water environment issues with new solutions. Once established, the new consulting business model can be expanded to other regions in Europe and globally. With a growing human population, the need for clean and safe water, the safe treatment of wastewater and the protection of the natural environment will continue to grow. Meeting this growing demand for new technology and services to ensure the health and safety of our planet and its inhabitants is a noble path for HORIBA to follow, and a profitable pathway too.

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

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HORIBA MEDISIDE LINKAGE next
~Revolutionizing the Medical Field with Smart Maintenance~

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HORIBA MEDISIDE LINKAGE next is a comprehensive maintenance service support system for medical instrument provided by HORIBA. In addition to monitoring the operation of medical instrument, it can automatically create ledgers based on medical laws and remotely change instrument settings and perform cleaning operations. The system was developed to reduce the workload and support work style reforms by improving operational efficiency in the medical field, and to promote safe and efficient operations. This article describes the overall picture of the system, as well as the form and usefulness of providing an integrated medical solution in combination with the GATELINK electronic medical record integration software.

Keywords
Remote monitoring, Predictive maintenance, Ledgers, Healthcare law reform, MEDISIDE, GATELINK

Introduction

In recent years, Japan has experienced progressing population decline and aging, resulting in chronic shortages of personnel in medical settings. This issue is particularly severe in small- and medium-sized medical institutions in rural areas, where limited staff must carry out numerous testing operations.

Although Point of Care Testing (POCT)[1] devices have been increasingly introduced in recent years and are expected to support medical care through rapid testing, their maintenance and quality control requirements impose burdens similar to those of conventional clinical laboratory instrument.

Furthermore, amendments to the Medical Care Act[2]-[5] in 2018 have made record-keeping a legal obligation for the purposes of maintenance and quality control of clinical laboratory instrument to preserve the quality of test data. This requires the creation of ledgers, including standard operating procedures and work logs, thereby further increasing the workload of laboratory departments. Additionally, with the enforcement of the revised Labor Standards Act[6]-[8] in April 2024, work style reforms for medical professionals have imposed stricter limits on overtime, further exacerbating operational burdens. Therefore, streamlining and improving the efficiency of testing operations, primarily through medical DX, has become an urgent issue.
To address these challenges in medical settings, we have developed a new support system—HORIBA MEDISIDE LINKAGE next (hereafter referred to as HML next)—which integrates clinical laboratory instrument condition monitoring, maintenance support, ledger management, and remote operation functions.

This article provides a detailed description of its main functions, implementation effects, and future prospects.

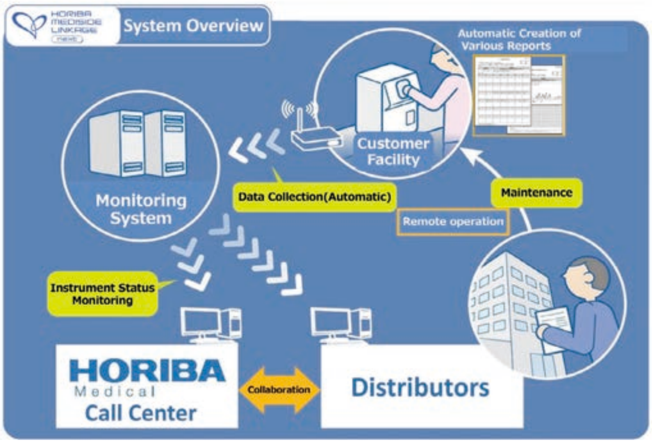


Figure 1 System Overview Diagram.

Overall System Architecture

Figure 1 presents the overall architecture of the HML next system. Clinical laboratory instrument installed at medical facilities transmits measurement results, error logs, and other device-stored data to the monitoring system via a router. The monitoring system analyzes the collected data and sends various ledgers monthly to pre-registered facility email addresses. If necessary, our service department can contact the facility or remotely operate clinical laboratory instrument. Multiple types of clinical laboratory instrument can be connected to a single router for communication.

Main Functions of HML next

This section outlines the main functions of HML next, designed for integrated remote support of multiple clinical laboratory devices and sites, beyond single-device management.

Real-Time Monitoring and Error Detection Technology

By acquiring and analyzing patient test results, logs, error codes, and raw data from various sensors in real time, HML next provides proprietary monitoring functions that support operational surveillance and early detection of error signs in clinical laboratory instrument, enabling prompt corrective actions. Email notifications can be configured to be sent only when errors exceed a certain frequency within a specified period, adjustable for each device.

This function is effective for field engineers, allowing them to confirm operating status and error history before site visits, thereby reducing the number of visits and optimizing initial responses.

Predictive Maintenance Using Raw Data

HML next features a mechanism that notifies service personnel of predictive maintenance alerts based on certain thresholds, even for “latent errors” undetected by the clinical laboratory instrument itself. For example, it can detect slight decreases in suction pressure, abnormal temperature control trends, or signs of deterioration in consumable parts. This enables maintenance visits before instrument failure occurs, minimizing the impact on testing operations in medical settings. The system can propose optimal maintenance timing tailored to the condition of each device rather than relying solely on scheduled maintenance, reducing unnecessary part replacement of parts and minimizing the risk of instrument downtime. This also helps optimize the balance between scheduled maintenance and emergency repairs.

Such functionality contributes to optimizing instrument operation through prediction of consumable part deterioration and anomaly detection, reducing workload and improving maintenance efficiency for small hospitals and testing centers.

Remote Input of Assay Value Data

For quality control measurements (hereafter QC measurements) performed on clinical laboratory instrument, HML next enables remote input of assay value data predetermined for each lot of control materials. Assay values are reference measurements set by manufacturers for control blood used to verify instrument accuracy. Traditionally, entering assay values required accessing a website, downloading files, saving them to a USB memory, and loading them into the instrument—operations prone to human error. HML next allows for accurate and immediate input of the latest assay values, greatly improving reliability and speed of testing operations.

Additionally, establishing a system for remote provision and input of assay value data serves as an effective means to raise awareness of QC measurement importance and promote proper quality control practices at medical sites.

This function also contributes to stabilizing testing operations at facilities requiring high reliability in quality control or during periods with few personnel.

Automatic Generation of Management Ledgers

To streamline clinical laboratory instrument management and ensure legal compliance, HML next automatically generates and periodically sends various management ledgers based on operational data and maintenance records. This greatly reduces the record-keeping burden for medical professionals and technical staff, allowing them to focus on core duties such as patient care.
The management ledgers include:

- Measurement work logs (**Figure 2**)
- Maintenance management standard work logs
- Reagent management records
- Quality control records

These documents are automatically formatted based on proprietary ledger templates and generated as PDFs monthly (or at user-specified intervals). Facility managers and maintenance personnel only need to print and store them, reducing the workload for legally mandated ledger retention.

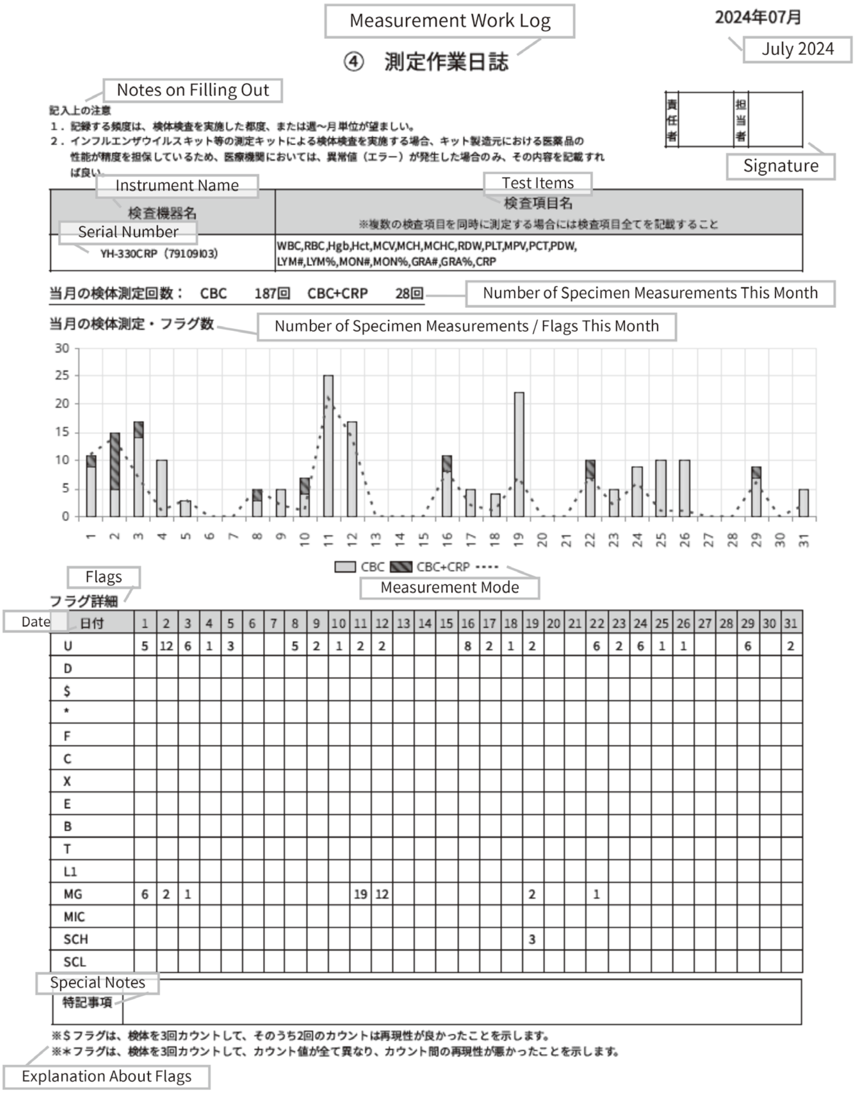
Notably, this provides practical solutions to the following on-site challenges:

Immediate and Consistent Evidence for Legal Compliance

Medical instruments used for clinical testing are subject to mandatory periodic maintenance and record retention under the Medical Care Act and related regulations set by the Ministry of Health, Labour and Welfare (2018). Automated record generation and storage in designated folders enable instant presentation of required documents during surprise audits, reducing psychological stress and preparation time for staff.

Elimination of Manual Work and Human Error

Previously, ledger creation required manual transcription, organization, and printing of logs from clinical laboratory instrument, a process susceptible to errors due to busy schedules. HML next automates ledger output via triggers and schedules, eliminating omissions, transcription errors, and formatting mistakes. In case of ledger damage or loss, past data can be instantly reissued, ensuring easy data retrieval and reproducibility.



Measurement Work Log

④　測定作業日誌

2024年07月

July 2024

Notes on Filling Out

記入上の注意

1．記録する頻度は、検体検査を実施した都度、または週～月単位が望ましい。

2．インフルエンザウイルスキット等の測定キットによる検体検査を実施する場合、キット製造元における医薬品の性能が精度を担保しているため、医療機関においては、異常値（エラー）が発生した場合のみ、その内容を記載すれば良い。

責任者		担当者	

Signature

検査機器名 (Instrument Name)	検査項目名 (Test Items) ※複数の検査項目を同時に測定する場合には検査項目全てを記載すること
YH-330CRP（79109I03） (Serial Number)	WBC,RBC,Hgb,Hct,MCV,MCH,MCHC,RDW,PLT,MPV,PCT,PDW, LYM#,LYM%,MON#,MON%,GRA#,GRA%,CRP

当月の検体測定回数：　CBC　187回　CBC+CRP　28回

Number of Specimen Measurements This Month

当月の検体測定・フラグ数

Number of Specimen Measurements / Flags This Month

Flags

フラグ詳細

日付 (Date)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
U	5	12	6	1	3			5	2	1	2	2				8	2	1	2			6	2	6	1	1			6		2
D																															
$																															
*																															
F																															
C																															
X																															
E																															
B																															
T																															
L1																															
MG	6	2	1								19	12							2			1									
MIC																															
SCH																			3												
SCL																															

Special Notes

特記事項	

※$フラグは、検体を3回カウントして、そのうち2回のカウントは再現性が良かったことを示します。
※*フラグは、検体を3回カウントして、カウント値が全て異なり、カウント間の再現性が悪かったことを示します。

Explanation About Flags

Figure 2　Measurement Record Log.
(Note: The original form is in Japanese. English words are added by the authors for reference only and do not constitute a full translation.)

Environment for Focusing on Core Duties (Patient Care)

Automating ledger creation enables medical staff—including doctors, laboratory technologists, and nurses—to devote more time to high-value medical activities and patient interaction. This is especially significant for small facilities or during night shifts, where optimal allocation of human resources is achieved through labor-saving measures.

This function greatly contributes to improved work efficiency and prevention of human error at medical institutions requiring legal compliance and unified ledger management. Corporations operating multiple sites can achieve standardized ledger management without inter-site discrepancies, enhancing internal and external audit responsiveness. It also alleviates the workload of busy laboratory technologists and administrative staff, promoting concentration on specialized tasks.

Remote Access to Clinical Laboratory Instrument

HML next provides remote access functionality for service engineers, aiming to streamline maintenance operations and enable rapid response to malfunctions.
Key features and effects include:

Practical Operation Style Based on Telephone Coordination

In practice, service engineers contact facility staff (e.g., laboratory technologists) by phone, confirm on-screen warnings on the clinical laboratory instrument, and then execute remote operations via HML next.

For example, if an alarm is displayed, the staff reads the alarm code and status, and the engineer executes appropriate remote commands (e.g., nozzle cleaning, reboot, parameter changes). Thus, HML next serves not only as a remote control system but also as an infrastructure for smooth communication between on-site and maintenance staff.

This hybrid operation prevents erroneous actions and provides reassurance to on-site staff.

Automation of Major Work Support via Remote Operations

Maintenance personnel can perform the following operations remotely without visiting the facility:

- Sending various commands (e.g., nozzle cleaning) for routine or immediate troubleshooting
- Changing reagent settings and confirming replenishment information
- Acquiring operation logs and checking device status
- Remote monitoring of alarm history and early prediction of troubles

Leveraging high compatibility with HORIBA products and command specifications tailored to each device, the system enables reliable control while minimizing operational risks.
This remote access environment allows safe, real-time execution of maintenance tasks from remote locations, significantly reducing the number and duration of required site visits.

Strict Management of Safety and Operational Permissions

As clinical laboratory instrument handles patient samples, erroneous or unauthorized operations could lead to serious medical incidents. HML next implements multi-layered security measures:

- User authentication and hierarchical permission management
- Automatic saving of operation logs and tamper-prevention mechanisms
- One-time remote connection approval (facility-side authorization required)

These measures ensure device operation is complemented remotely while maintaining safety and compliance in medical settings.

Transformation of Maintenance Services and Impact on On-Site Operations

This function enables rapid initial response in emergencies. For example, in minor issues such as reagent clogs, service engineers can immediately perform nozzle cleaning remotely via HML next, restoring instrument operation within minutes and minimizing disruption to testing operations and patient impact.

Remote preparation for scheduled maintenance also shortens on-site work time. Reduced site visit frequency lowers maintenance costs and supports sustainable maintenance frameworks for medical devices.

This function reduces field engineer travel and accelerates troubleshooting, minimizing downtime especially for remote or small facilities with limited after-hours support. It also enables standardized support regardless of technician experience, contributing to uniform service quality.

Advantages of Integration with GATELINK

Main Functions of GATELINK

GATELINK is an interface software that facilitates data linkage between upper-level systems (electronic medical records and LIS) and clinical laboratory instrument (**Figure 3**). Patient IDs and test order information entered into upper-level systems are transmitted in real time to clinical laboratory instrument via GATELINK, automating the process from test request to result acquisition and greatly improving operational efficiency.

Manual entry of test orders into laboratory instrument can result in input or transcription errors, potentially leading to misattribution of test results. Duplicate data entry and manual transcription errors decrease efficiency and cause delays, especially during busy clinical hours, negatively affecting patient service and reliability.

Introduction of GATELINK enables automatic linkage of test requests and results with upper-level systems, reducing the workload and risk of human error for laboratory technologists and nurses. GATELINK can connect up to 10 laboratory devices (including those from other manufacturers), flexibly integrating diverse in-hospital test data. Real-time access to test results during patient consultations via upper-level systems accelerates preparation and clinical decision-making, shortening response times and improving the quality of explanations.

Integration of GATELINK and HML next

Future integration of GATELINK and HML next will enable unified management and remote monitoring of test data and patient information, including data from devices made by other manufacturers. This is especially advantageous for small- and medium-sized facilities, allowing advanced collaboration environments to be built with limited resources.

Specifically, test data from clinical laboratory instrument for blood, biochemistry, urine, coagulation, genetics, etc. can be managed and analyzed in real time on HML next. Real-time understanding of patient conditions based on data collected from all connected devices will facilitate timely and appropriate treatment, potentially preventing disease progression. Integrated utilization of multi-disciplinary test data is expected to improve medical quality and realize higher standards of patient care.

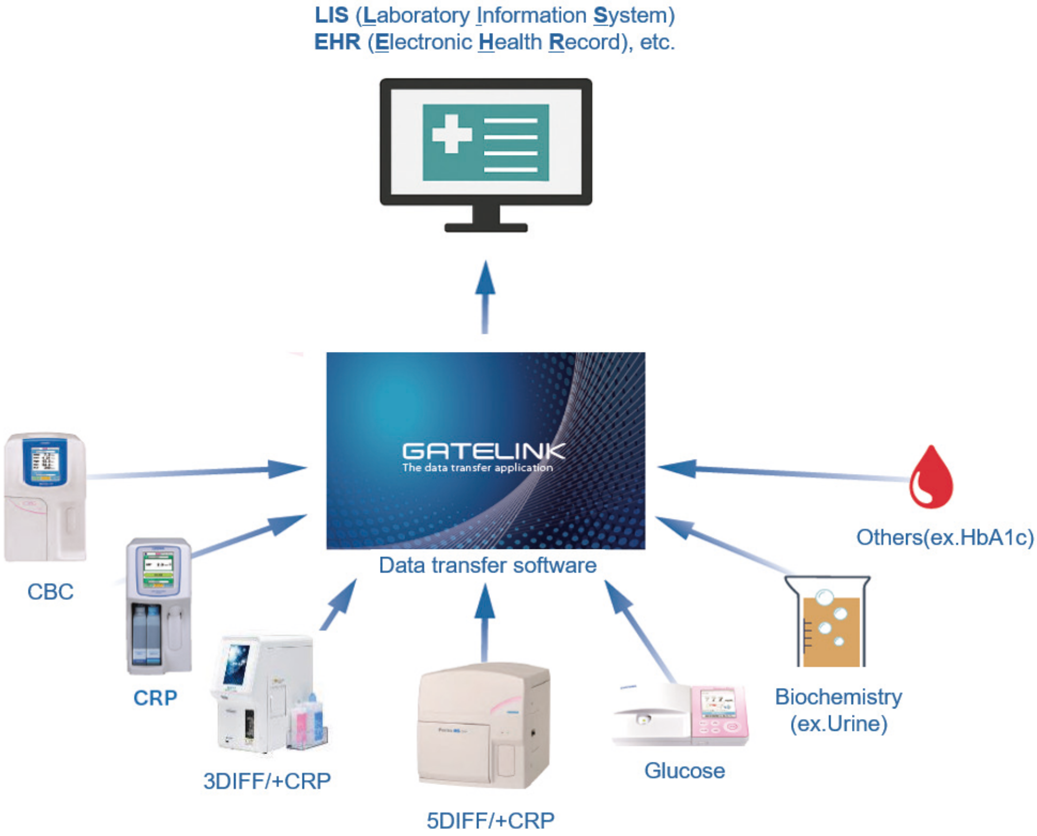


Figure 3 GATELINK connection configuration diagram.

Conclusion

This article has introduced HML next, which was designed and developed as an integrated IT-based solution rather than as a standalone clinical laboratory device.. Through diverse functions such as device operation monitoring, predictive maintenance, ledger output, and remote operation, HML next supports both operational efficiency and legal compliance in medical settings. Moving forward, we aim to accelerate the shift from product sales to solution sales by advancing technology development for clinical laboratory instrument and medical information systems, expanding our business with solutions such as automation and data management, and providing comprehensive solutions to operational challenges in medical institutions, thereby contributing to the creation of environments where medical professionals can devote themselves to their core medical duties.

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

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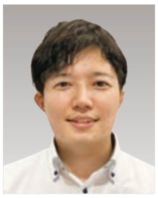

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Data Integrity Software HORIBA PLATINALINK

~Development of a platform that ensures data integrity for analytical instruments in the pharmaceutical industry~

FUNADA Tomohiro

In the pharmaceutical industry, accuracy and reliability of measurement data (data integrity) are required, and compliance with GMP (Good Manufacturing Practice) is essential. To address this, HORIBA has developed a new platform, HORIBA PLATINALINK (“PLATINALINK”), which complies with the international data management standard “ALCOA+” and integrates functions such as record accuracy, data retention, and tamper resistance. This platform aims to reduce user workload and enhance reliability. This article introduces the features and functions of PLATINALINK.

Keywords
GPM, Data Integrity, ALCOA, 21CFR Part11, CSV

Introduction

GMP (Good Manufacturing Practice) establishes standards for quality control and quality assurance in the manufacturing of pharmaceuticals and related products to ensure public safety within the pharmaceutical industry. Among these standards, data integrity refers to the assurance of completeness, consistency, and accuracy of data, which is essential for maintaining product traceability and guaranteeing product quality, safety, and efficacy. In recent years, inappropriate actions such as data falsification and manipulation have become social issues not only in the pharmaceutical sector but also across various industries, increasing the demand for reliability in data throughout the industrial landscape.

At HORIBA, data integrity functions have been individually implemented in products such as the particle size distribution analyzer (LA series). However, this product-specific approach has led to inefficiencies in design and development, inconsistencies in functionality across products, and cases where user requirements could not be adequately met, revealing significant issues.

To address these challenges, HORIBA has undertaken the development of a common application that standardizes and integrates data management functions, providing consistent features across multiple products (Figure 1).

ALCOA+ Principles and Correspondence with PLATINALINK

In the pharmaceutical industry, data integrity is evaluated based on the ALCOA+ principles. “ALCOA” represents five fundamental requirements for data integrity—Attributable, Legible, Contemporaneous, Original, and Accurate—first introduced by the FDA in 1994 and reaffirmed in the latest guidance, “Data Integrity and Compliance With Drug CGMP Questions and Answers Guidance for Industry”[1]. The “+” component refers to additional, more comprehensive requirements—Complete, Consistent, Enduring, and Available—introduced in FDA guidelines and further expanded in the latest EMA guideline, “Guideline on computerised systems and electronic data in clinical trials”[2], published in 2023.

Figure 1 Application image of a common platform centered on Data Integrity.

PLATINALINK is a platform application designed and developed to comply with these principles, supporting users in managing data in accordance with regulatory requirements. Table 1 presents the ALCOA+ principles and the corresponding functions provided by PLATINALINK.

By incorporating a comprehensive set of functions that address all these principles, PLATINALINK ensures users can maintain data reliability in daily operations and facilitates audit compliance and internal quality assurance.

Background and Design Philosophy of PLATINALINK Development

Unified Design Based on User Challenges

Traditionally, HORIBA products have individually implemented data integrity functions, expanding features in response to specific user requirements, resulting in a lack of standardization and differing specifications across products.

In addition, HORIBA's medium- to long-term business plan has declared a strategic focus on the pharmaceutical market. There has also been a growing need for data integrity support in existing products, such as the XGT-9000, previously used in quality testing laboratories.

Consequently, it was determined that data integrity support should be unified company-wide rather than handled on a per-product basis, leading to the development of PLATINALINK as a cross-product platform.

Design Concept and Application Structure

PLATINALINK is designed according to the following principles:

- Provision of standardized data integrity functions
- Ensuring compatibility for deployment across various analytical instruments
- Securing future expandability and maintainability as a DX (Digital Transformation) platform

The application is provided as a web application. In a networked configuration, it does not require installation on client PCs and can be accessed via standard web browsers, offering the following advantages:

- Accessibility from anywhere on the network, reducing administrator burden and improving maintainability
- Unified operability across different analytical instruments through the common PLATINALINK platform
- Operation on servers utilizing the customer's internal network ensures alignment with the customer's security policies
- Centralized data management by aggregating data from multiple analytical instruments

Table 1 Principles of ALCOA+ and Corresponding Measures in PLATINALINK

Principle	Description	Example of PLATINALINK Compliance
Attributable	It must be clear who recorded, changed, or deleted which data and when.	Audit trail function records user operations and system processes, enabling identification of the recorder.
Legible	Data must be recorded in a format that is easy to read and can be clearly understood when necessary.	Standard format files such as PDF, JPEG, and PNG can be saved and viewed.
Contemporaneous	Data must be recorded simultaneously with the actual work.	Automatic data acquisition and recording via real-time integration with measurement devices.
Original	Data must be the original record or an accurate copy equivalent to the original.	Automatic saving of measurement data, tamper-proof log management, and encryption for tamper prevention.
Accurate	Data must be accurate and complete, without errors.	Consistent recording methods, automatic backups, and data integrity verification functions included.
Complete	All data must be recorded without omission or deletion.	In principle, deletion and modification functions are not implemented; all data is saved and managed as logs.
Consistent	Data must be recorded and managed in a consistent manner.	Unified data recording method adopted across multiple devices.
Enduring	Data must be preserved in a state that allows long-term access.	Periodic automatic backups and log storage, as well as account control, enable long-term use.
Available	Data must be accessible whenever needed.	High availability ensured through access permissions, search functions, and web-based accessibility.

Figure 2 illustrates an example of PLATINALINK operation. In a standalone configuration, the analytical instrument and PLATINALINK are installed on the same PC for operation. In a network configuration, a server is installed within a closed network, such as an internal company network, with PLATINALINK installed on the server, allowing access from analytical instruments and other PCs within the network.

Currently, operation is limited to standalone and local network environments, but the web application architecture enables remote access within internal networks and centralized management of multiple products. In the future, the system is envisioned to support cloud-based multi-site integration and data utilization.

Main Functions of PLATINALINK

User and Permission Management

PPLATINALINK enables unified user management and flexible permission settings, realizing role-based access control. This allows each organizational role—such as IT administrators, measurement device operators, and approval personnel—to access only the necessary operational scope.

Through this mechanism, clear traceability of “who did what and when,” as required by GMP and other regulatory requirements, is ensured, while also serving to prevent unauthorized access and operations.

Security Policy Settings

PLATINALINK implements password policy management functions to maintain and reinforce the overall security level of the system, with compliance to GMP and other regulatory requirements as a prerequisite. In particular, strict user authentication is a vital element in ensuring data integrity.

Administrators can flexibly configure the following parameters to align with organizational security policies:

Figure 2 Example of PLATINALINK configuration.

- Minimum password length setting (e.g., at least 8 characters)
- Mandatory use of uppercase letters, lowercase letters, numbers, and symbols
- Enabling periodic password changes (e.g., every 90 days)
- Prevention of reuse of previously used passwords
- Setting a maximum number of failed login attempts and account lock functionality
- Automatic logout after a certain period of inactivity

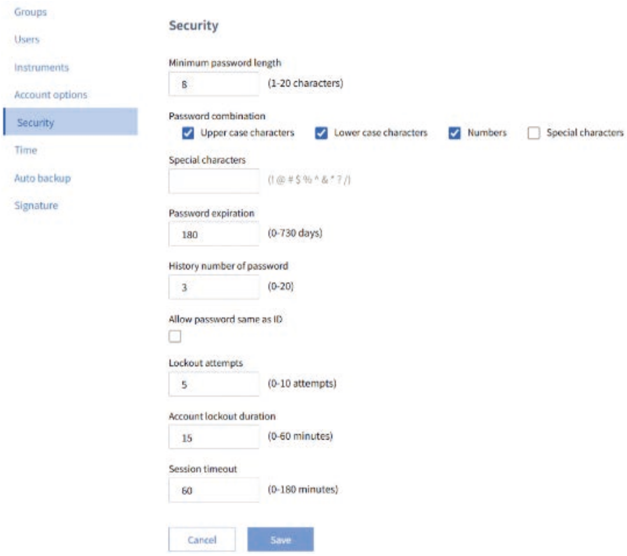
Additionally, login history and password change history are recorded as audit trails, providing a mechanism for early detection of signs of unauthorized access.

These functions are designed to maintain system robustness while ensuring user convenience, further enhancing the reliability and consistency of data managed by PLATINALINK (Figure 3).

Electronic Signature Function for Reports

PLATINALINK is equipped with report management functions after measurement completion, enabling PDF-format storage and electronic signature records.

These reports can be used directly as audit documentation, and since storage and retrieval are completed within PLATINALINK, the need for paper output and physical storage is eliminated. As a result, storage space and operational costs are reduced, and risks of record tampering or loss are minimized (Figure 4).



Security

Minimum password length: 8 (1-20 characters)

Password combination: ☑ Upper case characters ☑ Lower case characters ☑ Numbers ☐ Special characters

Special characters: (! @ # $ % ^ & * ? /)

Password expiration: 180 (0-730 days)

History number of password: 3 (0-20)

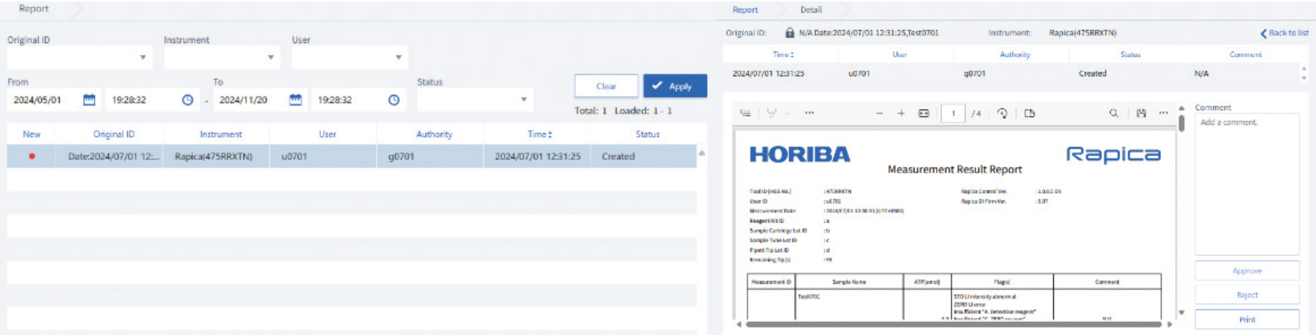
Allow password same as ID: ☐

Lockout attempts: 5 (0-10 attempts)

Account lockout duration: 15 (0-60 minutes)

Session timeout: 60 (0-180 minutes)

Figure 3 Security policy setting screen.



Original ID:
Instrument:
User:
From: 2024/05/01 19:28:32 - To: 2024/11/20 19:28:32
Status:
Total: 1 Loaded: 1 - 1

New	Original ID	Instrument	User	Authority	Time	Status
●	Date:2024/07/01 12:...	Rapica(475RRXTN)	u0701	g0701	2024/07/01 12:31:25	Created

Original ID: N/A Date:2024/07/01 12:31:25,Test0701
Instrument: Rapica(475RRXTN)

Time	User	Authority	Status	Comment
2024/07/01 12:31:25	u0701	g0701	Created	N/A

Measurement Result Report

Figure 4 Management screen for report search and display.

Audit Support Functions

In accordance with the ALCOA+ principles, PLATINALINK incorporates advanced audit trail functions. All operations are automatically recorded, and search/filtering features (by user, date/time, operation type, etc.) enable rapid information presentation during audits. This also allows for visualization and improvement of business processes in daily operations (Figure 5).

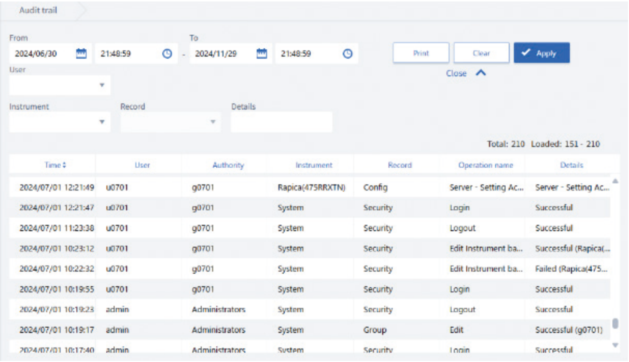
Data Management Functions

PLATINALINK provides an environment where users can centrally manage operation logs, measurement data, and analytical reports automatically collected from measurement devices. Automatic backup and related features reduce the risk of data loss, establishing a data storage system that complies with the “Enduring” principle of ALCOA+.

Future Prospects

PLATINALINK currently supports multiple products as a common platform, underpinning data integrity assurance and operational efficiency in pharmaceutical settings, and its role is expected to further expand.

In the future, we plan to increase the number of analytical instruments linked to PLATINALINK and expand sales, thereby incorporating more feedback from the field to enhance functionality.



From: 2024/06/30 21:48:59 - To: 2024/11/29 21:48:59
User:
Instrument:
Record:
Details:
Total: 210 Loaded: 151 - 210

Time	User	Authority	Instrument	Record	Operation name	Details
2024/07/01 12:21:49	u0701	g0701	Rapica(475RRXTN)	Config	Server - Setting Ac...	Server - Setting Ac...
2024/07/01 12:21:47	u0701	g0701	System	Security	Login	Successful
2024/07/01 11:23:38	u0701	g0701	System	Security	Logout	Successful
2024/07/01 10:23:12	u0701	g0701	System	Security	Edit Instrument ba...	Successful (Rapica(...
2024/07/01 10:22:32	u0701	g0701	System	Security	Edit Instrument ba...	Failed (Rapica(475...
2024/07/01 10:19:55	u0701	g0701	System	Security	Login	Successful
2024/07/01 10:19:23	admin	Administrators	System	Security	Logout	Successful
2024/07/01 10:19:17	admin	Administrators	System	Group	Edit	Successful (g0701)
2024/07/01 10:17:40	admin	Administrators	System	Security	Login	Successful

Figure 5 Audit trail list screen.

Although PLATINALINK is presently positioned as HORIBA’s data integrity platform, future developments are expected to include the following expansions as a web-based unified management system:

- Integration with devices from other manufacturers
- Introduction of automatic alert functions through user behavior analysis and anomaly detection
- Enhanced support for electronic records, such as electronic signatures for data

Furthermore, leveraging the reliability, scalability, and versatility of PLATINALINK, deployment to other industries where data reliability is critical—such as environment, food, chemicals, and semiconductors—is also envisioned. Through these efforts, HORIBA aims to contribute to improved quality and transparency across society.

Conclusion

PLATINALINK, developed by HORIBA, is a common platform that achieves both data integrity and operational efficiency required in the pharmaceutical industry. Its robust design, compliant with ALCOA+ principles, provides consistent data integrity functions across multiple products, contributing to reduced user burden and enhanced reliability.

Additionally, through working groups established within the company to address the pharmaceutical market and feedback from users, we will continue to pursue ongoing improvements that address real-world challenges.

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

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Efforts to Eliminate Malaria: Developing a Malaria Screening Capability Using Machine Learning on Blood Test Data

NAKATANI Hitoshi

Malaria remains endemic in many countries. In 2023, it affected 263 million people and caused 597,000 deaths[1]. The Sustainable Development Goals (SDGs) include malaria elimination by 2030 as one of their key targets[2]. Early detection and treatment are essential to prevent severe disease progression and further transmission. However, because initial symptoms are often mild, diagnosis may be delayed. To address this, we have developed a screening function—intended to suggest the possibility of disease rather than provide a definitive diagnosis—using complete blood count (CBC) and C-reactive protein (CRP) measurements obtained from the Microsemi LC-667G CRP, an automated hematology analyzer. This paper describes the hematological effects of malaria and the development of a machine learning model to identify malaria-related patterns from CBC and CRP data.

Introduction

Malaria is an infectious disease that is prevalent primarily in tropical and subtropical regions. After a person is bitten by an Anopheles mosquito, a unicellular protozoan parasite known as the malaria parasite enters the bloodstream and invades hepatocytes, leading to their destruction. Subsequently, the parasite invades red blood cells, where it multiplies and divides, eventually leading to their destruction. The parasites are then released into the bloodstream and repeat this cycle by invading new red blood cells[3]. Five species of malaria parasites are known to cause malaria in humans, among which Plasmodium falciparum and Plasmodium vivax pose the greatest threat. P. falciparum is the most widespread and life-threatening species in sub-Saharan Africa, while P. vivax is the predominant species in countries outside sub-Saharan Africa[4]. Common clinical features include fever, anemia, and splenomegaly (enlargement of the spleen)[5]. The initial symptoms are often mild and difficult to distinguish from those of other febrile illnesses. If left untreated, the disease can rapidly progress to a severe form and may be fatal within 24 hours, particularly in infections caused by P. falciparum[4]. Therefore, early detection and prompt initiation of appropriate treatment are crucial.

Typical diagnosis of malaria involves microscopic examination of stained blood smears and rapid diagnostic tests (RDTs) that detect malaria parasite–derived antigens or enzymes[6]. However, in cases of relatively mild infection, or depending on the physician's clinical judgment, malaria may not be suspected and thus not tested for, raising concerns about missed diagnoses. Furthermore, although microscopic examination is the most accurate method, it is time-consuming, making it impractical to perform this test on all specimens. To address these issues, screening for malaria using only routine blood tests that are commonly performed during febrile episodes has been proposed[7]. From the perspective of reducing diagnostic workload and dependence on individual expertise, it is desirable for automated hematology analyzers to be equipped with automated malaria screening functions that process blood samples after collection.

Research on malaria diagnosis using automated hematology analyzers has reported methods utilizing CBC and a 5-part white blood cell differential (neutrophils, lymphocytes, monocytes, eosinophils, and basophils; hereafter referred to as 5Diff)[7]. The HORIBA Group also markets products that provide malaria detection flags based on CBC and 5Diff parameters. However, studies using CBC and a 3-part white blood cell differential (lymphocytes, monocytes, and granulocytes; hereafter referred to as 3Diff) are limited[8]. In regions with a high prevalence of malaria, there is a demand to minimize measurement costs, making CBC- and 3Diff-based products, which are reasonably priced, more suitable. Therefore, we developed a function to flag suspected malaria cases based on CBC and 3Diff measurements (hereafter referred to as the malaria screening flag).

Microsemi LC-667G CRP

The Microsemi LC-667G CRP (hereafter LC-667G) is an automated hematology analyzer suitable for routine clinical use. In addition to CBC, it can measure 3Diff and CRP. The device features a compact design and reasonable cost, delivering CBC and 3Diff results in approximately one minute, and CRP results within approximately four minutes when CRP measurement is included.

The LC-667G measures white blood cell count (WBC), red blood cell count (RBC), hematocrit (Hct), and platelet count (PLT) using the electrical impedance method (Figure 1). In this method, blood cells suspended in saline pass through a micro-aperture while a constant current is applied, and the resulting changes in electrical resistance are measured as changes in voltage. The magnitude of the voltage change is proportional to the volume of each blood cell, allowing both cell count and cell volume to be determined from the voltage pulses. Because of its high accuracy in measuring particle size and volume, the electrical impedance method remains a standard technique for blood cell counting.

CRP concentration is measured using the latex immunoturbidimetric method. After hemolyzing whole blood with a lysing reagent, latex reagents sensitized with anti-human C-reactive protein antibodies are allowed to react in the presence of a stabilizer. CRP in the specimen and latex particles in the reagent undergo antigen–antibody reactions, leading to latex particle aggregation. The rate of change in turbidity due to this aggregation is measured using red light, and the CRP concentration in the hemolyzed specimen is determined using a polynomial calibration curve prepared from standard serum. Simultaneously, the measured Hct value is used to convert the result to the plasma CRP concentration.

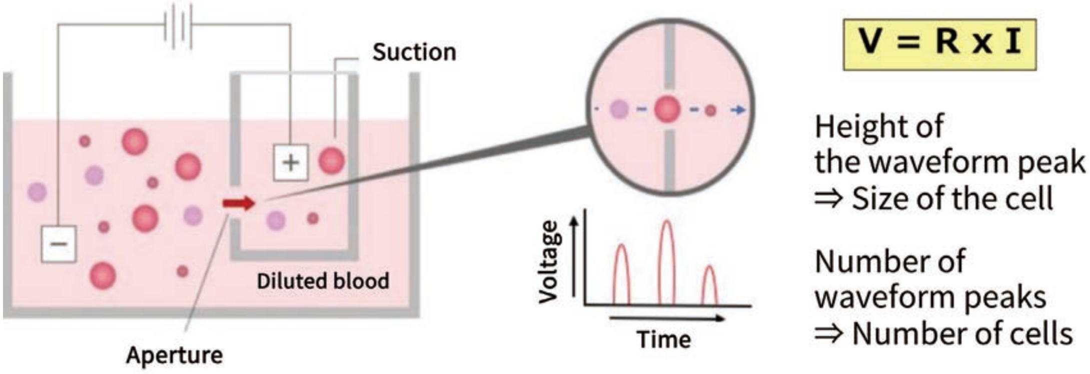

Figure 1 Impedance method

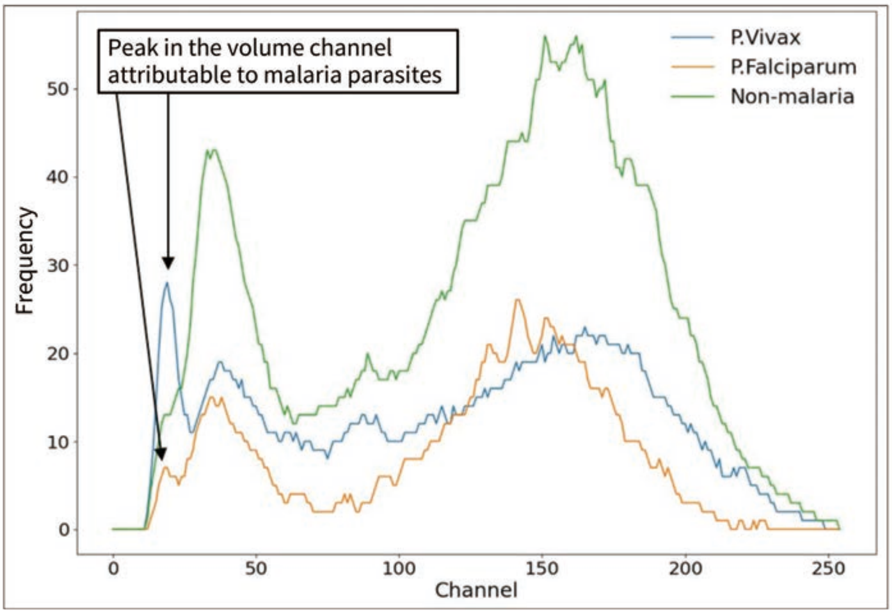

Figure 2 Volume distribution of white blood cells in samples of P. Vivax, P. Falciparum and Non-malaria. The unit of the horizontal axis, Channel, takes values from 0 to 255 that are proportional to the volume of white blood cells.

Examination of Predictive Factors

We examined which measurement parameters should be used as predictors of malaria infection, considering both data-analytic and hematological perspectives on how malaria affects the blood. First, data collection for developing the malaria screening flag was conducted at clinics in India during the monsoon seasons from 2018 to 2019 using the LC-667G. Blood tests were performed on all febrile patients, and CBC, 3Diff, and CRP results were collected. Simultaneously, malaria positivity or negativity was determined by microscopic examination of blood smears and RDTs.

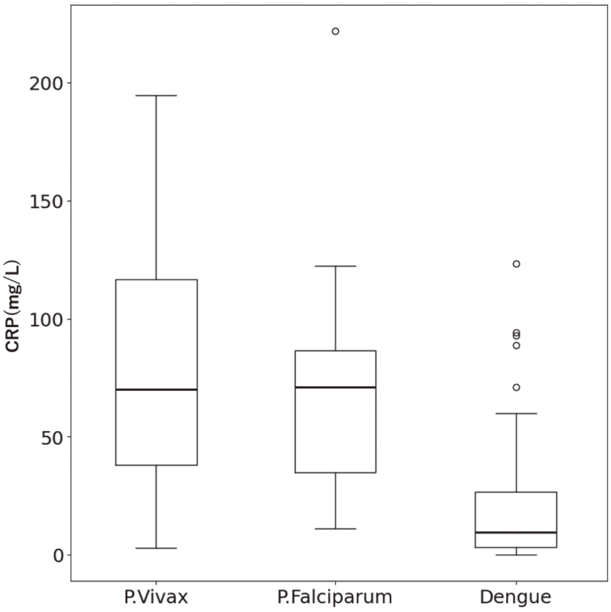

Figure 3 Comparison of CRP concentrations in samples of P. Vivax, P. Falciparum and dengue fever.

Analysis of the collected data revealed several trends in malaria-positive samples. One such trend is the appearance of an abnormal peak in the WBC volume–frequency distribution, which is more common in P. vivax malaria (Figure 2). This peak is believed to represent aggregates of malaria parasites rather than white blood cells. In contrast, this peak is smaller in P. falciparum malaria, likely because the larger P. falciparum parasites are more readily sequestered in the spleen and are less frequently present in peripheral blood[8].

An increase in CRP concentration was also observed. CRP is a biomarker of inflammation that is known to increase during infections. Although not specific to malaria, CRP has been reported as a useful marker for assessing malaria severity[9]. CRP is also useful for differentiating malaria from dengue fever, as these diseases often overlap geographically and present with similar symptoms and CBC results, complicating differential diagnosis. As shown in Figure 3, CRP concentrations tend to be higher in malaria than in dengue fever, because CRP elevation is generally mild in viral infections such as dengue, which is caused by the dengue virus[10].

A decrease in PLT was also noted. Multiple mechanisms are thought to contribute to thrombocytopenia, such as increased platelet sequestration in the spleen due to splenomegaly and aggregation of platelets into larger particles that are counted as single events following red blood cell destruction by malaria parasites[11].

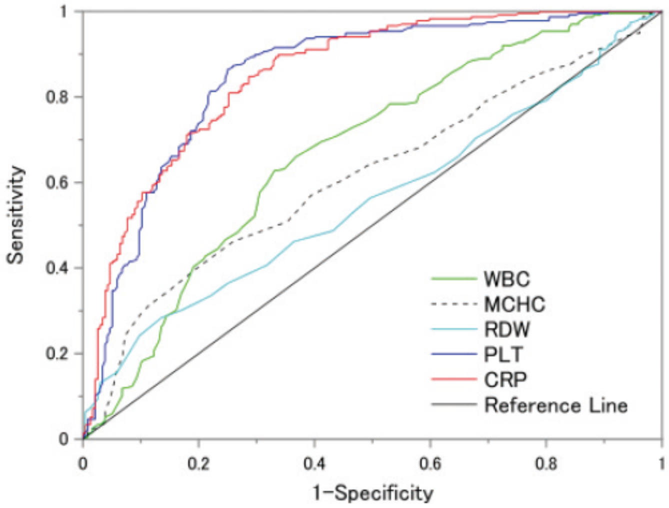

Figure 4 Comparison of ROC Curves for hematological parameters in the malaria diagnosis

Table 1 Comparison of AUCs for hematological parameters in the malaria diagnosis

	AUC
WBC	0.672
MCHC	0.613
RDW	0.558
PLT	0.849
CRP	0.852

To confirm the superior discriminatory power of CRP and PLT for malaria infection compared with other parameters, Figure 4 and Table 1 are presented. Figure 4 shows a receiver operating characteristic (ROC) curve for distinguishing malaria-positive from malaria-negative cases. The ROC curve plots "sensitivity" (the proportion of true positives correctly identified) against "1 − specificity" (the proportion of false positives among negatives) for varying cutoff values. Higher sensitivity and lower 1 − specificity indicate better discrimination, with superior performance represented by curves approaching the upper left corner of the graph. The area under the curve (AUC) quantifies this performance, representing the area beneath the ROC curve. From Figure 4 and Table 1, CRP and PLT demonstrate better discriminatory power than WBC, MCHC (mean corpuscular hemoglobin concentration), and RDW (red cell distribution width).

Modeling

The core of the malaria screening flag calculation method is a malaria screening model constructed using machine learning algorithms (Figure 5). Two key considerations were addressed in the machine learning process. The first is ensuring model interpretability and explainability. Interpretability refers to the extent to which it is possible to explain how the model derives outputs from inputs, whereas explainability refers to the extent to which the reasons for the outputs can be explained. Without sufficient interpretability and explainability, clinicians would

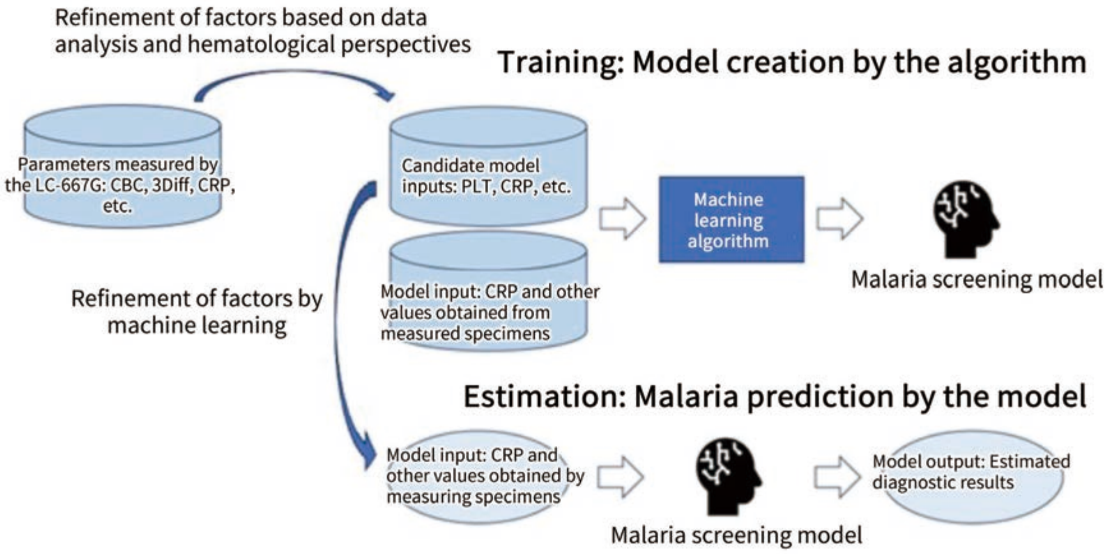

Figure 5 Workflow for the development and application of a machine learning model for malaria screening based on hematological parameters

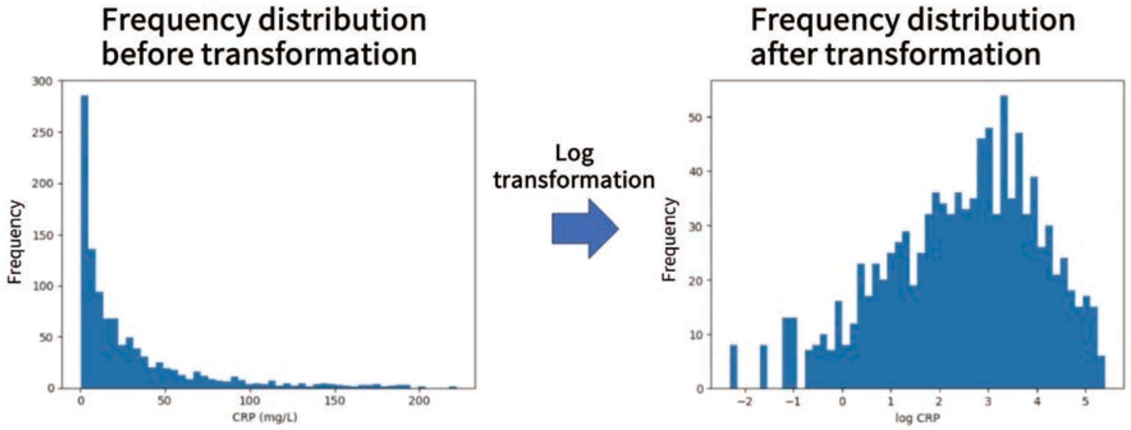

Figure 6 Comparison of CRP value distributions before and after log transformation, showing improved normalization

be unable to explain the diagnostic rationale to patients, making such models unsuitable for clinical adoption. In this study, we employed linear sparse modeling as the machine learning algorithm. This algorithm produces models in which the outputs are calculated by summing the products of the inputs and their corresponding weights (Equation 1), allowing the contribution of each input to be quantified and thereby ensuring interpretability. Additionally, the algorithm automatically selects important factors from the inputs and uses only those selected, thereby improving model explainability. As discussed in the previous section, the input factors are designed based on the mechanisms by which malaria affects the blood, and each factor correlates with the degree of suspicion of malaria infection, facilitating understanding of their impact on the outputs.

$$Y = \sum_{i=1}^{n} W_i X_i \qquad (1)$$

Here, $\boldsymbol{X_i}$ denotes the $\boldsymbol{i}$-th input, $\boldsymbol{W_i}$ the weight corresponding to $\boldsymbol{X_i}$, and $\boldsymbol{Y}$ the output representing the degree of suspected malaria infection.

The second consideration is achieving sufficient accuracy. For the screening flag to be reliable, its correlation with the gold standard—microscopic diagnosis of blood smears—must be high. To achieve this, we made several adjustments. The algorithm assumes that the input factors follow a normal distribution, but the actual data distributions may differ. For example, CRP exhibits a right-skewed distribution, so a logarithmic transformation was applied to approximate a normal distribution (Figure 6). Also, although data were collected during the monsoon seasons, when malaria incidence peaks, the number of malaria-positive samples was smaller than the number of negative samples. In machine learning, models tend to learn more from the majority class, so we adjusted the learning weights for each sample to control this bias. Since high sensitivity is required for screening purposes, we adjusted the learning procedure to optimize the decision threshold, based on ROC curve analysis, to meet the required level of accuracy. Furthermore, because blood characteristics are significantly influenced by race, age, and sex, we considered the applicable range of the model to reduce the risk of erroneous judgments. These measures contributed to improving the accuracy of the model.

Conclusion

We have developed a malaria screening flag based on CBC, 3Diff, and CRP measurements. The model underlying this flag utilizes machine learning, enabling automated, highly accurate, and explainable judgments that are independent of individual expertise. Labor savings allow for the testing of more patients than was previously possible, and screening of patients without overt symptoms contributes to the early detection of malaria. The HORIBA Group will continue to contribute to global health through measurement and analysis utilizing digital transformation (DX) and artificial intelligence (AI) technologies.

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

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Automation and Technological Evolution of Trace Element Analysis in the Iron and Steel Industry

~The Role and Prospects of the EMIA and EMGA Series~

PARK Sangwoon

The analysis of trace elements such as carbon, sulfur, oxygen, nitrogen, and hydrogen in steel is an important process directly related to the control of mechanical properties and corrosion resistance. In the past, manual analysis by skilled operators was standard practice, but from the perspective of eliminating human variability, stabilizing measurement accuracy, and improving throughput, there is now a strong demand for operator-independent operation and automation of the analyzers themselves. HORIBA's EMIA series (carbon and sulfur analyzers) and EMGA series (oxygen, nitrogen, and hydrogen analyzers) have evolved in response to these industrial needs. This paper reviews the technological development of the EMIA and EMGA series and their progress toward automation, and discusses the role of analyzers in the steel industry and their future prospects.

Introduction

In the manufacturing industry, efforts to maintain stable product quality while simultaneously increasing productivity are becoming increasingly important, driven by intensifying competition in the global market and the need to address sustainability. In particular, the steel industry faces a pronounced need for traceability across the entire manufacturing process and real-time quality evaluation, due to the advancement of material properties and the adoption of international quality assurance standards[1].

Against this backdrop, the analysis of trace elements such as carbon, sulfur, oxygen, nitrogen, and hydrogen in steel is a critical process directly linked to the management of mechanical properties and corrosion resistance. These components significantly affect properties such as toughness and susceptibility to cracking, necessitating precise quantification at the ppm level. Traditionally, manual analyses performed by skilled operators were the norm, but there has been a strong demand for simplifying and automating the operation of analytical instruments to eliminate human variability, stabilize measurement accuracy, and improve throughput[2].

HORIBA's EMIA series (carbon and sulfur analyzers) and EMGA series (oxygen, nitrogen, and hydrogen analyzers) have evolved in response to these industrial needs[3]. In recent years, with the trend toward smart factories as part of Industry 4.0, analytical instruments are also required to offer network connectivity, remote operability, and automatic adaptation of measurement conditions[4],[5].

The Japanese Steel Industry and Demand for Analytical Instruments

Increasing Quality Requirements in the Steel Industry

Japan's steel industry has long supported the development of diverse sectors—including construction, automotive, machinery, shipbuilding, and energy—by supplying high-quality and highly reliable steel. Since the 1980s, the demand for functional properties such as lightweight construction, high strength, and improved corrosion resistance has increased, resulting in more complex material design and the need for advanced quality management throughout the manufacturing process[6].

Among these rising quality requirements, the quantitative management of trace elements—such as oxygen, nitrogen, and hydrogen in steel—has become particularly important. Even in minute quantities, these elements can significantly impact the mechanical properties of materials. For example, oxygen reduces ductility and toughness; nitrogen causes age hardening and degrades ductility; and hydrogen leads to delayed fracture[1]. Therefore, precise and highly reproducible analysis at the on the order of ppm is essential for improving product reliability and reducing defect rates (see Table 1).

Table 1 Effects of each element on steel materials

Element	Effect on Steel
carbon (C)	Affects mechanical properties
	Affects hardness
sulfur (S)	Corrosion resistance
	Deteriorates workability and weldability
oxygen (O)	Fatigue strength
	Reduces ductility and toughness
nitrogen (N)	Increases strength but reduces ductility and toughness
hydrogen (H)	Delayed fracture
	Reduces ductility

Furthermore, as international standardization of quality assurance progresses, compliance with overseas standards such as ASTM and ISO, in addition to JIS (Japanese Industrial Standards), is becoming indispensable. Analytical instruments are consequently required to deliver even greater precision, reliability, and reproducibility[1].

On-Site Needs for Trace Element Analysis

Historically, chemical composition analysis of steel depended on manual work by skilled operators. In particular, qualitative methods such as spark testing were susceptible to significant variability and errors due to differences in operator skill and procedures (see Figure 1). Such operator dependency and high workload posed major challenges to achieving stable quality assurance.

HORIBA's EMIA and EMGA series emerged to address these challenges. These instruments combine highly sensitive measurement technologies based on chemical reactions with automated operation systems, enabling a shift from human-dependent analysis to instrument-based, high-precision, and highly reproducible analysis. Figure 2 shows an example of oxygen, nitrogen, and hydrogen analysis using EMGA, demonstrating highly reproducible results.

Advances in quantitative analysis technology have enabled the steel industry to achieve both quality stabilization and mass production, and automation has long been strongly demanded not only for improved analytical precision but also for reduced labor and enhanced safety.

HORIBA's EMIA and EMGA series meet these needs with high sensitivity and reproducibility, providing standardized quantitative results rapidly. Various automation features—such as automatic crucible ejection and autosamplers—enable unmanned nighttime operation, positioning the EMIA and EMGA series as "automation-compatible quality evaluation platforms" highly regarded by the steel industry both domestically and internationally[2],[3].

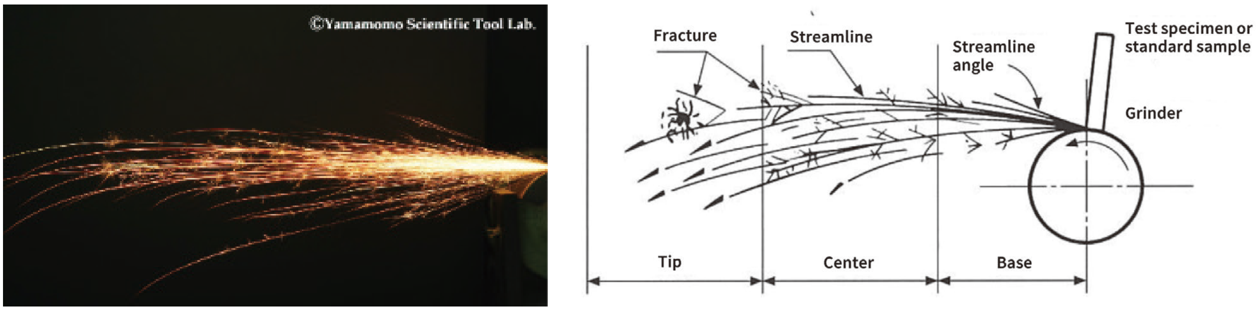
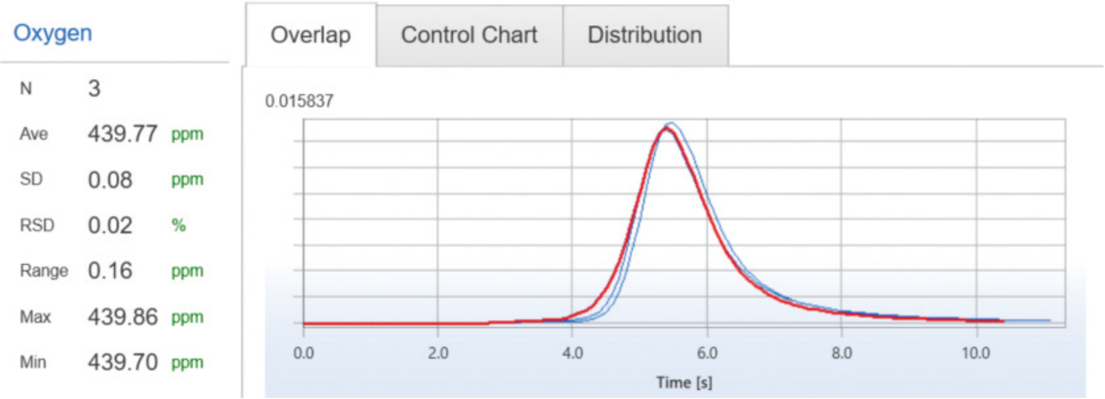


Figure 1 JIS G 0566(1980) Spark test method for steel.*

*Photo by Yamamoto Scientific Tool Laboratory Co., Ltd. https://www.ystl.jp/products/spark/index.html



Oxygen

N	3	
Ave	439.77	ppm
SD	0.08	ppm
RSD	0.02	%
Range	0.16	ppm
Max	439.86	ppm
Min	439.70	ppm

Figure 2 Example of EMGA analysis results.

Technical Evolution and Automation of the EMIA and EMGA Series

Overview of Analytical Principles and Instrument Configuration

HORIBA's EMIA and EMGA series are specialized instruments for quantitative analysis of trace elements in inorganic materials such as steel. The former targets carbon and sulfur analysis, while the latter addresses oxygen, nitrogen, and hydrogen, with both series offering highly sensitive and precise measurements.

The EMIA series employs a method in which samples are combusted at high temperature, and the resulting CO_2 and SO_2 gases are quantified using non-dispersive infrared absorption (NDIR) (see Figure 3). In contrast, the EMGA series melts samples in an inert gas atmosphere, detects CO, N_2, and H_2 generated through oxidation and carbon reduction using thermal conductivity detection (TCD) and NDIR (see Figure 4).

Common components of both instruments include a precisely controlled furnace (impulse furnace), gas flow paths, gas purification systems, and detection units. The furnace vaporizes samples at high temperature, converts them into measurable gases, and utilizes the superior gas selectivity of NDIR detectors for measurement.

Advances in Operability and Automation Features

Early analytical instruments required manual execution of preprocessing, crucible exchange, and sample loading, making analytical accuracy and throughput dependent on operator skill. In contrast, the EMIA and EMGA series have undergone the following technological advancements to realize automation and efficiency[3]:

1. Continuous measurement via autosampler integration
2. Shortened measurement cycles with automatic crucible cooling and ejection mechanisms
3. Elimination of errors and contamination risks through sample ID management systems
4. Recipe-based measurement conditions to eliminate user operation differences
5. Device status monitoring and error notification to minimize downtime
6. Full automation of sample analysis via pneumatic tube transport

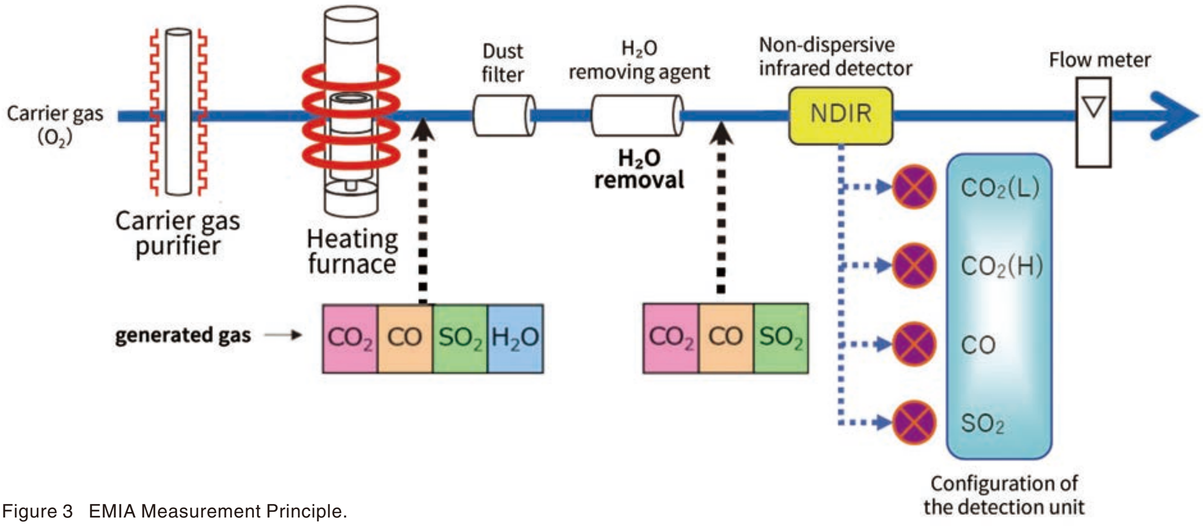


Figure 3 EMIA Measurement Principle.

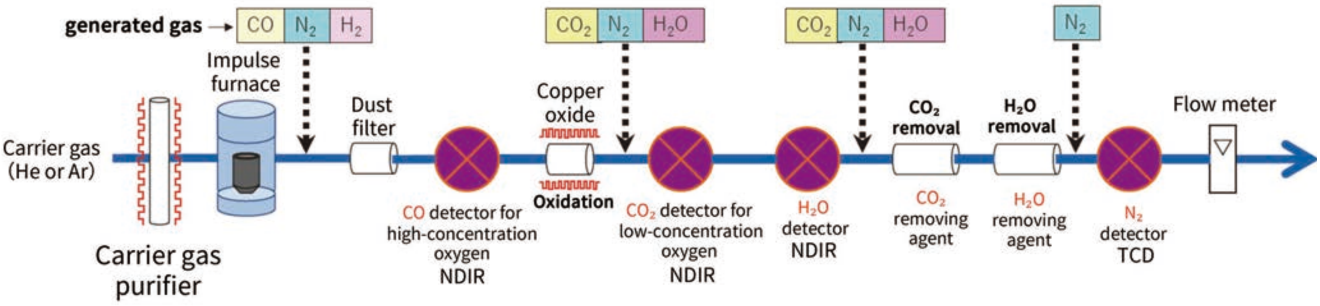


Figure 4 EMGA Measurement Principle.

As shown in Figure 5, the EMGA-730 released in the 1980s was HORIBA's first automated analytical instrument. At the time, it featured automatic crucible cleaning, a robot specialized for X-axis movement, and Y-Z axis control via pneumatic cylinders. As shown in Figure 6, there were two system types: one with automatic weighing and another centered on a sample stocker, allowing users to select based on their requirements[6].

Figure 7 illustrates the basic operational flow of automated analysis at that time, focusing mainly on weighing and

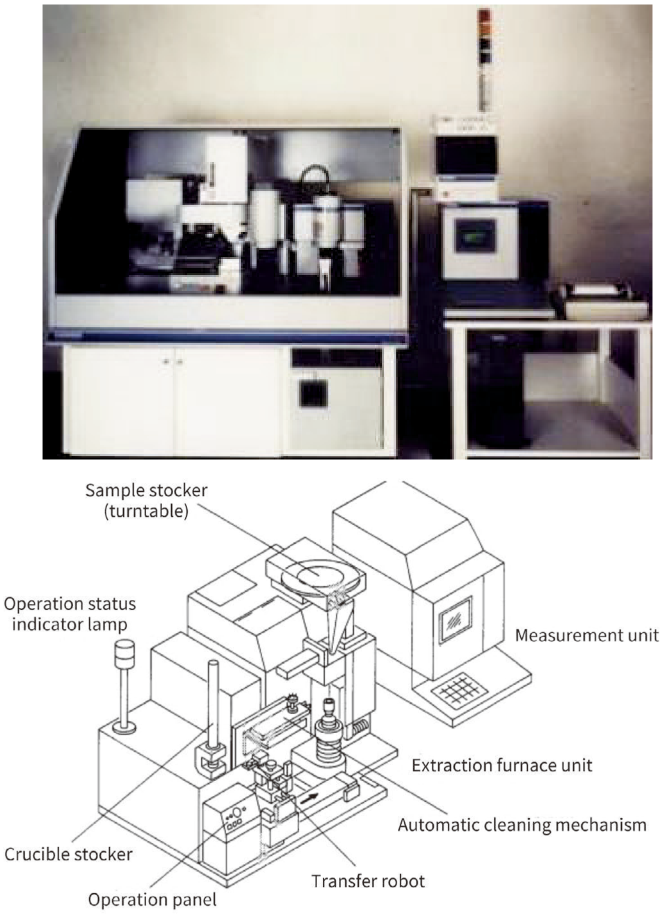


Figure 5 The first automation system, EMGA-730 (top)
System configuration with sample stocker function (bottom).

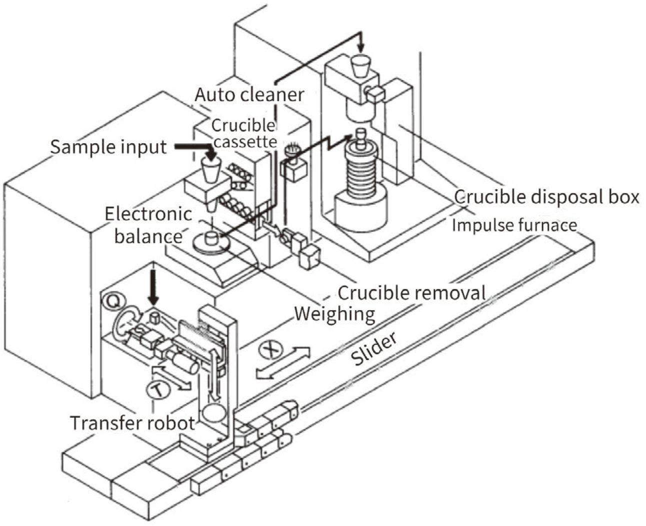


Figure 6 Automated system EMGA-730 with automatic weighing function.

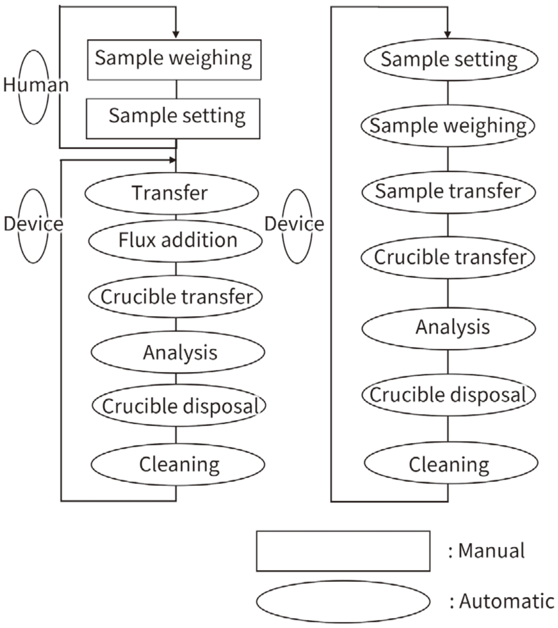


Figure 7 Basic operation of automation equipment.

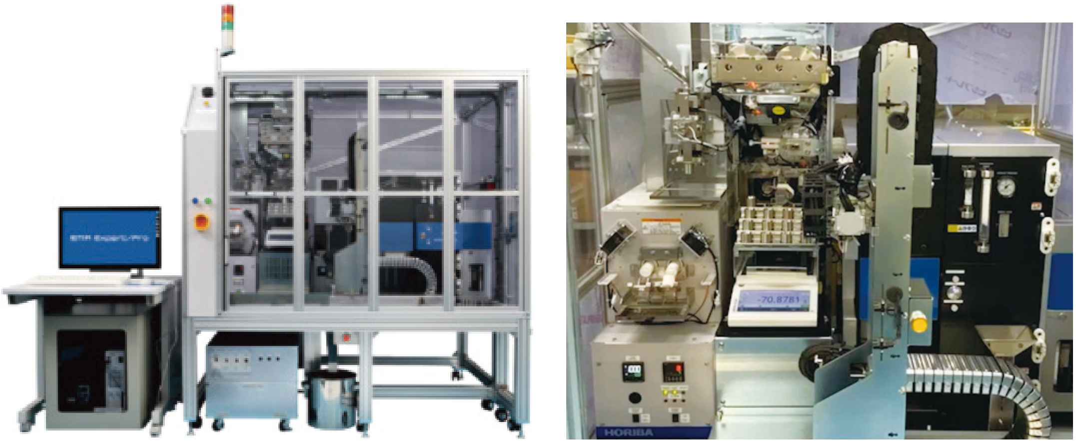


Figure 8 EMIA-2000 automatic machine (left) and interior (right).

sample loading. The central issue in automation was how to reduce the labor required for sample processing, apart from the instrument's own operation.

Forty years later, the EMIA series has further evolved, and the latest fully automated EMIA-2000 features a robotic arm capable of free XYZ-axis movement, enabling advanced operations as shown below (Figure 8).

As depicted in Figure 9, the crucible is extracted from the heating unit by the robotic arm and transported to its designated position. This operation is designed for highly accurate positioning via gravity transport and fine control with air cylinders.

Subsequently, as shown in Figure 10, the robot accurately loads samples and flux, and performs automatic weighing. Unlike the two initial automation configurations, the current model integrates these processes into a single unified system.

Finally, the robot inserts the sample into the main unit (EMIA-Pro/Expert) (Figures 11 and 12). Unlike previous designs relying on linear axis movement, free control

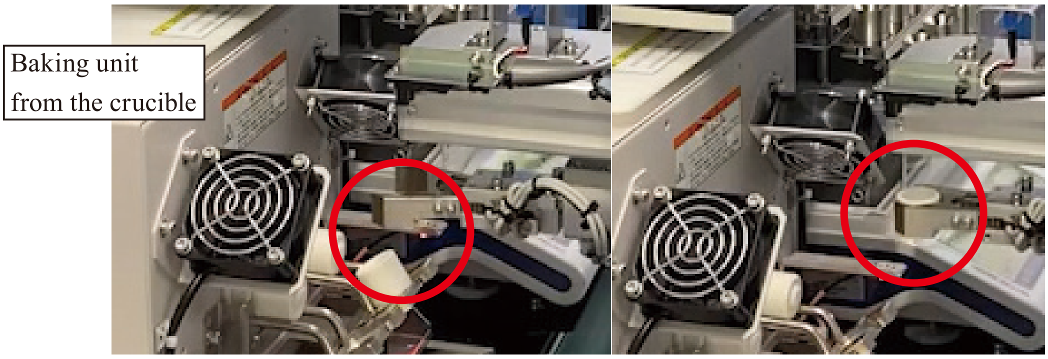


Figure 9 Crucible set from the baking unit from the crucible.

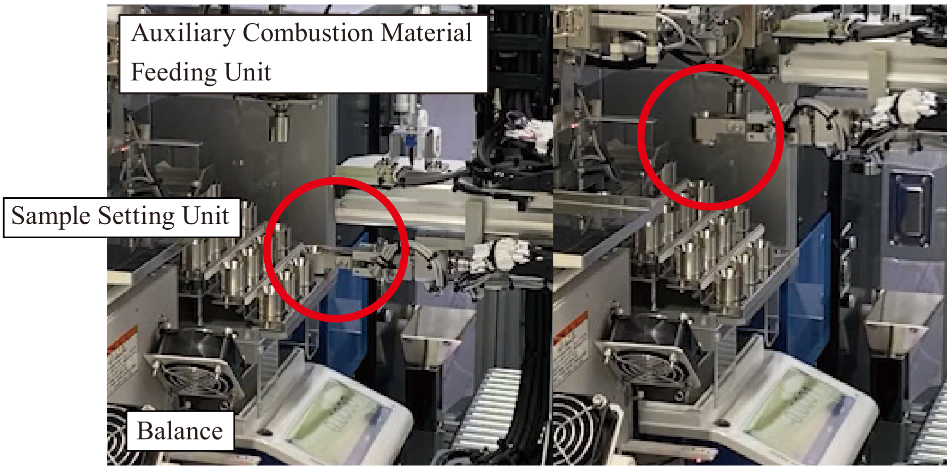


Figure 10 Sample sets, weighing.

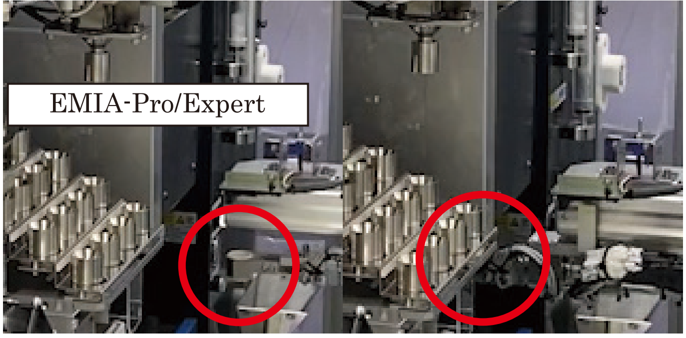


Figure 11 Sample set for EMIA - Pro/Expert.

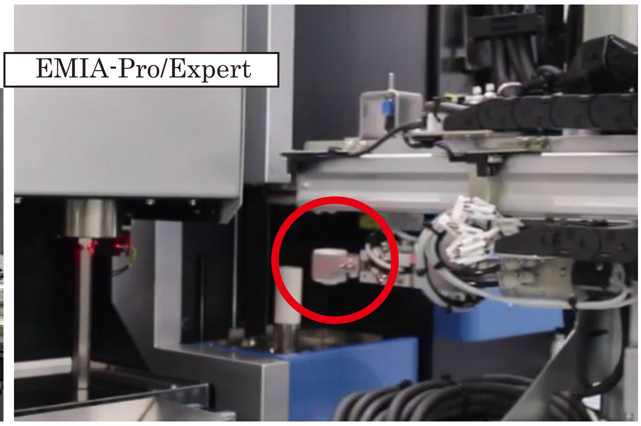


Figure 12 EMIA-Pro/Expert sample set (angle change).

of the X-Y-Z axes allows flexible adaptation to the shape of safety covers and instrument layout.

Thus, automation of processes such as sample setting and weighing directly reduces operator workload and labor hours, and the EMIA and EMGA series continue to meet market demands for automation.

Case Studies and Evaluation in the Steel Industry

Analytical instruments such as the EMIA and EMGA series are now deployed not only in quality assurance departments but also in key production processes such as steelmaking and rolling. In particular, rapid analysis of samples taken from manufacturing lines and immediate reflection of results in furnace conditions have become standard practice at major steel manufacturers. Such real-time integrated operations provide the following operational benefits:

1. Suppression of quality fluctuations through immediate feedback from analysis to process control
2. Enhanced traceability via accumulation and visualization of data
3. Reduced operator workload and training costs through automated measurement operations

The EMIA and EMGA series are being redefined as intelligent analytical systems that support real-time optimization of production processes, transcending the role of simple measurement devices. Case studies in the steel industry demonstrate that these instruments have evolved from tools for “obtaining data” to strategic solutions for achieving both quality and efficiency.

Prospects for Automated Instruments

Maturation and Multifunctionality of Automation Mechanisms

In recent years, automation technologies for analytical instruments have advanced significantly beyond mere labor-saving in specimen processing, showing major progress in areas such as user interfaces, control algorithms, and autonomous decision-making capabilities. Integration between autosamplers and transport systems, as well as sophisticated self-detection and recovery from errors, are becoming increasingly refined, transforming instruments from passive tools into systems that “judge and propose together” with the user.

Against this background, the following extended functionalities are anticipated for the EMIA and EMGA series:

1. Enhancement of automatic correction of measurement conditions and error prediction functions using AI
2. Fully automated switching of measurement profiles through specimen information reading (barcode, RFID)
3. Implementation of job scheduling and load balancing control among multiple analytical instruments
4. Dynamic measurement interruption and resumption mechanisms, and flexible recalculation modes

Impact of Automation on the Workplace

Advancements in automation at analytical sites are shifting the role of operators from “manual controllers” to “monitors and optimizers.” This transition is expected to reduce dependence on individual expertise, lower training costs, and accelerate troubleshooting. As material complexity and the development of new materials progress, rationalizing the setting and standardization of test conditions will become increasingly important.

In the future, the realization of “contactless operation”—where operators can monitor and control remotely without being physically present—and “real-time condition optimization AI” that adapts to lot differences and specimen shapes, as well as “prediction-driven analysis,” where instruments actively propose measurement timing based on data from other processes, will further reduce labor and promote the automation of analytical procedures.

The Future of Automated Analytical Instruments

Looking ahead, analytical instruments represented by the EMIA and EMGA series will assume roles not only as “high-precision measurement devices” but also as “autonomous decision-support systems” positioned between manufacturing and quality assurance. Especially in the context of emerging trends such as carbon neutrality and smart material development, analytical instruments will be required to function within broader information networks rather than as standalone devices. Furthermore, HORIBA aims to pioneer automated analysis using AI and machine learning.

The design philosophy for such instruments should be based on three pillars: user-centricity, trouble-free operation, and future scalability. HORIBA’s product development is expected to continue evolving around these principles.

Conclusion

This paper has discussed the advancement of quality assurance in Japan's steel industry and the corresponding technical evolution of analytical instruments, focusing on the history, current status, and future of HORIBA's EMIA and EMGA series automation systems.

Trace element analysis is an extremely important process directly linked to ensuring the reliability of steel products, and its automation and precision significantly influence overall manufacturing efficiency and quality. The EMIA and EMGA series have responded to diverse user needs not only by improving analytical accuracy, but also by incorporating features such as autosamplers, automatic ejection mechanisms, recipe management for measurement conditions, network connectivity, and remote monitoring for smart factory compatibility. As a result, analytical instruments have expanded their roles from "inspection devices" to "components of the manufacturing process" and "information systems supporting management decisions."

Looking forward, further development of Industry 4.0, as well as the integration of AI-based automatic anomaly detection, measurement condition optimization, and real-time connectivity with LIMS (Laboratory Information Management Systems) and ERP (Enterprise Resource Planning) systems, will continue to raise the functional requirements for analytical instruments. In particular, to address societal demands such as realizing a decarbonized society and ensuring transparency in global supply chains, the existence of analytical instruments capable of reliably supplying high-quality data will be indispensable.

With a foundation of long-accumulated analytical technology and instrument development expertise, HORIBA's EMIA and EMGA automation systems are expected to continue serving as central pillars supporting the smart transformation and quality innovation of manufacturing, further enhancing competitiveness in the global market.

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

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Service solutions with remote monitoring

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HORIBA Techno Service (HTS) is responsible for the maintenance, repair, and servicing of HORIBA products. Since 2020, under the constraints imposed by the COVID-19 pandemic that limited customer site visits, HTS has developed remote solutions as new service proposals, leveraging advancements in information technology, IoT, and AI. This paper introduces efforts not only to achieve stable operation of instruments through remote monitoring, but also to reduce on-site workload, expedite problem resolution, and enhance the skills of service engineers, which are essential for service quality.

Introduction

For enhancing the reliability and maintaining the performance of analytical instruments, not only improvements in instrument functions and capabilities but also routine maintenance are indispensable. In particular, analytical and measurement instruments are often required to operate continuously under constant monitoring, and the installation environment or characteristics of measurement samples can frequently present harsh conditions for the instruments. As such, daily maintenance plays a significant role in ensuring the reliability of measurement results.

Company Overview of HORIBA Techno Service

HTS is a service division spun off as a wholly owned subsidiary of HORIBA, established on March 21, 2000, and celebrating its 25th anniversary in 2025. As of 2025, 27 service stations are located in major regions and industrial areas nationwide as operational bases. The national service stations are managed by four regions: East Japan, Central Japan, Headquarters, and West Japan, providing maintenance and repair of HORIBA analytical instruments and responding to customer needs in each area.

In February 2021, the new headquarters and Kyoto Service Station building (Figure 1) was completed. To strengthen and expand domestic and international service operations, HTS established the Analytical Solution Plaza—an analytical laboratory—along with centralized facilities for training, calibration, and technical support centers to serve as customer inquiry points[1]. By collaborating with group companies operating in 29 countries and regions worldwide, HTS is reinforcing the construction of “Service Lifecycle Management,” which supports customer product operation, equipment management, and analytical consulting. Emphasizing customer proximity and regional engagement, HTS aims to provide prompt service and pursue solution-based business through application proposals and consulting.

Figure 1 HORIBA Techno Service Head office.

Maintenance of Analytical Instruments and Troubleshooting Cases

The substances and physical properties analyzed and measured are diverse and numerous, and HORIBA offers a wide variety of analytical instruments with differing measurement principles depending on sample characteristics and measurement targets. To perform qualitative and quantitative analysis, instruments utilize various chemical and physical reactions of the measurement targets. When instrument trouble occurs, causes are investigated by collecting objective facts based on measurement principles, product structure, and characteristics, and by referencing past troubleshooting cases. However, when troubles arise from complex factors or unprecedented cases, identifying the cause may take time. Many issues can only be understood on-site, necessitating direct investigation by service engineers. Consequently, lengthy periods from on-site cause identification to repair completion can occur, potentially lowering customer satisfaction.

Since 2020, with the social push for telework and restrictions on customer site visits due to COVID-19, customers strongly demanded rapid restoration to normal operation when instrument failures led to missing measurement data. To address this, HTS developed a remote monitoring system for data collection and visualization of instrument status, enabling swift identification of failure points and causes and facilitating efficient repair responses.

Overview of the Remote Monitoring System

Figure 2 shows the configuration of the remote monitoring system using the EMIA solid carbon/sulfur analyzer.

The EMIA terminal PC and Gateway are connected via RS-232C serial communication. Signals received from the instrument are encrypted by the Gateway and transmitted (uploaded) to the server via carrier network and internet. Signals from the instrument (measurement counts, maintenance signals, maintenance history, alarm history, etc.) are monitored at the Technical Support Center (Figure 3) for signs preceding abnormalities, abnormal values at the time of failure, and critical alarms, enabling prompt customer support. The monitored signals are one-way and do not acquire any analytical data from customer instruments. Monitored signal values and data are reported monthly to customers as operational status reports.

Currently, this remote monitoring system is being fully deployed for solid carbon/sulfur analyzers “EMIA-Pro/Expert”, solid oxygen/nitrogen/hydrogen analyzers “EMGA-Pro/Expert”, and laser diffraction/scattering particle size analyzers “LA-960V2/LA-350”. These instruments are widely used in quality assurance and quality control departments, playing a vital role in customer product quality management. Because instrument performance is closely linked to product quality, ensuring normal operation is of utmost importance.

HTS also offers various efficiency improvement services tailored to customer needs, such as “AOP Connects” (Figure 4), which adds remote instrument status monitoring by specialized engineers to the comprehensive maintenance service plan “AOP (All in One Plan).”

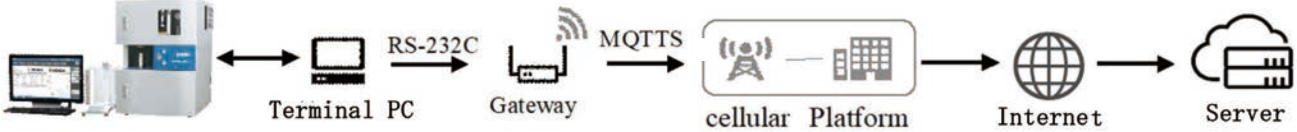

Figure 2 Outline of Remote monitoring system for EMIA.

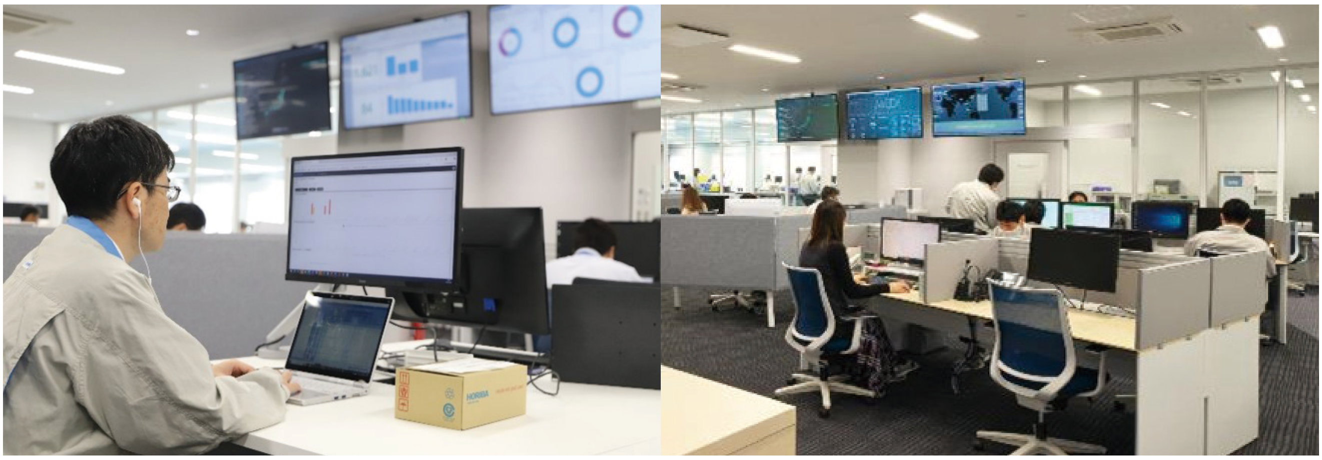

Figure 3 Technical Support Center.

Preventing Equipment Failures through Early Detection of Abnormalities

Remote monitoring allows for tracking changes in instrument signal values over time. Dedicated engineers at the Technical Support Center monitor daily fluctuations, and as shown in the red box in Figure 5, when a signal value begins to fluctuate beyond its usual range, it is recognized as “abnormal.” The engineer contacts the instrument user to confirm whether any abnormal measurements have been detected and recommends maintenance.

While annual maintenance is typically scheduled at the customer’s convenience, in this case, HTS was able to provide maintenance service at the optimal timing before the abnormality affected analytical measurements, thereby preventing equipment failure.

Reducing Downtime by Predicting Failures in Advance

In standard repair responses, engineers often identify failures or defective parts based on information from customers and past cases via phone or email, but discrepancies between estimated and actual issues frequently occur, necessitating re-visits or additional work.

A dedicated engineer at the Technical Support Center detected a detector temperature alarm and analyzed recent temperature changes. Normally, detector temperature fluctuates within 55°C ± 0.2°C, but as shown by the blue graph in Figure 6, increased fluctuations were observed and judged abnormal. Suspecting depletion of thermal compound (heat-conductive grease), the engineer coordinated with on-site engineer to prepare in advance, enabling rapid repairs and reducing analyzer downtime.

In the unlikely event of a failure, HTS will respond free of charge from investigation to recovery, including parts replacement. (Excludes holidays and outside business hours.)

HTS constantly monitors the equipment status and provides optimal support.

HTS confirms stable equipment operation with an annual inspection.

Figure 4 Comprehensive maintenance inspection service with added remote monitoring[2].

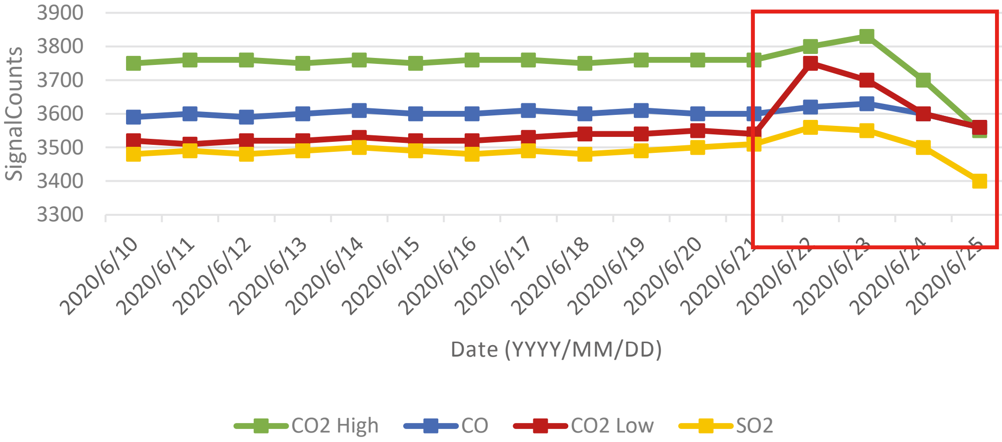

Figure 5 Interday variation of signal counts from instrument.

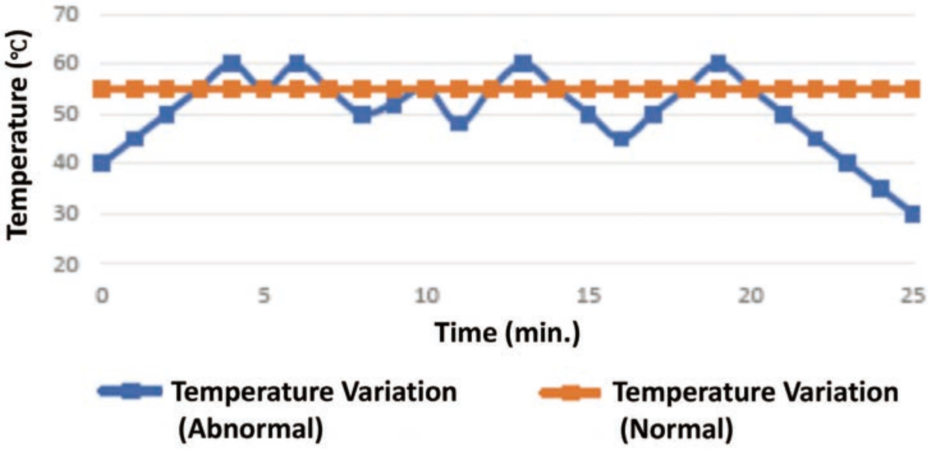

Figure 6 Transition of detector temperature.

Monitoring Installation Environment via Remote Management

As shown in Figure 7, monitoring revealed several increases in CO_2 Low count values throughout the day. Since it was difficult to determine from monitoring alone whether this indicated an instrument abnormality, the dedicated engineer at the Technical Support Center contacted the on-site engineer to check the customer's usage conditions. It was found that a stove was being used to heat the analysis room. After confirming the measurement conditions, it was verified that the instrument readings were unaffected. When monitoring data alone is insufficient for judgment, collaboration with on-site engineers allows HTS to provide services that enable customers to use analytical instruments with greater peace of mind.

Remote Monitoring during Earthquakes

Remote monitoring also enables tracking of instrument operational status. While HTS's strength lies in providing prompt support from service stations close to users, there are cases where distant users cannot be reached quickly. For example, when a major earthquake (maximum seismic intensity 6+) struck off Fukushima Prefecture in March 2022, the Technical Support Center checked the operational status of customer instruments equipped with remote monitoring. For customers whose instruments were not operating, HTS contacted them to confirm their safety and status. Fortunately, no instruments were affected by the earthquake, and customers expressed gratitude for the check-in. Thus, remote monitoring serves not only as a support for instrument failures but also as a solution providing reassurance to customers.

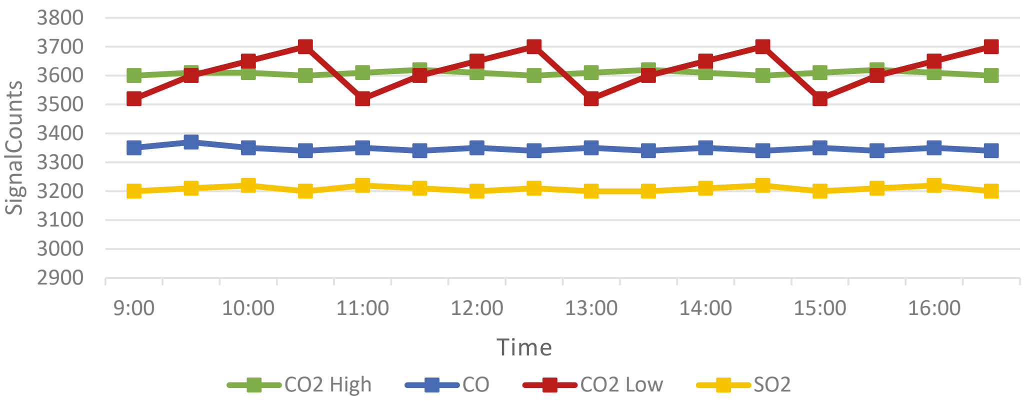

Figure 7 Interday variation of signal counts.

Global Support and Training of Service Engineers

HORIBA's measurement and analytical instruments are sold worldwide, making support for overseas engineers increasingly important. For instance, when a reticle/mask defect inspection system for semiconductors was delivered to the Middle East, local engineers lacked sufficient product knowledge and technical skills. Initially, experienced engineers from Japan were scheduled to be dispatched for installation, but international conflict made this impossible. Instead, remote support was provided from Japan for the local engineers' installation work. Camera footage was used for guidance, and analytical software operation was instructed remotely via TeamViewer™*1. In this way, remote support enabled HTS to meet customer needs and support engineers even when local service was difficult.

*1 TEAMVIEWER is a registered trademark or trademark of TEAMVIEWER GERMANY GMBH.

Conclusion

This paper has described the remote monitoring services provided by HTS, related case studies, and skill enhancement of engineers through remote support. While IoT and AI utilization are becoming commonplace, how they are applied has a significant impact on business. As automation and labor-saving in corporate manufacturing processes increase, the need for stable instrument operation and rapid response to failures also rises. Furthermore, training engineers with high-level skills remains an urgent issue in the field.

HTS aims to improve customer satisfaction by continuously providing new solutions that meet evolving needs from a position closer to customers. Additionally, HTS is committed to enhancing the skills and problem-solving abilities of engineers both domestically and internationally through online training, remote support, webinars, and online manuals.

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

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PI Parameter Optimization for Pressure-Based MFC (D700) Using Gaussian Mixture Model

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A vast number of mass flow controllers (MFCs) are used in semiconductor industry. An efficient production method of MFC is required. The gain tuning of the proportional-integral (PI) control to realize a setting flow rate is essential for efficient mass production. The gains are tuned to meet the specifications required for evaluation indices of response time and overshoot amount in a step response waveform. In this paper, we propose a simple method for the PI gain tuning using the Gaussian Mixture Model (GMM) and the direct inverse analysis applicable to the pressure-based MFCs' production. The relationship between the gains and evaluation indices for a standard unit of the MFC is modeled as the GMM. The direct inverse analysis calculates the difference between the standard and a test unit. Under the assumption that the difference can be compensated by a simple shift, gains likely to meet the specifications for the test unit are searched. We applied the method to seven test units. The result showed that the gains of all the test units were tuned within only a few iterations.

Keywords
Semiconductor, Gaussian mixture mode, PI control, Mass flow controller, Manufacturing.

1. Introduction

A mass flow controller (MFC), which precisely controls fluid mass flow rate, is widely used in the semiconductor manufacturing[1]. Since a whole process of semiconductor manufacturing consists of many reaction steps, a vast number of MFCs are required for each plant. Therefore, establishing an efficient production method of MFC has become more important.

The MFC controls fluid's flow rate by adjusting a valve opening to realize a setting flow rate. The pressure-based MFC, which measures flow rate with pressure sensors, has advantages on its fast response and high accuracy.

The design of controller including an algorithm for the adjustment is essential for the MFCs' production. The proportional-integral (PI) or proportional-integral-derivative (PID) controls are widely employed for the algorithm, where the PI or PID gains determine an applied voltage to the valve so that the variation between the setting and measured flow rates can be converged. The gains are tuned to meet the specifications required for evaluation indices, which are a response time and an overshoot amount obtained from a step response waveform. In most MFCs' productions, the gains are tuned through trial and error for every unit, which is a bottleneck against establishing the efficient production method. The Gaussian mixture model (GMM) is a simple model to express a relationship among multiple variables with a superposition of Gaussian probability densities[2],[3]. The application can provide a simple model for the relationship between the gains and resulting evaluation indices. In addition, the direct inverse analysis based on the Bayes theorem enables us to estimate the most likely gains for obtained indices, conversely. However, as devices installed in the control target system have different characteristics among individual MFC units, the relationship modeled for a single unit cannot be simply applied for every unit.

In this paper, we propose a simple method for the PI gain tuning using the GMM and the direct inverse analysis applicable to the pressure-based MFCs' production. The relationship between the PI gains and evaluation indices are investigated for a standard unit. Using the GMM and the direct inverse analysis, the difference of every test unit from the standard unit is calculated. By compensating the difference, the gains are tuned to meet the specifications for every test unit. After formulating the method, we applied it to the tuning for a couple of pressure-based MFCs to confirm the applicability in mass production.

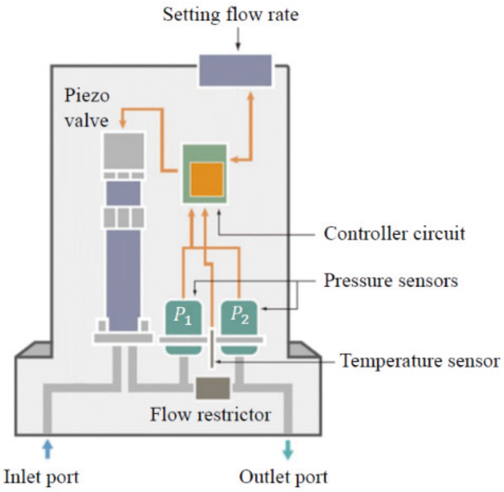


Figure 1 Internal structure of a pressure-based gas MFC.

2. CHARACTERISTICS OF PRESSURE-BASED MFCS

2.1 MFC structure

A schematic of a pressure-based gas MFC is shown in Figure 1. The MFC includes a piezo valve, two pressure sensors, a temperature sensor, a flow restrictor, and a controller circuit. The inlet and outlet ports for gas are respectively connected with upstream and downstream pipelines. Gas entered from the inlet port passes through the piezo valve and flow restrictor, and then goes out from the outlet port. The flow rate of output gas (Q_{out}) is calculated as follows:

$$Q_{out} = k(p_1^2 - p_2^2), \tag{1}$$

where k is a flow restrictor constant having a temperature dependence, and p_1, p_2 are outputs of pressure sensors P1, P2, respectively.

The controller circuit adjusts the valve opening through applied voltage to realize a setting flow rate (Q_{set}). The block diagram of PI control installed in the controller is shown in Figure 2. Here, K_P, K_I mean P and I gains,

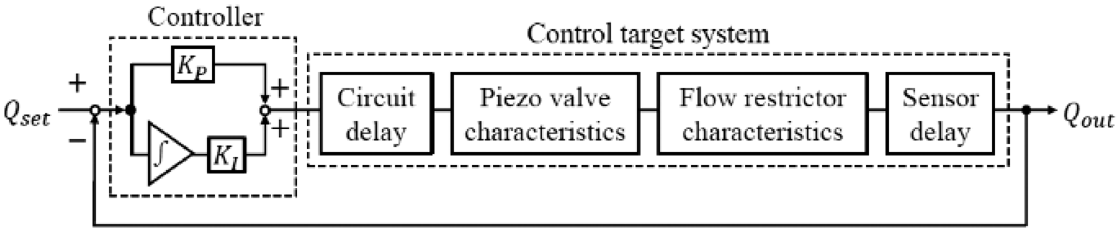


Figure 2 Block diagram of PI control system for the pressure-based MFC.

respectively. The gains are tuned in accordance with characteristics of the control target including circuit delay, characteristics of piezo valve and flow restrictor, and sensor delay, which are generally complicated. Furthermore, as the characteristics are different among individual units, every MFC unit requires individual gain tuning.

2.2 Evaluation indices for PI gain tuning

In this study, we consider the case that the PI gains are tuned based on the following two evaluation indices in a step response for 0→100%FS input ("%FS" means flow rate normalized by control full scale): (i) T_r(ms): response time defined as a period from the Q_{set} input to the timing when Q_{out} achieves 98% of Q_{set} and (ii) Q_{os} (%): overshoot amount defined as,

$$Q_{Os} = \frac{Q_{peak} - Q_{set}}{Q_{set}} \times 100, \tag{2}$$

where Q_{peak} is the flow rate having the maximum difference from Q_{set} after once Q_{out} exceeds Q_{set}. ($Q_{os} = 0$ if Q never exceeds Q_{set}) The total test duration for step response is fixed at 200 ms. The specifications require that T_r and Q_{os} should be within the range of 85 ± 5 ms and $0^{+0.50}_{-0.55}$ %, respectively. Here, we denote that the optimal indices $(T_{r0}, Q_{os0}) = (85, 0)$ and the tolerances $(\Delta T_r, \Delta Q_{os}) = (10, 1.05)$.

A global relationship between (K_P, K_I) and (T_r, Q_{os}) were investigated for a standard unit that are arbitrarily selected from among mass produced MFCs. We independently varied (K_P, K_I) in the range of [0.5,1.5] with intervals of 0.02, and thus 2,500 step response waveforms in total are acquired to get (T_r, Q_{os}). For the standard unit of this study, the optimal gains that gave the indices closest to (T_{r0}, Q_{os0}) were $(K_{P0}, K_{I0}) = (0.94, 0.94)$. Figure 3 shows the step response waveforms at $(K_P, K_I) = (K_{P0}, K_{I0})$, (1.50, 0.50), and (0.50, 1.50). For $(K_P, K_I) = (K_{P0}, K_{I0})$, a preferable waveform with $(T_r, Q_{os}) = (85, -0.046)$ were obtained. For $(K_P, K_I) = (1.50, 0.50)$, the waveform had an oscillation with a large overshoot. For $(K_P, K_I) = (0.50, 1.50)$, the waveform indicated a too slow response.

To simply evaluate the step response, we defined the deviation index z as follows:

$$z = \frac{|T_r - T_{r0}|}{\Delta T_r} + \frac{|Q_{os}|}{\Delta Q_{os}}. \tag{3}$$

The necessary condition in which either index certainly meets the specifications is $z \leq 1.02$, and the sufficient condition in which both indices certainly meet the specifications is $z \leq 0.50$. For $0.50 < z \leq 1.02$, the balance of each term in Eq. (3) determines whether the specifications are satisfied or not. The distribution of z on a K_P - K_I plane for the standard unit is illustrated in Figure 4, together with regions of the necessary (white dashed line) and sufficient (white solid line) conditions and (T_{r0}, Q_{os0}) location (red spot). The PI gains likely to meet the specifications are configured in a narrow region around $K_P \approx K_I$. The distribution reflects the characteristics of the pressure-based MFC structure.

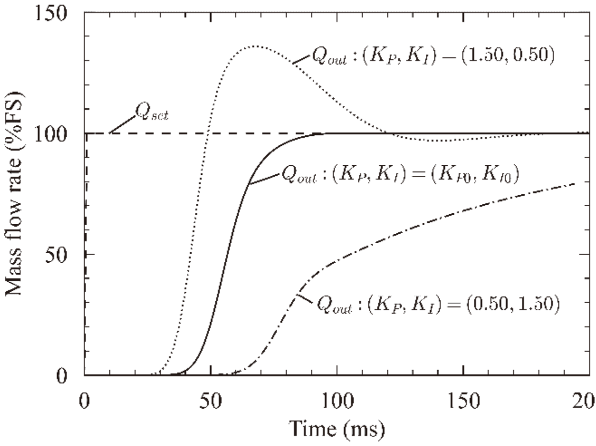


Figure 3 Step response waveforms of standard unit at $(K_P, K_I) = (K_{P0}, K_{I0})$, (1.50, 0.50) and (0.50, 1.50).

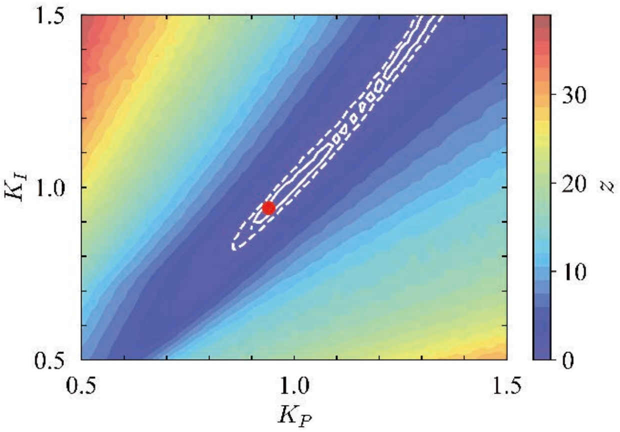


Figure 4 Distribution of the deviation index z for the standard unit (See Eq. (3)).

3. PI GAIN TUNING METHOD

The procedure of PI gain tuning follows the next two phases: learning for the standard unit and tuning for test units. For the formulation, the explanatory and objective variables ($\boldsymbol{x}$, $\boldsymbol{y}$) are defined as follows:

$$\boldsymbol{x} = (K_{P,}K_I), \tag{4}$$

$$\boldsymbol{y} = (T_r, Q_{os}), \tag{5}$$

and $\boldsymbol{x}_0 = (K_{P0}, K_{I0})$, $\boldsymbol{y}_0 = (T_{r0}, Q_{os0})$.

3.1 Learning for standard unit

From the collected 2,500 data of ($\boldsymbol{x}$, $\boldsymbol{y}$) for the standard unit, the probability density distribution is modeled as the form of the GMM:

$$p(\boldsymbol{x}, \boldsymbol{y}) = \sum_{i=1}^{n_G} \pi_i N\left([\boldsymbol{x}, \boldsymbol{y}] \middle| [\boldsymbol{\mu}_{x,i}, \boldsymbol{\mu}_{y,i}], \begin{bmatrix} \Sigma_{xx,i} & \Sigma_{yx,i} \\ \Sigma_{xy,i} & \Sigma_{yy,i} \end{bmatrix}\right). \tag{6}$$

Here, π_i is the weight of the i -th Gaussian, $\boldsymbol{\mu}_{x,i}$, $\boldsymbol{\mu}_{y,i}$ are the mean vectors of $\boldsymbol{x}$, $\boldsymbol{y}$, and $\Sigma_{xx,i}$, $\Sigma_{xy,i}$, $\Sigma_{yx,i}$, $\Sigma_{yy,i}$ are their variance-covariance matrices, respectively, which are determined by the expectation-maximization method. The number of Gaussian n_G is determined to minimize the square error without an overfitting. In this case, we set $n_G = 10$.

3.2 PI gain tuning for test units

A step response waveform is acquired for each test unit by setting the initial gain at $\boldsymbol{x} = \boldsymbol{x}_0$. If the p($\boldsymbol{x}$, $\boldsymbol{y}$) for the considering test unit is almost the same as the one for the standard unit, the resulting $\boldsymbol{y}$ is supposed to meet the specifications immediately. If the resulting $\boldsymbol{y}$ fails to meet the specifications, the direct inverse analysis of GMM with respect to the $\boldsymbol{y}$ is applied to get the predictive gains $\hat{\boldsymbol{x}} = (\hat{K}_P, \hat{K}_I)$, which is expected to give the same $\boldsymbol{y}$ for the standard unit. The probability density of $\boldsymbol{x}$ under given $\boldsymbol{y}$ can be calculated as,

$$p(\boldsymbol{x}|\boldsymbol{y}) = \sum_{i=1}^{n_G} \omega_{y,i} p(\boldsymbol{x}|\boldsymbol{y}, \boldsymbol{\mu}_{y,i}, \Sigma_{yy,i}), \tag{7}$$

where $p\ (\boldsymbol{x}|\boldsymbol{y}, \boldsymbol{\mu}_{y,i}, \Sigma_{yy,i})$ is the probability density distribution of $\boldsymbol{x}$ in the i -th Gaussian in Eq. (6) under $\boldsymbol{\mu}_{y,i}$, $\Sigma_{yy,i}$ (yy,i) and given $\boldsymbol{y}$, and $\omega_{y,i}$ is the weight calculated as,

$$\omega_{y,i} = \frac{\pi_i p(\boldsymbol{y}|\boldsymbol{\mu}_{y,i}, \Sigma_{yy,i})}{\sum_{j=1}^{n_G} \pi_j p(\boldsymbol{y}|\boldsymbol{\mu}_{y,j}, \Sigma_{yy,j})}. \tag{8}$$

The mean vector of $\boldsymbol{x}$ in the i-th Gaussian under given $\boldsymbol{y}$, is calculated as,

$$\boldsymbol{m}_i(y) = \boldsymbol{\mu}_{x,i} + (\boldsymbol{y} - \boldsymbol{\mu}_{y,i})\Sigma_{yy,i}^{-1}\Sigma_{yx,i}^{-1}. \tag{9}$$

Assuming that z -distribution for the test unit can be approximately overlapped by simply shifting the distribution for the standard unit in $\boldsymbol{x}$-direction, the newly defined $\boldsymbol{x}$ as,

$$\boldsymbol{x} = \boldsymbol{x}_0 + \Delta\boldsymbol{x}, \tag{10}$$

is expected to give $\boldsymbol{y}$ close to $\boldsymbol{y}_0$ for the test unit. Here, the shift vector is

$$\Delta\boldsymbol{x} = (K_{P0} - \hat{K}_P, K_{I0} - \hat{K}_I). \tag{11}$$

If the new $\boldsymbol{x}$ fails again to give $\boldsymbol{y}$ meeting the specifications, the same cycle is repeated unless the number of iterations n reaches a specific maximum value n_{max}. The flow chart of this procedure is summarized in Figure 5.

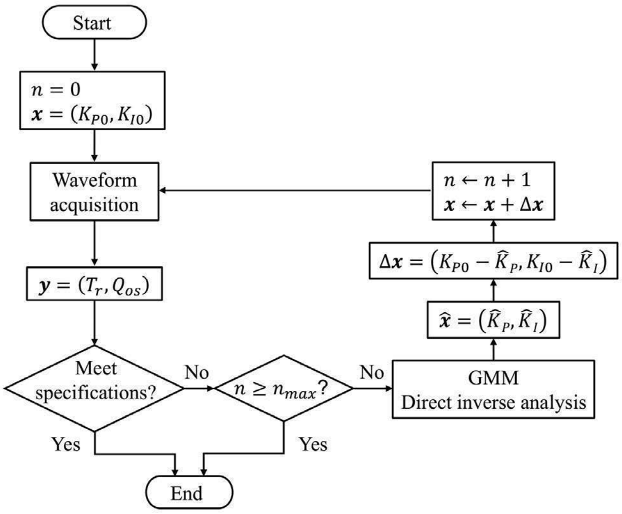


Figure 5 Flow chart of PI tuning for test units.

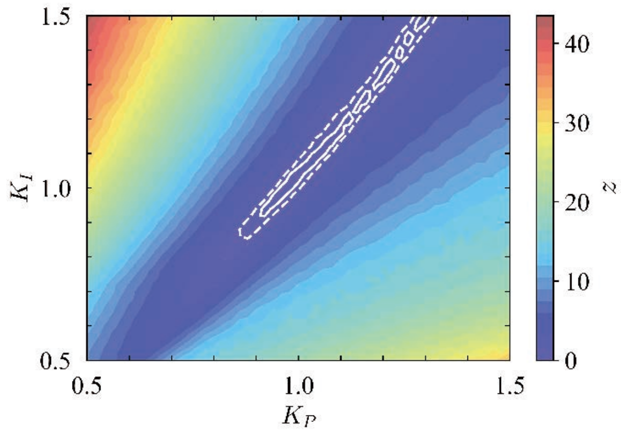
4. RESULTS

We applied the PI gain tuning method for seven test units. The results are listed in Table 1. The evaluation indices that meet the specifications were obtained for all the test units with $n \leq 4$, though we set $n_{max}=10$.

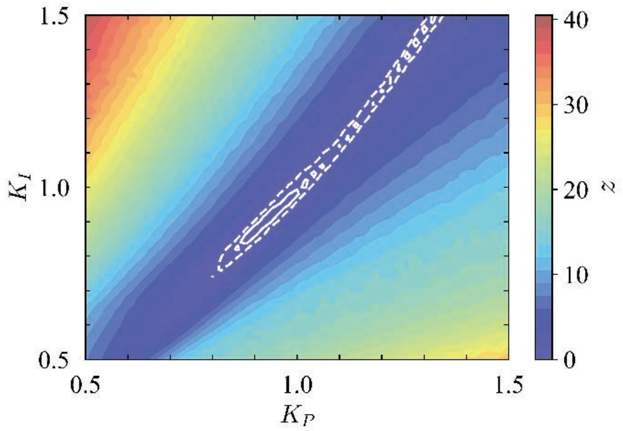
Table 1 Results of PI tuning for test units

Unit no.	(K_P, K_I)	T_r (ms)	Q_{os} (%)	n
1	(0.91, 0.88)	82	0.214	2
2	(0.94, 0.94)	86	−0.061	0
3	(0.97, 0.91)	86	−0.165	1
4	(0.90, 0.86)	84	−0.161	4
5	(0.90, 0.85)	88	−0.228	4
6	(0.93, 0.89)	84	−0.118	1
7	(0.99, 0.98)	84	−0.174	1

The required iterations were different depending on individual units as n = 0-4. To consider the difference, we investigated z-distributions of units with the minimum (no.2) and maximum (no.4) iterations, as shown in Figure 6. Both units indicated similar distributions to the standard unit's distribution having the necessary and sufficient regions around $K_P \approx K_I$. Thus, the assumption that a test unit's z-distribution can be approximately overlapped by simply shifting the standard unit's one in x-direction was appropriate. As the location and area of necessary and sufficient region in no. 4 differed more from those of the standard unit's distribution compared to no. 2, no. 4 unit required more iterations than no. 2. However, the differences were small enough to be compensated by repeating the cycle of the direct inverse analysis and x-direction shift. As the PI gains likely to realize the target waveform are set repeatedly, we can achieve the target with a few iterations.



Unit no. 2



Unit no. 4

Figure 6 Comparison of distributions of the deviation index z (See Eq. (3))

5. CONCLUSION

The method for PI gain tuning using the GMM and the direct inverse analysis applicable to pressure-based MFCs' production are proposed. We applied the method to seven test units. The result showed that the gains of all the test units were tuned within only a few iterations. As this method can efficiently find the optimal gains that are located at a narrow region in the K_P - K_I plane, it is promising for the mass production of the pressure-based MFC whose control target is significantly complicated. We believe this method can simplify the manufacturing process for the complicated pressure-based MFC and contribute its stable delivery.

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

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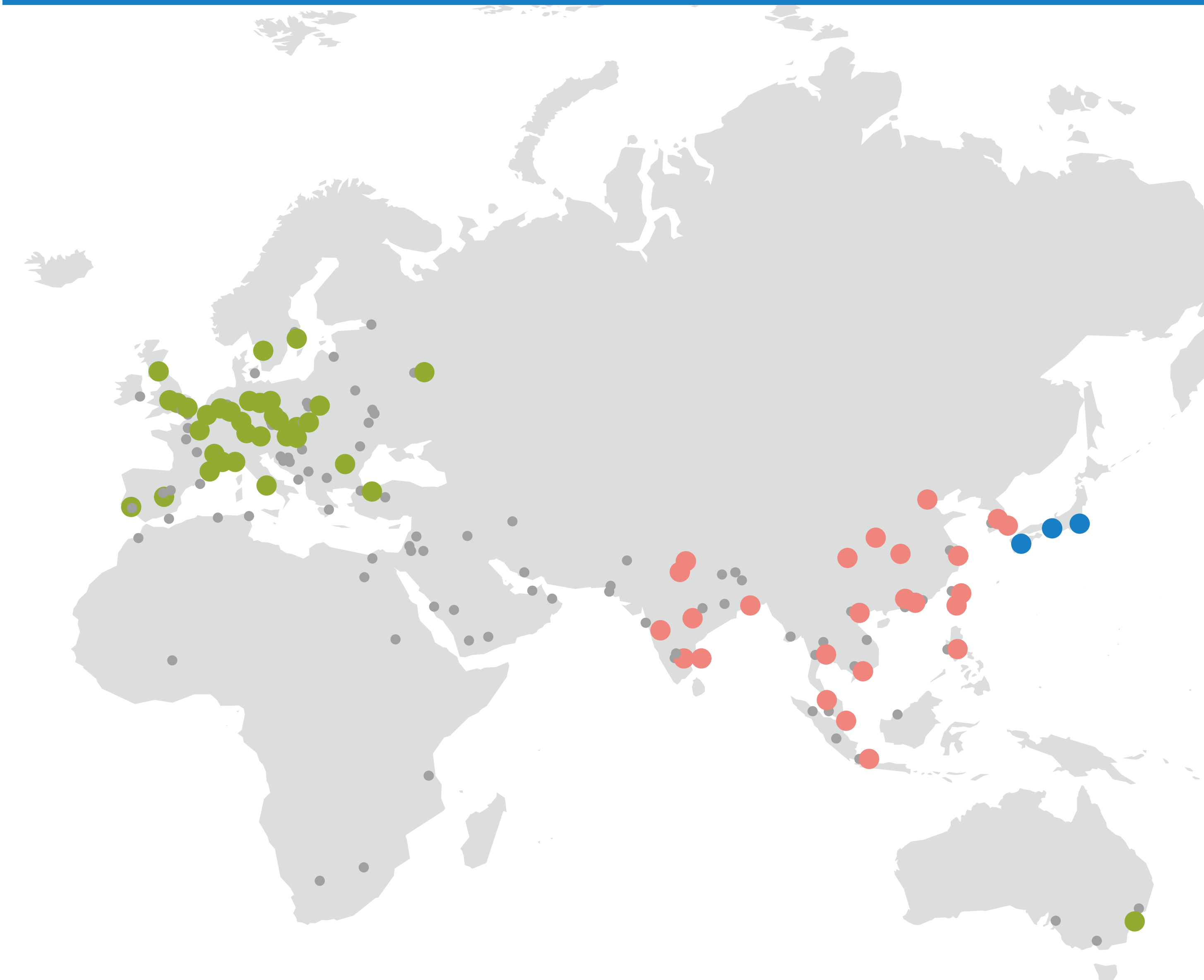

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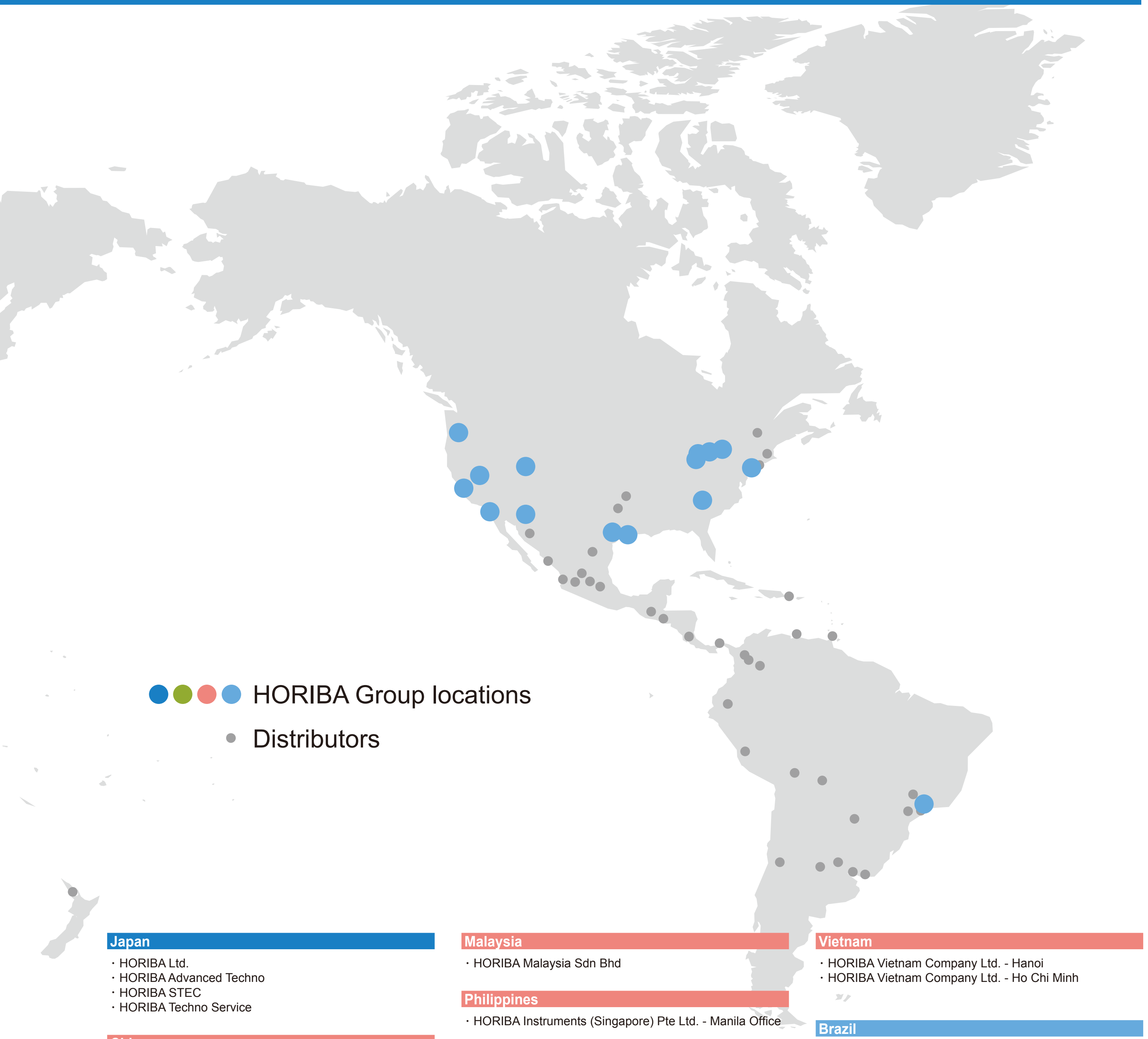

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Readout HORIBA Technical Reports English Edition No.60

Publication Date : April 30th, 2026
Publisher : HORIBA, Ltd.
Editor : NAKAMURA Hiroshi
Associate Editor : HAYASHI Susumu
Publication Members : URAKAMI Chikako, MATSUDA Tetsuya, HAMAGAMI Ikuko
SATAKE Hiromi, MISUMI Akihiro, SHIROSAKI Akari
DTP, Printing : SHASHIN KAGAKU Co., Ltd.
Information : R&D Planning Center, R&D Division, HORIBA, Ltd.
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