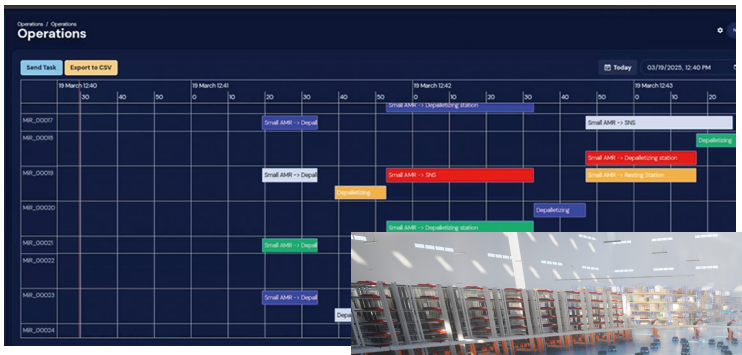
A Platform for Implementing Operational Technology Across Diverse IHI Group Sites

Development of RMF 2.0, a software framework for fleet control of robots and automated equipment

IHI is developing RMF 2.0, an open-source framework for integrated management of multiple robots and equipment, to accelerate automation at manufacturing and logistics sites. By improving work efficiency, reducing human workloads, and enabling flexible process changes, this framework is expected to serve as a foundational technology supporting digital transformation (DX) in the industrial sector through operational technology (OT).



Optimized scheduling of robot tasks



Image capture of a digital simulation video

Simulation of the fleet control system under development

Social background and the need for automation

In recent years, developed countries including Japan have faced a serious social challenge: a shrinking workforce caused by rapid population aging and declining birthrates. In Japan's manufacturing and logistics sectors, securing personnel for on-site operations is becoming increasingly difficult, raising concerns about operational continuity and maintaining productivity. Under these circumstances, process automation using robotic technologies has been advancing rapidly.

Traditionally, automation in factories and warehouses was primarily limited to partial automation using a single robot or piece of equipment. As a result, automated and non-automated machinery and equipment coexisted, making it difficult to change the configuration once the production or conveying lines were established. Nevertheless, this seldom posed a significant issue due to the infrequent need for

modifications. Recently, however, the growing demand from e-commerce and the diversification of consumer preferences have increased supply and demand fluctuations in logistics operations, while manufacturing sites are experiencing an increasing need for variable-mix, variable-volume production. Therefore, there is a growing need to build flexibly reconfigurable production and conveying lines using minimal stationary equipment. In these new factories and warehouses, the following three perspectives must be realized:

- Scalability: Ability to handle changes in scale
- Flexibility: Ability to efficiently change handled items and processes
- Availability: Uninterrupted overall operation in the event of partial equipment failure

Technical challenges in advanced automation and the evolution of OT

To meet the above three, companies are developing technologies for fleet control and system-level integrated automation, which combine multiple robots and diverse equipment to achieve overall operational optimization through collaboration and integration. However, such advanced process automation faces the following challenges:

- Difficulty in accurately assessing the capabilities and constraints of individual robots and equipment to determine an optimal combination
- Limited maturity of methods for predicting and evaluating overall system productivity and efficiency in advance
- Limited means of verifying the feasibility of recovery scenarios when troubles occur
- Complex coordination among devices from different manufacturers due to non-standardized support frameworks and communication specifications
- Necessity of preparing the operational environment and establishing close integration with IT infrastructure during system deployment

In addition to conventional partial automation, the need for integrated automation has been growing in recent years. Technologies for operating and controlling interconnected machinery and equipment in an automated manner have recently come to be referred to as operational technology (OT), as opposed to IT.

Conventionally, OT has been utilized in the manufacturing and infrastructure sectors as part of operational know-how and electrical control technologies to optimize individual operations. However, recent advances in IT, AI technology, and robotics have evolved OT into an integrated foundational technology that enables more flexible and advanced collaborative operations.

This evolution of OT enables operational optimization such as:

- Achieving precise takt times (the target time required to maintain a constant production rate) and synchronized control between processes in factories
- Improving the efficiency in warehouse receiving and shipping operations and reducing shipping lead times
- Optimizing resource allocation and increasing utilization rates through the collaboration of multiple robots
- Executing autonomous recovery scenarios and ensuring operational continuity in the event of failures

Open-source technology and IHI's approach

Currently, OT-related technologies are developed not only by companies that own factories and warehouses, but also frequently by major equipment manufacturers and system integrators responsible for designing production lines. In many cases, these technologies are built on each company's proprietary platform, posing challenges to achieving versatility and interoperability.

On the other hand, recent years have seen the development of open-source middleware aiming to make robot-to-robot collaboration available to anyone. A representative example is the robot operating system (ROS), which is widely used globally for robot development. In particular, the robotics middleware framework (RMF) — software designed to optimize the operation of multiple mobile robots — is attracting attention as open-source software (OSS) capable of communicating not only with mobile robots but also with facilities such as automatic doors and elevators, as well as stationary machinery such as manipulators.

The IHI Group's products, along with the manufacturing and logistics operations of its customers, span a wide range of domains, including land, sea, air, and space. This diversity demands highly versatile OT that is independent of specific products and manufacturer platforms.

In response, IHI focused on the potential of RMF, and in 2023 began joint development of the technology with the ROS-Industrial Consortium Asia Pacific (ROS-I AP)(†1), a consortium based at the A*STAR Advanced Remanufacturing and Technology Centre (ARTC) in Singapore, which promotes the industrial application of ROS and is engaged in the development of RMF. The development target is "RMF 2.0," a new software framework for the integrated management and control of warehouse-wide equipment, including not only mobile robots but also stationary equipment and conveyors. RMF 2.0 extends the capabilities of the conventional RMF and features an architecture capable of supporting more complex and diverse equipment configurations. While OSS development is often perceived as disadvantageous because the invested technology becomes open and freely accessible to anyone, open-sourcing software allows anyone to participate in its development and offers several advantages such as:

(1) Quality improvements, such as bug fixes and vulnerability countermeasures, as well as updates including integration with other software and systems and the addition of new functionalities, can be carried out by the community rather than by a single company.
(2) Widespread adoption can establish the software as a de

facto standard, significantly reducing the need for in-house development resources in the future.

Examples of companies that strategically promote OSS include Google and NVIDIA.

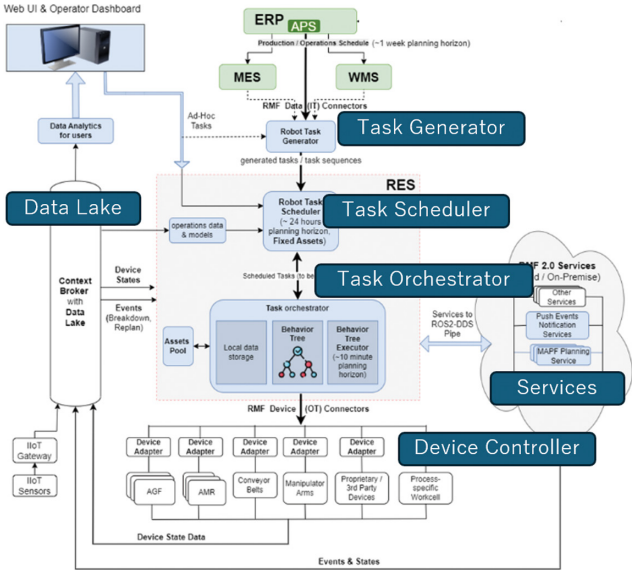
Furthermore, IHI promotes open research and development by participating in leading global ecosystems that bring together world-class researchers and engineers from a wide range of fields. This development is also positioned as one of IHI's initiatives to participate in the ecosystem of the ROS software, which is widely used in the robotics industry.

The following sections introduce the technical architecture and features of RMF 2.0, as well as its anticipated application scenarios.

Technical architecture and features of RMF 2.0

The main components of RMF 2.0 are as follows:

- Task Generator
  Breaks down operational instructions received from higher-level systems and generates individual tasks for each robot and piece of equipment. This process transforms abstract operational instructions into specific executable tasks.
- Task Scheduler
  Optimizes the execution timing of each task while maintaining the task sequence and taking into account the availability of shared resources (robots, equipment, pathways, etc.). This prevents resource contention and improves overall efficiency.
- Task Orchestrator
  Dispatches scheduled tasks to each robot and piece of equipment while taking into account task dependencies, execution order, and progress. In the event of task delays or incomplete execution, this component dynamically adjusts execution timing to maintain workflow coherence.
- Device Controller
  Controls each robot and piece of equipment according to instructions from the Task Orchestrator. When multiple autonomous mobile robots (AMRs) are deployed, this component can select a specific robot and assign work to it.
- Data Lake
  Centrally collects and stores sensor data from the field as well as robot status information.
- Services
  Provide the components, including the Task Orchestrator and Task Scheduler, with support functions for mobile robots, such as map information, traffic congestion status, and charging plans, according to the operating environment. This enables flexible responses to on-site operating conditions.
- Broker
  Converts and relays communications between components that use different communication protocols, facilitating integration with various software systems.



RMF 2.0 system configuration diagram

- Simulator
  Simulates environments in which more than 100 robots operate simultaneously and evaluates factors such as process feasibility, motion interference, and estimated execution times in advance. This enables feasibility verification and efficiency prediction prior to deployment.

The open-source version of RMF 2.0 has been partially released by ROS-I AP under the name of RMF Industrial(†2), and is currently under preparation for the full release in the near future. Although this framework was originally developed for automated warehouse systems, it is expected to be applied not only in logistics but also in a wide range of fields, including manufacturing and automation in specialized environments.

As the development of RMF 2.0 is ongoing, the allocation of functions among components may change and new components may be added. Therefore, the components described above represent only the current architecture and are subject to change.

Expected application scenarios for RMF 2.0

The application of RMF 2.0 is being considered for the on-site use cases shown in the following table.

As an open-source framework for the integrated management and control of multiple robots and equipment, RMF 2.0 has the potential to significantly advance process automation. It is expected to find applications in a wide range of fields, including logistics warehouses, manufacturing sites, and operations in special environments, and is anticipated to become a standard technology supporting future industrial infrastructure.

However, the following technical and operational challenges remain for the real-world implementation of RMF 2.0:

Usage scenario	Applications	Key functions and benefits of RMF 2.0
Robotic warehouse systems in logistics centers	Transport, cargo handling, storage, inspection, and packing change	- Process synchronization and resource allocation of receiving/shipping operations - Automation of workflows including inspection and packing change - Optimal route control of mobile robots including congestion avoidance and charging plans Benefits: Improved operational efficiency, reduced shipping lead times, reduced human workload
Process optimization in smart factories	Processing, assembling, inspection, and transport	- Task coordination among equipment and dynamic scheduling - Process reconfiguration and resource reallocation based on production plans - Autonomous recovery and process continuity assurance in the event of anomalies - Achieving both safety and efficiency in collaborative operations with workers - Applicable to outdoor environments such as construction sites Benefits: Enable flexible support to variable-mix, variable-volume production and enhanced competitiveness
Automation support in special environments such as decommissioning operations	Remote operations (cutting, transport, and inspection)	- Integrated control of collaborative operations performed by multiple robots (such as cutting, transport, and inspection) - Pre-verification and risk assessment using simulators Benefits: Achieving both safety and efficiency, and ensuring planned execution of operations
Automation of large-scale transport operations across land, sea, air, and space	Transport and cargo handling	- Automation and optimization of transport operations using multiple mobile robots, including trailers, drones, unmanned underwater vehicles (UUVs), and unmanned surface vehicles (USVs), across a wide range of environments and applications - Cargo handling operations such as unloading can also be automated through integration with equipment Benefits: Improved safety and efficiency, and reduced human workload

Expected application scenarios for RMF 2.0

(1) Standardizing interfaces among diverse equipment
(2) Improving scalability and real-time performance
(3) Improving security and reliability
(4) Enhancing user interfaces and operational support
(5) Building an ecosystem and fostering an active community

Regarding items (1) and (3), standardization efforts are underway within each industry, and future activities are expected to align with these efforts. For item (2), possible solutions include separating centralized and local control, increasing robot autonomy, and partially incorporating elements of distributed control. Item (4) is likely to be addressed through the individual efforts of each company. Regardless of the challenges, however, RMF 2.0 is expected to continue evolving as an open framework through contributions of engineers worldwide, centered on the community described in item (5). IHI also plans to contribute to these activities.

Future outlook

RMF 2.0 is expected to play an essential role as a foundational technology for process automation, supporting digital transformation (DX) across industry. Toward building next-generation smart infrastructure, we will continue development with the aim of overcoming technical challenges and achieving deployment in real operational environments.

†1 : ROS-Industrial Consortium Asia Pacific (ROS-I AP) is the Asia-Pacific organization of the global Robot Operating System Industrial (ROS-I) initiative and is operated by the Advanced Remanufacturing and Technology Centre (ARTC), which is under the Agency for Science, Technology, and Research (A*STAR), Singapore.

†2 : RMF Industrial : https://www.rmf-industrial.org/