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KAWASAKI TECHNICAL REVIEW

Special Issue on DX × MONODZUKURI

DX×MONODZUKURI

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Kawasaki Heavy Industries, Ltd.

Best of all worlds–
Workability × Manufacturability × Usability

Manufacturing DX

KAWASAKI TECHNICAL REVIEW

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Acceleration of Innovation in Manufacturing

Hiroshi Nakatani

Representative Director,
Senior Corporate Executive Officer

How do you approach innovation?

We strive to innovate along three axes. The first involves directly providing value to customers. This is what we call "product innovation," which aims to transform the products that we provide to customers, such as by creating new products. In addition, we have recently begun focusing on "solution innovation," which aims to transform the services that we provide to solve the issues that our customers face.

The last axis is "process innovation," which aims to transform work processes, such as design and manufacturing. Through this axis, we strive to accelerate the development of new products and services, which indirectly provide value to customers. Process innovation is often conducted behind the scenes, and the results of these efforts often go unnoticed from the outside, but it plays an important role in supporting companies' sustainable growth.

Tell us about the process innovation initiatives.

Our process innovation initiatives strive to transform business processes across the entire value chain. The basis for this is our company-wide deployment of TQM (Total Quality Management) promotion activities. In addition to instilling our management policies throughout the company as well as creating an environment that facilitates company-wide collaboration towards achieving goals, we are improving management quality by standardizing daily operations and constantly improving them through the PDCA cycle. In the engineering chain, which is part of the development and design process, we are engaging in reforms we call K-DPX (Kawasaki Design Process Transformation) promotion activities, which aim to standardize and sophisticate the development and design processes. In addition, in the supply chain, which is part of the manufacturing process, we continue to promote KPS (Kawasaki Production System), and we have pushed forward with production improvement initiatives that aim to reduce workloads and cut down on in-process inventory.

Recently, the scale of the global market has been expanding due to the development of emerging markets, and the market environment has changed significantly. There is an urgent need to accelerate innovation activities to maintain our competitive edge.

How do you plan to accelerate process innovation?

As part of our DX (Digital Transformation) strategy, we are promoting the areas of “DX for customers, “DX for businesses,” and “DX for employees.” Among these, in the domain of “DX for businesses,” we are working to accelerate process innovation by actively employing digital technology. By doing so, we aim to streamline the value chain, optimize the overall process, and enhance individual work processes.

With regard to manufacturing at production sites, by introducing digital technologies such as various sensors and electronic tags, robots and automated equipment, AI for processing big data, the implementation of CPS (Cyber Physical System) that optimizes all processes in real time, high-speed networks (local 5G, etc.), cloud systems, and visualization using XR technology, we aim to develop technologies that enable us to iterate the PDCA cycle of conventional on-site improvement activities in a way that is accurate, fast, and visible. Through these efforts, we endeavor to optimize operations throughout the entire supply chain, including at our factories; to dramatically improve productivity by introducing innovative production methods; and to realize a working environment where people from all backgrounds can work comfortably.

Closing comments

We have established Group Vision 2030 as our goal for 2030, and we aim to contribute to the global market by providing solutions to issues that society will face. As part of our efforts to do so, we aim to achieve process innovation in manufacturing by utilizing digital technology, thereby revolutionizing manufacturing.

Manufacturing Innovation with Digital Transformation

Hironobu Urabe
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General Manager of the DX Strategy Division

Yuji Horiuchi
Executive Officer,
Group Manager of the Process Engineering Center, Corporate Technology Division

Introduction

It has been said that around 2010, we entered the new era of VUCA (Volatility, Uncertainty, Complexity, and Ambiguity), in which the future is uncertain and cannot be forecast. In the energy and environmental field, for example, the shift toward decarbonization is accelerating more quickly than anticipated. In addition, the COVID-19 pandemic, war, and other disasters have resulted in shortages of fuel, raw materials, and semiconductors and disruptions in logistics, and global supply chains are rapidly becoming unstable.

In such a situation, in order to offer customers valuable products and services, we are required to realize digital transformation (DX) with digital technologies in the field of manufacturing and accelerate our efforts to improve our ability to respond to rabidly changing markets, develop a strong quality assurance system, drastically enhance productivity, and establish a system to ensure compliance with delivery times with combination of the Kawasaki Production System (KPS) and digital technologies.

At the same time, we must develop a working environment befitting of this new era to address challenges, including labor shortages due to the aging population and the transfer of skills to the next generation, and realize innovation through research and development, including provision of new solutions with our manufacturing know-how for solving customers' problems in this complex era.

1 Our efforts toward DX (digital transformation)

We formulated our Group Vision 2030 and announced that we would work valiantly to solve social issues. This Vision aims to offer innovative solutions to social issues, such as global warming and the declining workforce, in a timely manner and to realize a more affluent society. To this end, the Vision refers to our intention to speedily provide social value beyond various borders from a "market-in" perspective.

This requires that we dramatically change our business style and the processes that support it. Kawasaki DX is one of our activities to do so. With the power of digitization, we are working hard on Kawasaki DX in order to shift our business model to focus more on market-in and speed as well as to realize process innovation.

By focusing on three areas, namely "DX for customers," "DX for business," and "DX for employees," Kawasaki DX aims to create new customer value, to shift our business model from offering products and services to offering experiences and value, to strengthen our business foundation's agility, and to change the way our employees work. Also, we are making efforts to strengthen our cybersecurity system and to safeguard privacy so as to promote safe and secure use of digital technology.

2 Our efforts thus far in manufacturing

Our production improvement activities on the shop floor began in the late 1970s when we introduced a new production system based on the TPS (Toyota Production System) into our manufacturing departments for mass-production products, including motorcycles and hydraulic equipment. We subsequently improved this system so that it can be applied to build-to-order products, such as aircraft and ships, and expanded its application to every product, regardless of production volume, lead time, and order type. This production system, called KPS, is our company's standard and embodies our manufacturing principles.

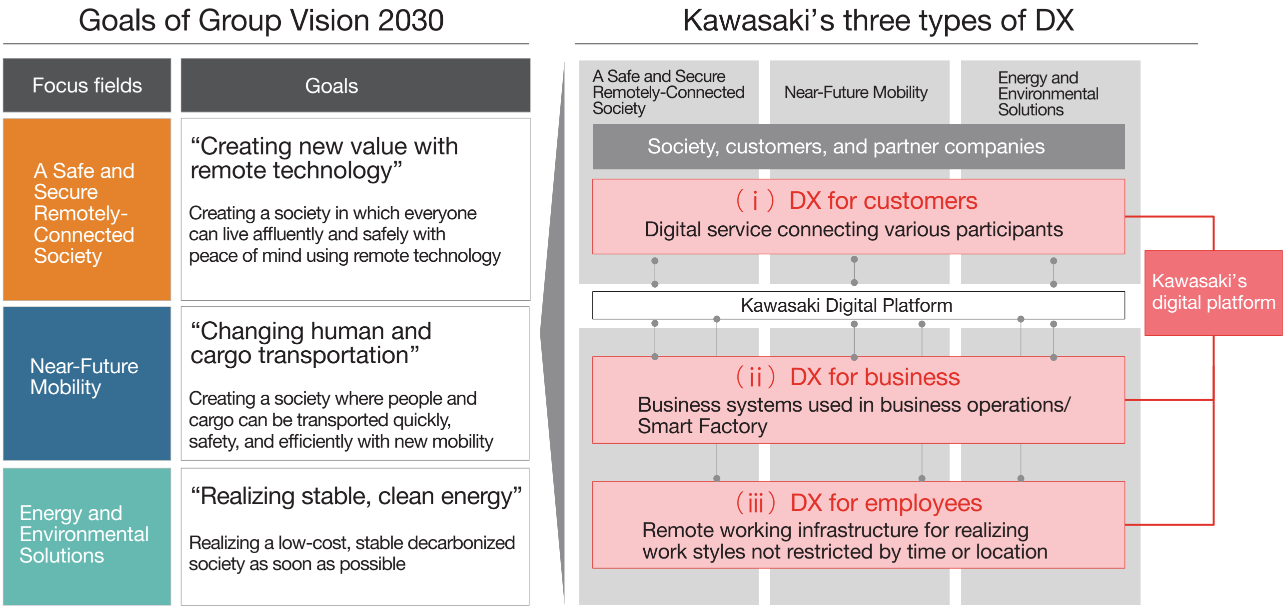


Fig. 1 Overall image of Kawasaki's DX strategy

In KPS, one important point regarding shop floor management is to visualize the actual situation and to iterate the improvement cycle. Here, visualizing refers to standardizing work and assessing differences between the plan and actual results. This clarifies which points should be improved. An important thing in KPS's shop floor management is to implement the PDCA improvement cycle, starting at the identified improvement point, in order to evolve our factories day by day.

In line with the progress of digital technology, since around 2000, we have been actively adopting new technologies to iterate the PDCA improvement cycle more accurately, speedily, and visibly within KPS. For example, we use a visual work instruction system that features monitors to prevent operational errors and transfer work skills to the next generation. In addition, we use a work result collection system that employs barcodes to assess the shop floor concisely and accurately in real-time and to analyze differences between the plan and actual results. However, thus far our utilization of digital technology has focused on streamlining improvement activities on the shop floor, the results of which have often been merely partial optimization of individual workplaces.

3 Manufacturing innovation with DX (digital transformation)

"DX for business," one of the Kawasaki DX activities, aims to reform engineering, manufacturing, and other work processes in the value chain with digital technology as well as to streamline and sophisticate them to maximize customer value and then to utilize the collected digital data to provide experiences and value. As part of such efforts, we are promoting "cross-divisional digitalization," which is intended to rectify connections between work processes in order to optimize the entire value chain, and "divisional digitalization," which is intended to sophisticate operations in individual work processes in order to create new value.

(1) Cross-divisional digitalization

"Cross-sectional" refers to digitalizing information throughout the entire value chain, across different work processes from sales and order acceptance to development and design, procurement and manufacturing, and maintenance and servicing. This enables information to be shared without human intervention and is aimed at eliminating communication of unnecessary information and information stagnation while facilitating prompt, accurate, efficient collaboration towards the rectification and overall optimization of the value chain.

As an initiative to improve development and design processes with advanced digital technology, we have launched the K-DPX (Kawasaki Design Process Transformation) activity. With K-DPX and KPS, all stages can be connected seamlessly, from the engineering chain, including product development, production preparations, and production, to the supply chain.

In an effort to build a foundation for promoting DX, we are improving manufacturing-related work processes throughout the entire group, enhancing work quality, and promoting streamlining of work by viewing the entire value chain, including the engineering chain and supply chain, in

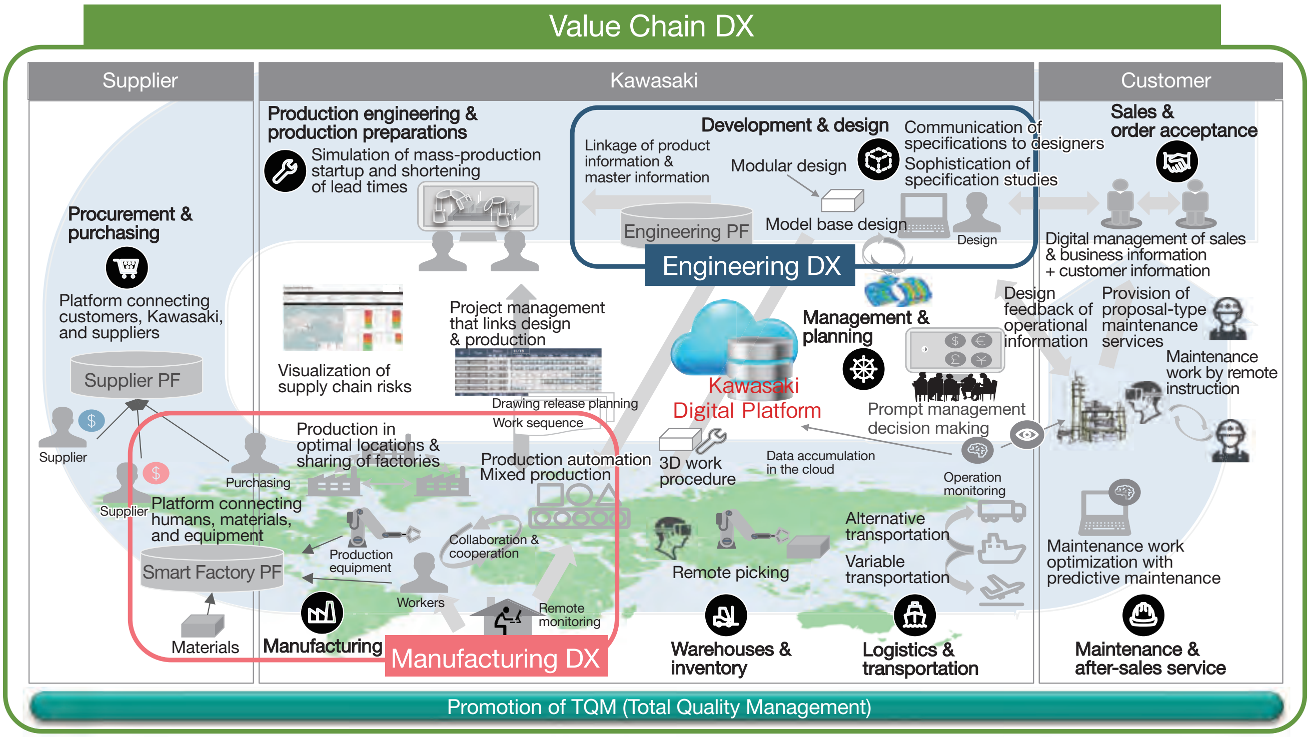


Fig. 2 DX for business

a cross-divisional manner through TQM (Total Quality Management) activities, thereby developing a strong corporate culture through which we can respond to the changing business environment.

Toward manufacturing DX, with the aim of optimizing the operation of entire factories using AI (artificial intelligence) and data analysis techniques, we are working to digitalize the information in each process, including design, process design, and production planning.

(2) Divisional digitalization

"Divisional digitalization" refers to using digital technologies to deepen individual work processes in the value chain. In the development and design process, we precisely verify design models in virtual spaces with high-precision simulation technology to shorten development time and to develop high quality products. In the maintenance and servicing process, we remotely monitor the operation of delivered products to prevent failures and to support optimal operation.

As an effort toward manufacturing DX, we are developing new ways of manufacturing and working. With respect to new ways of manufacturing, we are working to improve assembly times and quality using XR (Extended Reality) technology, which renders digital information into something that can actually be seen. Also, we are using AI technology for analyzing camera images and robot technology to automate and/or mechanize visual inspections in inspection processes, which are currently done by people.

As for new ways of working, we are using XR technology and robot remote control technology to develop an environment in which diverse people can work without being constrained by time or location.

Also, with regard to manufacturing going forward, we are making use of data science, including machine learning, in development and designing. We are actively working on materials informatics to efficiently predict and discover new materials and devices, process informatics to efficiently create the materials and devices, and generative design to generate optimal product designs.

4 Optimization of factory operations (Smart Factory)

Many of our factories are of the high-mix, low-volume production type, being job-shop factories where the production volume of each product is low and where parts of various types are machined and assembled in a limited amount of space. These factories play host to an enormous number of processes in which materials, parts, and products move in a complex way. The automation rate is still low, and production machines and people work side by side. In addition, when trouble or design changes occur, they have been addressed on-site, relying on communication between people.

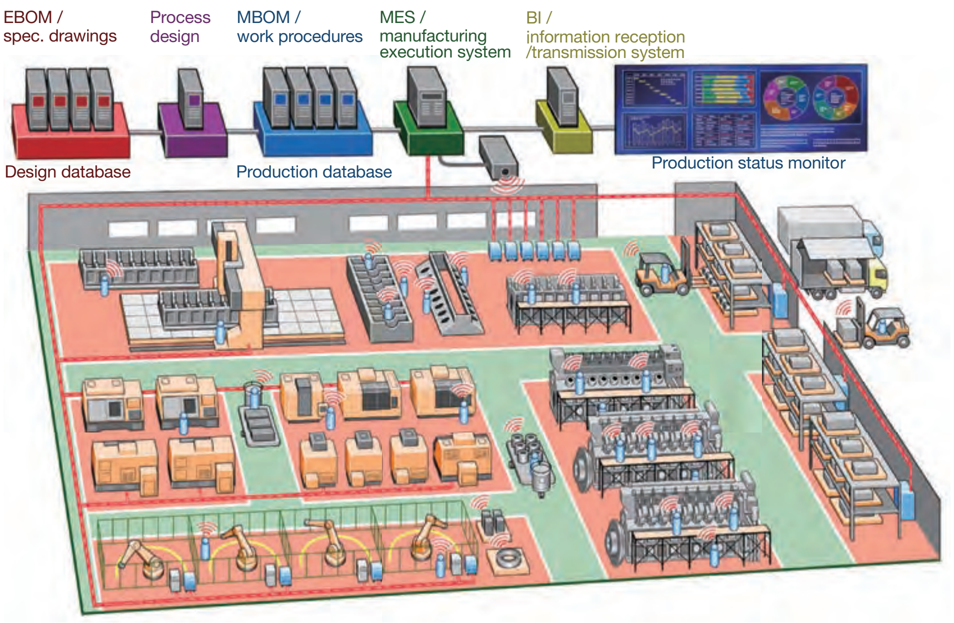


Fig. 3 Smart Factory

In such job-shop factories, our goal is to digitalize and link every piece of data and to operate the factory based on the principles of KPS's shop floor management with the minimum resources and the shortest cycle. To this end, we will set up a core system ERP (Enterprise Resource Planning) for making production plans and operating the entire factory, and based on such production plans, issue work instructions from the MES (Manufacturing Execution System) to each process. We will then collect the work results and indicate these results as KPIs (Key Performance Indicators).

In addition, we are working to create measures to improve the PDCA (Plan-Do-Check-Act) cycle through optimization computation methods, including genetic algorithms, and AI, such as deep learning and machine learning. For example, we are developing a system that determines the order in which products are fed into the final assembly line with optimization computation using genetic algorithms and AI. Moreover, we are developing a system that uses AI for analyzing camera images to monitor whether work is being done safely and whether work standards are being observed.

To realize Smart Factories, we thus aim to accurately, speedily, and visibly carry out all of KPS's PDCA improvement cycle activities, including everything from planning to instruction and recording, analysis, and improvement, with digital technology.

5 New ways of manufacturing

As for new ways of manufacturing, we are using XR technology to improve assembly times and quality. XR technology is a generic term for technologies to realize "Extended Reality," which include VR (Virtual Reality), AR (Augmented Reality), and MR (Mixed Reality) technologies.

VR technology enables people to work virtually without an actual product or workspace, and is used, for example, to train inexperienced workers or workers who are to engage in dangerous work prior to that work. AR technology enables workers to check work procedures and drawings during work without looking away or changing their body positions. MR technology, as typified by Microsoft's HoloLens, provides concrete visual representations of work procedures, including work positions, tools, and actions, which empowers even inexperienced workers to ensure a certain level of quality while observing work standards.

In addition to the use of these technologies, we are utilizing technology for analyzing camera images with AI and robot technology to automate and/or mechanize visual inspections in inspection processes, which are currently done by people.

6 New ways of working

As for new ways of working, with the aim of realizing a society in which everyone can work productively under humane conditions, we are working to promote remote manufacturing with remote control in order to develop an environment in which diverse people can work without being constrained by time or location.

To this end, in addition to developing remote-controlled

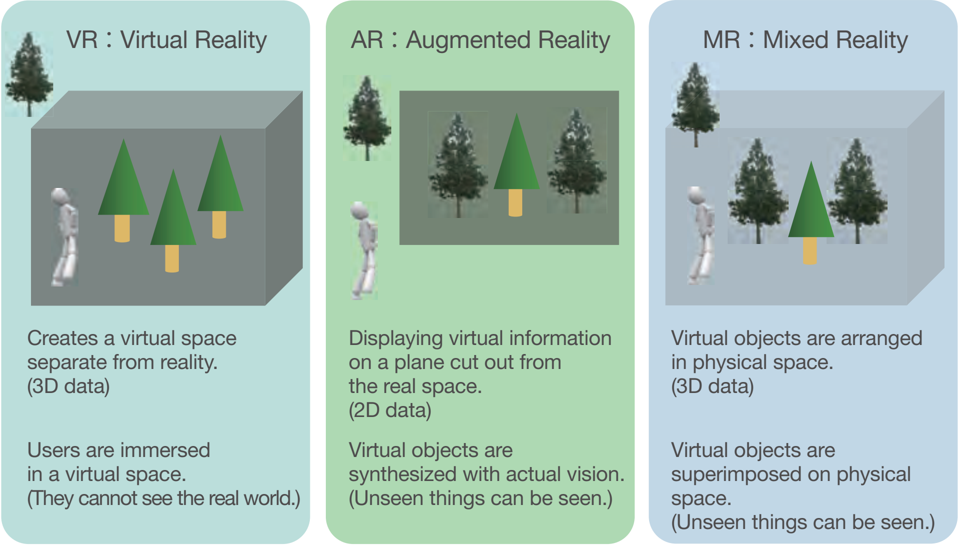


Fig. 4 XR (VR/AR/MR) technologies

robots, we are evaluating high-speed wireless communication technologies, particularly private 5G technology, as key digital technologies. Private 5G enables us to flexibly and efficiently build networks in factories.

Private 5G has three basic performance characteristics: high speeds with high capacity, ultra-low latency, and massive connected devices. These features can be customized to meet the user's needs, and effective use of private 5G on the shop floor is expected to improve productivity.

We will proactively adopt private 5G in factories. This will enable us to carry out various tasks with wireless remote control, which is effective for addressing labor shortages due to the declining population; for improving the working environment, and for transferring experienced workers' skills to the next generation. In addition, we will promote "Remote Factory" by implementing remote working, which has become a common practice during the COVID-19 pandemic, on the shop floor.

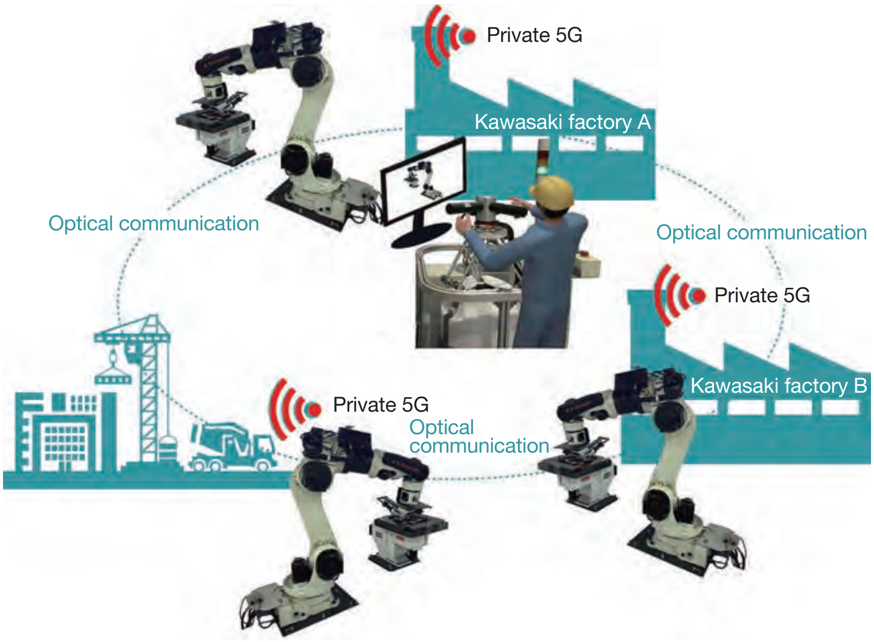


Fig. 5 Utilization of private 5G for remote control

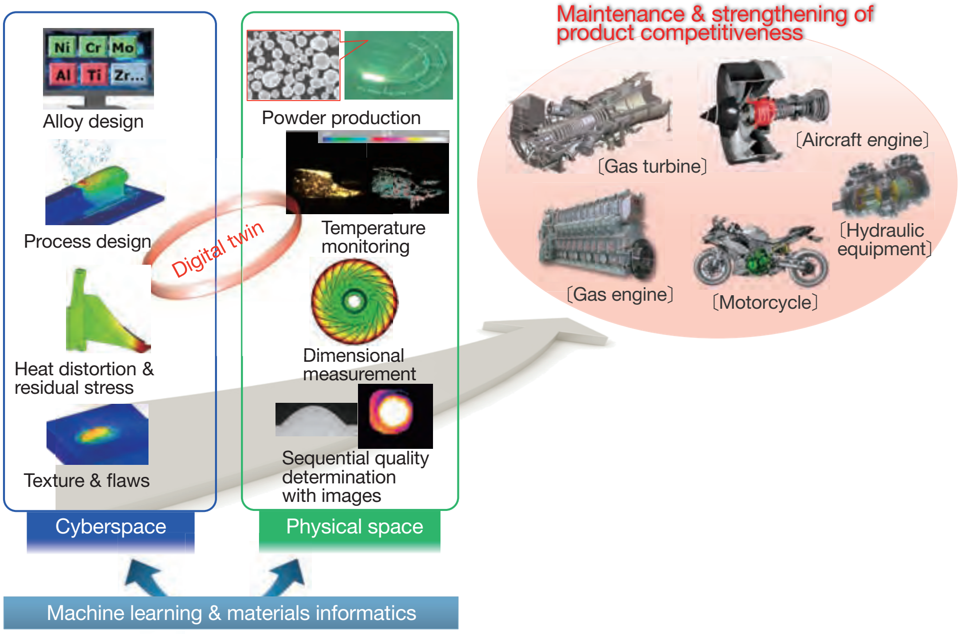


Fig. 6 Enhancement of products' added value

7 The future of manufacturing

We aim to develop a new manufacturing workflow that incorporates information science to optimize performance and manufacturing in the initial stage of development by applying digital twin technology, which will enable reproducing a series of verifications from design to manufacturing in cyberspace.

AM (Additive Manufacturing) technology, which is a manufacturing method by which a material is stacked in layers (as typified by 3D printers) to form a shape, has advanced remarkably, and efforts are underway to put this technology to practical use mainly in Europe and the USA. AM technology allows for more flexible design than conventional manufacturing methods, and in addition, has high affinity with today's digitalization, suggesting high potential for significantly streamlining design and manufacturing processes (in terms of cost, lead times, and energy use). Thus, we believe that developing "Design for AM," a design methodology for additive manufacturing, and promoting materials informatics, including new alloy design and material development, will lead to enhancing our products' added value.

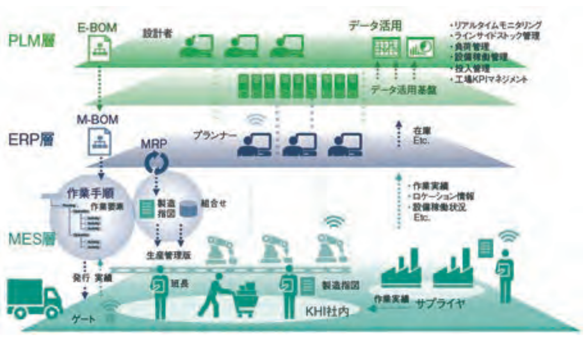
Through these efforts, we will sophisticate our production engineering development and develop new materials, reform our design and manufacturing processes, and enhance our products' added value, thereby contributing to maintaining and strengthening our competitiveness in the global market.

Conclusion

Thus far, we have engaged in manufacturing based on KPS, our unique production system. We are now promoting Kawasaki DX to actively utilize digital technologies throughout the company.

In the field of manufacturing, we will combine the techniques and innovations of KPS that we have accumulated over our long history with the power of digital technologies of DX, including AI, in order to deepen KPS in a revolutionary way and to develop a corporate culture that has diverse values and a sense of speed, thereby giving shape to our slogan "Changing forward."

Smart-K Enables Digital Integration of Information from Design to the Shop Floor



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In aircraft manufacturing, it is necessary to control an enormous number of parts based on strict quality standards. Until now, different pieces of information have been connected by paper and human labor to assure quality. Going forward, we are required to further enhance productivity while meeting strict quality requirements. Under such circumstances, we have successfully digitalized our work processes through digital transformation (DX), thereby achieving both quality assurance and productivity enhancement.

Introduction

Aircraft demand slowed temporarily due to the COVID-19 pandemic, but over the medium- and long-term, it is forecast to recover and surpass the pre-COVID-19 level [1)].

1 Background

Aircraft require large-scale, complex manufacturing processes, but their operation long relies on human labor and paper. Digital transformation (DX) of factories is required to manufacture aircraft more efficiently with higher quality, as there are limits as to what can be done with conventional work processes that rely on human labor and paper.

2 Characteristics of aircraft manufacturing

The characteristics of aircraft manufacturing include a "characteristic body structure," "high-mix, low-volume production," and "strict quality requirements." Above all, an aircraft is a large structure that consists of over three million parts. To complete an aircraft, aluminum, titanium, carbon fiber reinforced plastic (CFRP), and various other materials are used in the appropriate locations after undergoing various processes, including machining, sheet-metal working, welding, chemical processing, and wiring. Meanwhile, aircraft need to minimize weight. As a result of pursuit of weight saving, many parts that appear the same at a glance have different specifications (custom-made parts), and these are generally manufactured in small lots. Since various products and processes exist, it is difficult to automate production lines and develop dedicated production lines; therefore, the job-shop production system has been adopted, whereby different products go through several hundreds of workplaces inside and outside a company in various routes. Unlike ground transportation vehicles, aircraft cannot stop operating in the air even if they experience trouble. To ensure safety, extremely strict quality requirements are imposed on their manufacturing processes, and certification systems and required specifications unique to aircraft exist, including JIS Q 9100 (Quality management systems–Requirements for aviation, space and defense organizations), which specifies requirements for ISO certification. Aircraft manufacturers must manufacture aircraft in accordance with these standards, ensure that records are kept properly, and promptly disclose such records as needed.

As described above, one difficulty unique to aircraft is that parts of various types that undergo complex processes must be controlled based on strict standards. On a shop floor for aircraft, a large amount of information, including drawings, work instructions, and records, have conventionally been controlled using paper to ensure quality, and it is even said that "Aircraft fly on paper." Millions of pieces of paper represent the accumulation of engineers' know-how and craftsmanship, and preparing various paper documents and connecting one piece of paper to another is an important duty in manufacturing processes. However, product structures are becoming more complex by the year, and an ever higher level of quality control is required. Conventional systems that rely on paper and human labor have nearly reached their limits.

3 Smart-K Project

To overcome this situation, we launched the Smart-K Project. The project's concept is to digitalize all information in the processes from drawing release, process design, production, and results collection, and to connect every work process digitally as shown in **Fig. 1** The project primarily consists of three activities: prompt, proper communication of design requirements; digitalization of work instructions; and aggregation and visualization of all data. The aim is not only to increase the speed and reliability of work through digitalization but also to enhance productivity through effective use of accumulated data.

This project covers operations and workplaces throughout the entire factory and necessitates the establishment of an extremely large system. Therefore, team members were assembled from the design, production engineering, production control, manufacturing, quality assurance, and information system departments in order to organize a new section, and the project was carried out in close collaboration with external partner companies, including Fujitsu Limited and SAP Japan Co., Ltd.

(1) Prompt, proper communication of design requirements

(i) Background

In aircraft manufacturing, tests and auxiliary analyses should be conducted for the individual products to be manufactured in principle, but tests may be simplified or omitted by applying type certification to drawings. It is unrealistic to conduct many tests and analyses for each individual aircraft to be manufactured, so the type certification system can be said to be essential for business continuity. For the type certification system to function, repeatability must be ensured—in other words, one must have the capability to manufacture aircraft as per drawings and standards that have been proven by preliminary tests—and records from manufacturing processes must be controlled appropriately.

Ensuring repeatability requires ensuring that technical information is properly communicated to the shop floor (referred to as the "flow-down of technical information"). In practical work, three processes are necessary. First, design personnel create an engineering bill of materials (E-BOM) and drawings based on the customer's requirements and technical specifications. Next, production engineering personnel incorporate manufacturing specifications into the E-BOM and drawings, and then create a manufacturing bill of materials (M-BOM) and work procedures based on them. Finally, field workers carry out the work according to the work procedures developed by the production engineering personnel. The field workers are also required to properly record all necessary information, such as work results and

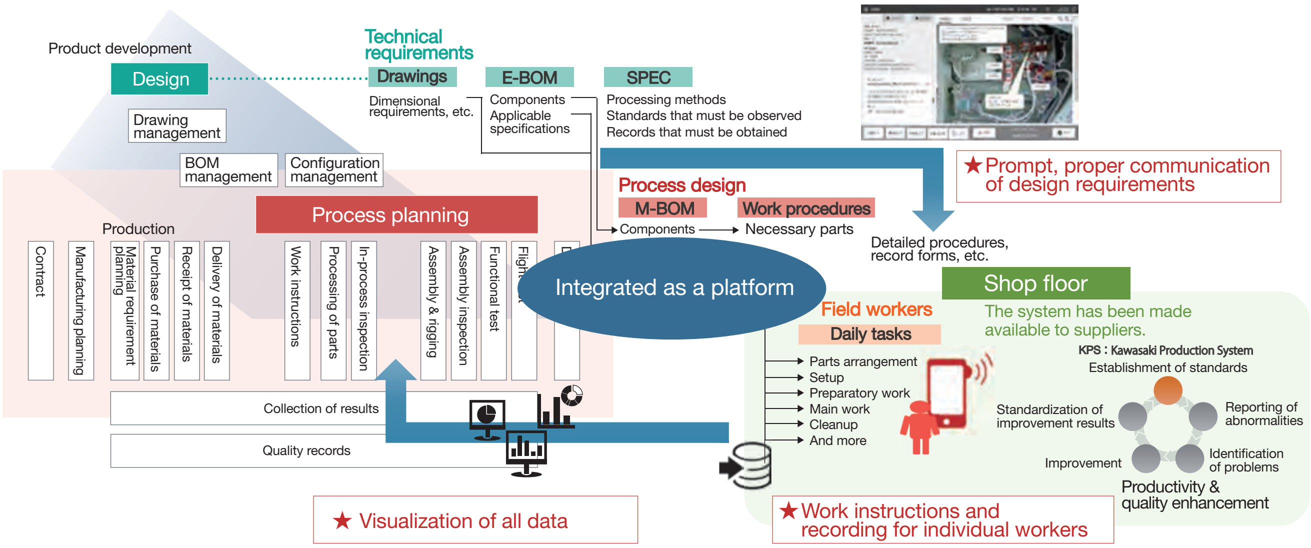

Fig. 1 Concept of Smart-K

the names of the workers in each process. It is essential to store such records as quality records and make them available as needed, or ensure traceability in manufacturing.

(ii) Challenges

As already discussed, aircraft manufacturing involves a large-scale, complex shop floor, and in a factory, several hundreds of thousands of parts are flowing continuously via tens of thousands of routes. Given the enormous number of parts, technical information has flowed down by manually connecting a huge number of pieces of paper, but this incurs a huge amount of labor to reflect changes, such as design changes and process changes, and control information. In addition, though paper ensures traceability, if specific information is required, the desired information must be searched for among a nearly infinite number of pieces of paper, making it difficult to disclosure information speedily.

(iii) Solution policy

To address the above-described situation, in the Smart-K Project, we had the idea of converting paper-based information to digital data in order to handle the enormous amount of information more quickly and reliably. Through this project, we expect to create hundreds of millions of records across a wide range of operations, from drawing release to production. For appropriate data control, we first identified the challenges in our existing work processes and formulated ideal work processes to summarize our requirements. We examined well over 100 work processes. We consulted with the relevant departments, identified the necessary data and operational functions, and developed an integrated platform that can collect every piece of data necessary for operations as shown in **Fig. 2**.

This integrated platform covers many operations and is used by thousands of employees; therefore, it could not be implemented as a single system. Consequently, with the commercially available package SAP S/4HANA Manufacturing for Production Engineering and Operations (PEO) as the core, we organically linked multiple existing systems, including the integrated core business system ERP[2]. Though PEO has a function for maintaining the consistency of manufacturing data, which matches with our goal, when we considered adopting PEO in 2017, it was quite a new solution and had not yet been adopted anywhere in the world. Thus, adopting such a system was a risky and bold move, but we made maximum use of PEO's standard functions to avoid additional development, and we successfully developed a large-scale system in a short time.

In the integrated platform, all data, from drawing release to production, is aggregated and stored, and each piece of data is linked with the others. This enables all technical requirements and change information for several hundreds of thousands of parts to be promptly communicated to the shop floor without omission. In addition, the integrated platform incorporates a unique mechanism for issuing work instructions to the shop floor and collecting results, which is described later. This ensures correspondence between instructions and results and makes it possible to know at a glance when, how, and by whom a product was manufactured. Thus, we

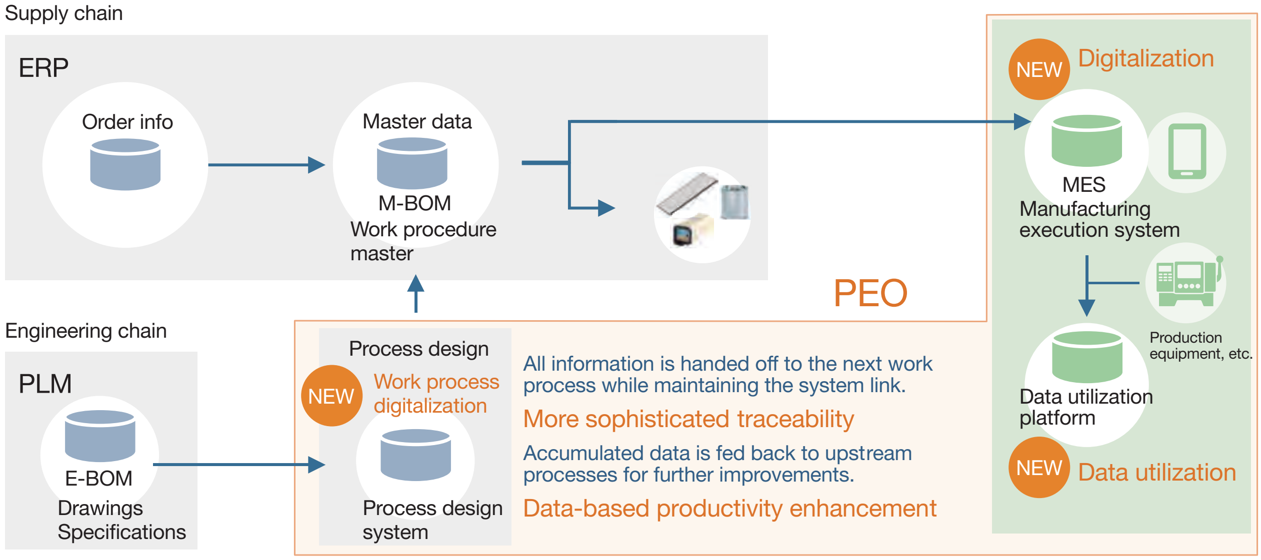

Fig. 2 Integrated platform

strengthened flow-down and traceability of technical information and prepared for future production increases.

(2) Digitalization of work instructions

(i) Background

With our unique production system KPS (Kawasaki Production System), we are improving our shop floor day by day to enhance productivity. Detailed work instructions for individual workers are a representative tool for iterating such an improvement cycle. Such instructions describe every action that workers need to perform in their field work on an element-by-element basis. Work is divided into smaller tasks so that even inexperienced workers can maintain high levels of work efficiency and quality. In addition, using these instructions, information on actual work times is collected, and differences between actual and target work times are analyzed to discover better work methods. The detailed work instructions for individual workers enable us to iterate an improvement cycle such that none of our workplaces are stagnant for even a single day.

(ii) Challenges

The detailed work instructions for individual workers can be said to be an accumulation of the shop floor's manufacturing know-how and our unique competitive strength. However, many of them are used in print form, and it takes a long time to create instructions and collect the results. Therefore, there is a limit to the number of times that the improvement cycle can be iterated. In addition, as previously mentioned, flow-down of technical information is required, but much labor is involved in frequently updating work instructions while maintaining consistency between the work procedures prepared by the production engineering department, which are higher-level instructions, and the detailed work instructions for individual workers. Thus, iterating the improvement cycle while maintaining strict consistency is difficult, so this is a challenge in using the detailed work instructions for individual workers.

(iii) Solution policy

In the Smart-K Project, we digitalized the detailed work instructions for individual workers used at each workplace, thereby reducing the amount of labor necessary to create instructions and collect results. The aforementioned integrated platform includes the function that the detailed work instructions for individual workers have as a manufacturing execution system (MES) in the ERP downstream. This enables people on the shop floor to easily create detailed work instructions for individual workers while maintaining consistency with the work procedures developed in the MES by production engineering personnel. In addition, the detailed work instructions for individual workers are stored in the MES as master data, where they are accumulated and refined as a source of competitive advantage.

The created detailed work instructions for individual workers can be displayed on workers' tablets as shown in **Fig. 3**. Workers can understand their tasks at a glance with

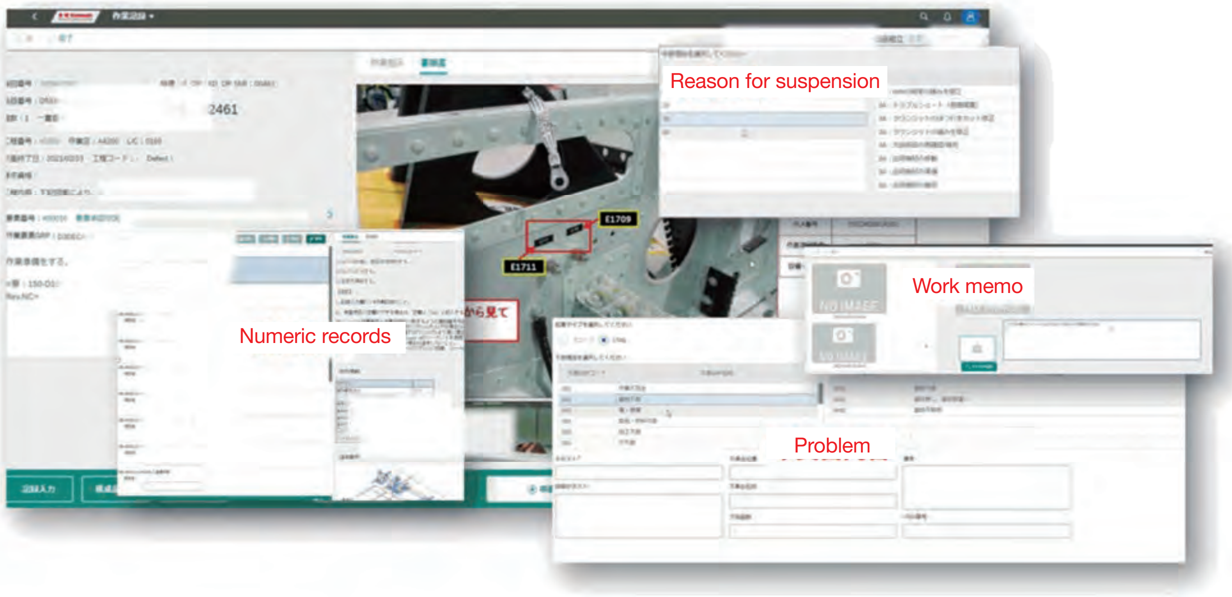

Fig. 3 Detailed work instructions for individual workers

graphics, including photos and drawings, and can browse relevant documents as necessary, enabling them to work without making mistakes. At the same time, results information can easily be collected from the tablets and accumulated on the integrated platform, enabling on-the-spot assessment of work efficiency. In addition, things workers notice and workers' know-how can be recorded with photos and text, which makes it possible to analyze actual work times and things workers notice in an integrated manner, thereby facilitating quicker, deeper improvements.

In this way, we have successfully established conditions under which we can speedily iterate the improvement cycle while maintaining the strict consistency required for aircraft manufacturing.

(3) Aggregation and visualization of all data

(i) Background

Thus far, we have discussed the collection and accumulation of data in factories. To improve quality and productivity, utilization of such accumulated data is important. On the shop floor, a shift is required from subjective decisions that rely on seasoned workers' experience and intuition to objective decisions based on data.

(ii) Challenges

On the aircraft shop floor, there are nearly infinite numbers of people, materials, and equipment, which makes it extremely difficult to accurately understand what is going on in the factory. In addition, generally speaking, data has been collected and analyzed by individual departments, so there are concerns that decisions may be only locally optimal.

(iii) Solution policy

As we have mentioned repeatedly, every piece of data in the factory has been aggregated on the integrated platform and can be accessed at any time. By using such data, we will conduct analyses across different products and departments to make decisions that are optimal overall, which will enable us to obtain ideas for further enhancing the factory's capabilities and noticing new things.

To effectively utilize data, we first visualized the accumulated data. For example, we have already implemented a function for monitoring manufacturing progress in real time, which enables us to know what is happening on the shop floor without going there. We will next expand the scope of visualization, aiming to eventually visualize every production activity. In addition to visualization, we are analyzing data for management. We have established a system to assist management in making decisions by using information obtained from production activities as KPIs (Key Performance Indicators) for factory operation and management as shown in **Fig. 4**. Going forward, we will provide information that contributes to management with the aim of realizing data-driven management.

In addition to analyses and visualization, we plan to provide more active feedback with data—in other words, to control and optimize factories with AI—through which

Fig. 4 Dashboard for management

we aim to reduce lead times and costs as well as to develop factories that are more efficient than those of our competitors.

Conclusion

The Smart-K Project is a digital transformation (DX) activity for large-scale, complex aircraft shop floors. In this project, we developed an integrated platform and solved various challenges, including those related to ensuring quality and enhancing productivity. The system is already in operation for some models, such as BK117 and B787, and we will expand application to other models. Also, we will apply the Smart-K Project's philosophy and best practices to factories for our other products, thereby making our company "smarter."

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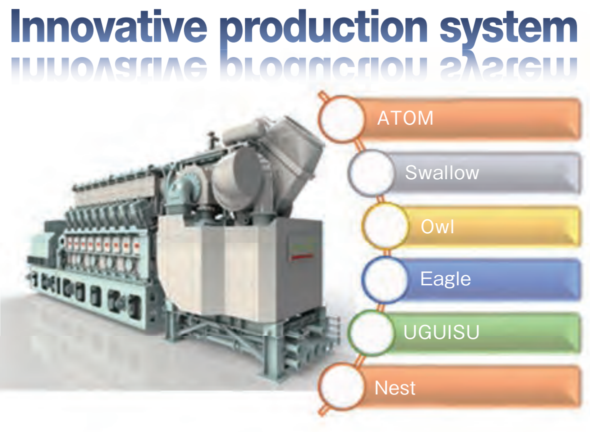
Establishment of an Innovative Production System to Support Flexible Production



In order to gain a competitive advantage in the increasingly competitive global market, we have developed and deployed an innovative production system for supporting high-quality and quick-delivery production aimed at overall optimization, with the combination of the Kawasaki Production System (KPS) and digital technologies. We have established this innovative production system with the aim of realizing Smart Factory, which supports flexible production that enables real-time coordination. Also, we have connected this system with our welding management system so as to make full use of human resources, materials, equipment and information.

Introduction

It is imperative to carry out high-quality, quick-delivery production and to realize cost reductions and profitability improvements while addressing intensifying competition to win orders as well as addressing changes in the management environment and responding to market and customer needs.

1 Background

Establishing an advanced flexible production system that enables real-time coordination by fully utilizing accurate information for manufacturing has become essential. Therefore, we aim to realize an unrivaled Smart Factory by establishing an innovative production system that seamlessly obtains information on human resources, materials, equipment, processes, procedures, and other matters related to manufacturing (big data) and will lead us to optimal production.

(1) KHI's production system (KPS)

We are promoting the Kawasaki Production System (KPS) at all of our sites involved in manufacturing. KPS's basic concept is to improve production efficiency by striving to thoroughly eliminate all waste related to human resources, materials, and equipment, establishing a system that fully utilizes these elements and shortening lead times by realizing just-in-time production, aiming to achieve the ideal vision. In other words, we pursue profits that can be obtained by improving factory controls such as production controls, process controls, and quality controls, and we obtain such unseen profits by improving and innovating in manufacturing. One source of these profits is hidden among muri (unreasonableness), mura (inconsistencies), and muda (waste) in manufacturing. If one can find and eliminate the unreasonableness, inconsistencies, and waste hidden at production sites, one can obtain profits. Unreasonableness refers to interruptions and forcing production sites to do jobs in an unscientific amount of time, which drastically worsens a production site's production efficiency. Inconsistencies refer to variance in quality and man-hours per production run. Reducing such variance produces profits. Lastly, waste refers to losses. At production sites, types of losses include time loss, material loss, and loss caused by failure. Manufacturing that reduces such losses produces profits.

(2) Advancement of digital technologies

In recent years, innovative digital technologies for manufacturing have been developed, such as cloud technology and AI technology. Supply chain management that employs cloud technology makes it possibly to instantly and effortlessly know the positions and statuses of materials. Also, the arrival of material transport equipment that employs AI has opened up possibilities for automatically transporting materials that differ per ordered model.

We have also been developing an electronic production

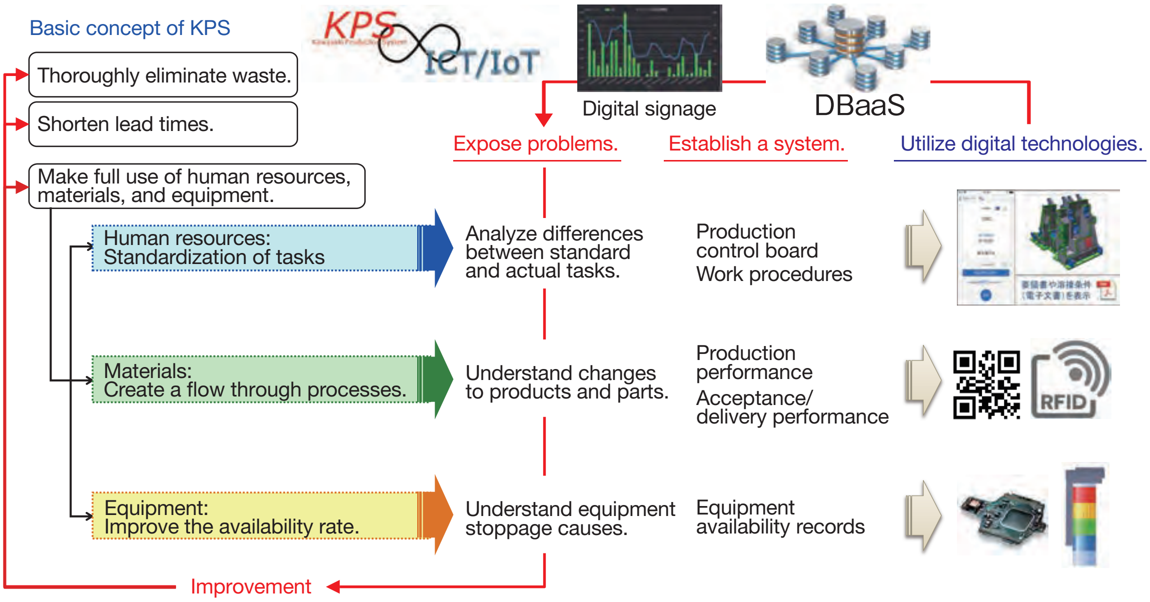


Fig. 1 Integration of KPS and digital technologies

control board, which provides detailed visual instructions for detailed tasks, and other element technologies that enable us to digitalize material IDs as well as digitally measure equipment availability and operations.

(3) Aiming to establish a KHI version of Smart Factory

The KHI version of Smart Factory is realized by integrating KPS with digital technologies as shown in **Fig. 1**.

We are moving forward with the Smart-K Project, which aims to establish a new core system that will play a main role in the production system. To realize it quicker at lower cost, we have decided to develop an innovative production system by adding practical functions to our existing core system.

2 Development policies for the innovative production system

The Energy Solution & Marine Engineering Company performs mixed production of variable types and volumes of six products (naval machinery, turbine, diesel, hydraulic, aerodynamic, and gas engine) at three factories (canning, machinery, and assembly). In the past, the complicated flow of materials was managed by a variety of work instructions at each factory.

To secure a competitive advantage for our products by strengthening our manufacturing capabilities for the future and to enhance lead time optimization aimed at overall optimization as well as a system for fully utilizing human resources, materials, and equipment, in addition to observing delivery dates within factories and to customers, we have decided to improve productivity by promoting KPS in individual build-to-order manufacturing and sophisticating factory management using digital technologies in cooperation and collaboration with Energy Solution & Marine Engineering Company.

Promoting KPS has enabled us to improve and innovate in manufacturing very quickly. To keep up, we needed to speed up the addition of functions to and release of applications. To address such needs, we proactively assimilated the development concepts of agile development, which quickly repeats the cycle of development, release, and improvement, and of a microservice architecture, which enables efficient development of individual functions of complicated applications.

3 Development items for the innovative production system

The innovative production system is configured by combining the applications (e.g., ATOM, Swallow, and OWL) shown in **Fig. 2**. The applications we have developed include those listed below.

(1) Centralized core system management function (ATOM)

This function centrally manages the standard data organized in the existing core system by promoting KPS.

(2) Schedule planning support (Swallow)

This function establishes new tasks to centrally manage and operate the schedule at each factory and prepares a consistent production plan table, medium-term

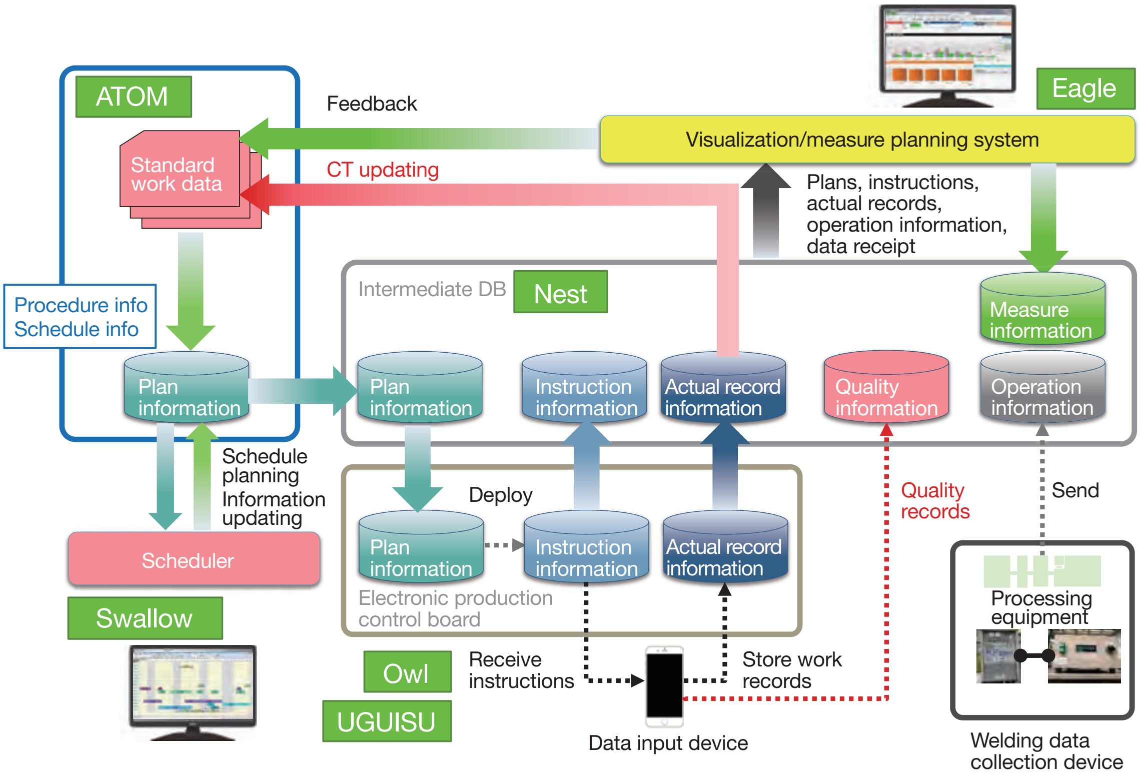


Fig. 2 Overview of the innovative production system

schedule, and short-term schedule according to the master schedule.

(3) Electronic individual production control board (OWL)

This function stores digital work instructions and work records that are connected to the standard data registered in the core system.

(4) Production status real-time visualization (Eagle)

This function introduces functions that collect and store work instruction data and work record data and visualizes the progress of processes and equipment operating statuses for multiple purposes. Also,this function is directly linked to KPS improvement activities, such as work time analysis and understanding the reasons for differences.

(5) Information consolidation via an integrated database (Nest)

These are databases used to centrally manage all manufacturing information related to production controls, process controls, and daily controls.

(6) Andon that visualizes work progress (UGUISU)

This function displays the work progress per worker and the time required to finish the remaining tasks, which enables the supervisor to manage the progress in real time.

4 Results of deploying the innovative production system

We have successfully established a foundation for Smart Factory, which enables visualization of production systems and quick iteration of the improvement activity cycle.

For example, the electronic production control board (OWL) plays the role of storing each day's work instructions and work records for each worker as shown in **Fig. 3**, and this has enabled us to flexibly address high-mix, low-volume production. The products handled at our factories include individually differentiated products, the shapes of which differ per customer, and repeat products, which are produced repeatedly several times a year, each of which requires characteristic manufacturing. Individually differentiated products require a function that separates long-term lead times into processes of appropriate lengths and provides work instructions. Therefore, we provide an interface that features an image of a calendar-based process sheet. In addition, for some repeat products, multiple workers are assigned to work together. We thus provide an interface for assembly work that features an image of a sheet that shows multiple workers' tasks in combination. Particularly at machine processing factories, a single worker must operate multiple pieces of equipment simultaneously and day/night shifts are implemented, so a function that facilitates the handover process between

Fig. 3 Electronic production control board (OWL)

workers who work during the day and workers who work at night is required. Furthermore, it is also necessary to have a function that provides instructions on regular tasks such as direct tasks for product production and indirect tasks to be performed daily such as morning meetings and equipment checks. To support instant understanding of work instructions that have been segmented into tasks taking one minute or less, electronic work procedures display photos and figures rather than text.

The production status visualization (Eagle) can now play a role as a BI tool, which tallies the work records stored by the aforementioned electronic production control board (OWL) and generates a graph of them. Equipped with a drill-down function that tallies work times in terms of different units such as products, processes, procedures, and tasks, Eagle can evaluate work records from various perspectives and expose problems. In addition, it enables one to ascertain work progress by evaluating the work records using an index known as the “achievement rate,” which is the ratio of the target time versus the actual time; sorting the records in achievement rate order to make it easier to find problems with each task; and comparing the scheduled work volume against the finished work volume.

These functions standardize KPS daily controls, work instruction and work record collection via the electronic production control board, and the PDCA methodology for improvement activities by visualizing such data as shown in **Fig. 4**, thereby enabling anyone to implement advanced

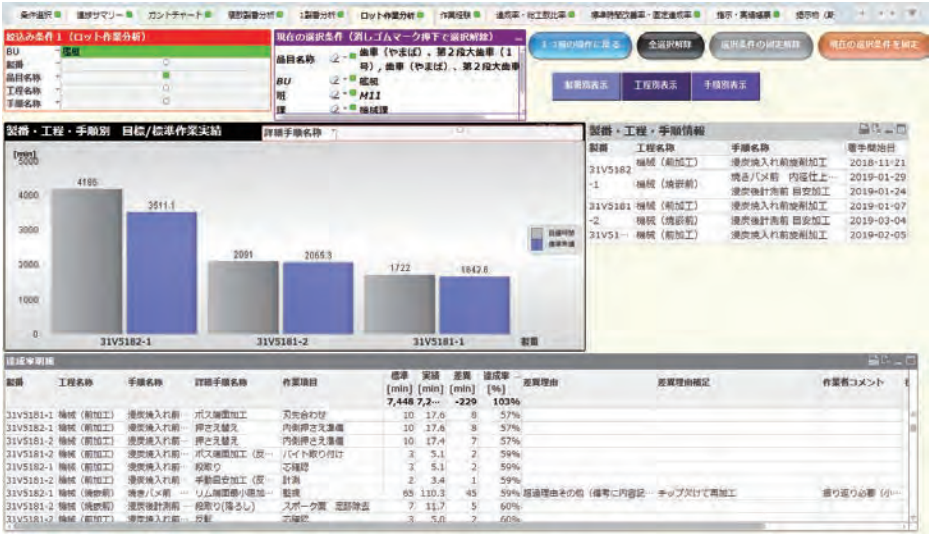


Fig. 4 Visualization of muri (unreasonableness), mura (inconsistencies), and muda (waste)

improvements. Improvement methods have become more sophisticated and the PDCA cycle speed has been improved, and output levels have also been improved by repeatedly making improvements. On-site supervisors can now provide workers with detailed work instructions for the day, and the workers can carry out the work according to the instructed procedures without hesitation. By evaluating any deviations from the standard work time by using a clear figure of the achievement rate, we can immediately identify problems that have occurred during the work, investigate the causes, and take countermeasures, which has resulted in the elimination of unreasonableness, inconsistencies, and waste hidden within work.

As described above, although past improvements depended on the skills of supervisors—in other words, were improvements that depended on people—the digitalization of improvement tools has standardized improvement methods and enabled everyone to implement high-level improvements.

5 Connection with the welding management system

In addition to the utilization of digital technologies for processes and tasks, which has been realized by the innovative production system, we have also enabled data on equipment, which is another of KPS's elements, to be utilized in the production system by digitalizing welding management and connecting it to the innovative production system as shown in **Fig. 5**.

To respond to high-level quality requirements that involve complicated welding conditions, we have fundamentally reformed our welding management. Aiming to streamline work management, we collected various types of information generated from welders as data and employed digitization to transfer manual management that consisted of manual operations and handwritten documentation, which was the status quo prior to the introduction of the innovative production system, to automatic recording as needed. The welding data collection system we developed consists of three components: a welding data collection device (SB: Sensor Box) that retrieves data from welders, a quality control function that collects welder data and work record data as well as stores and visualizes them in the form of welding work records, and an electronic production control board (OWL) that instructs the welding workers about which sections are to be welded and welding procedures.

Introducing this system has enabled us to realize the following:

(1) Digital storage of welding information

Digitally stores welding information required for welding work records, which was handwritten in the past.

(2) Notification of deviations from welding conditions

Instantly notifies workers of any deviations in welding conditions from the welding range, such as welding current.

(3) Automatic collection and transmission of welding data

Obtains the welding current, welding voltage, and welding ON/OFF signal from a welder and the worker ID, production number, joint number, and other information

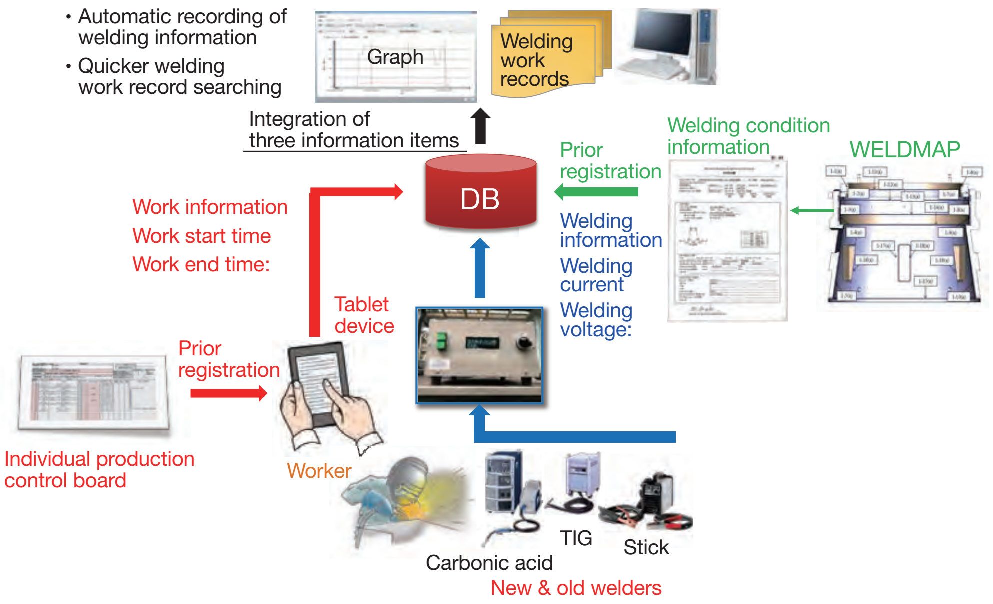


Fig. 5 Connection to the welding management system

from a barcode. Transmits the collected data to an upper-level storage/display application via wireless LAN.

(4) Quality control by visualization

Registers data transmitted from the welding data collection device in a database as needed and visualizes the welding current and welding voltage in real time. In addition, stores the welding information required for welding work records as electronic data and automatically maps the welding data to a specified welding condition recording sheet.

Conclusion

By establishing and introducing the innovative production system, we have secured and enhanced the fundamental technologies for Smart Factory. By deploying these horizontally, we have established a system for a specific project through which we aim to pursue and further deepen KPS's philosophy of "fully utilize human resources, materials, and equipment" as well as fully utilizing information.

With regard to collection and storage of production site data, we are now developing an environment for collecting information on human resources, materials, and equipment at actual production sites, by assigning digital IDs (digitalization) to materials and obtaining equipment operation data, and enhancing the horizontally deployable Smart Factory foundation that realizes quicker, lower-cost introduction of the environment through standardization and modulation. Actual production data collected and stored from the environment thus established can be used to follow-up on production progress and optimization, which is expected to realize quicker response and shorten lead times.

Going forward, we will make maximum use of the resources we possess including human resources, materials, and equipment, and we will contribute to further promoting KPS by sophisticating our digital technologies for manufacturing and striving to expand their range of applications.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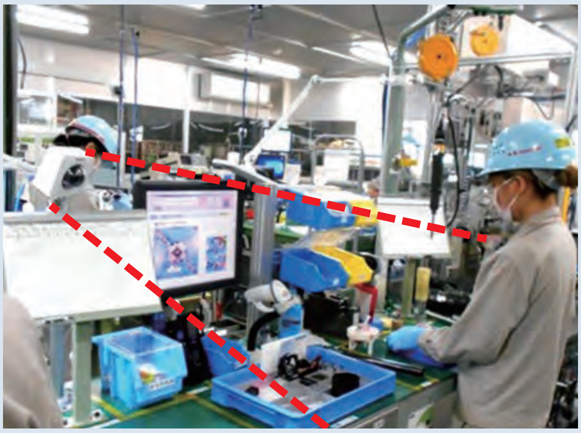
Utilization of AI and Optimization Technologies for Productivity Enhancement with Manufacturing Data



Uncertainty in business is increasing. In order to survive as a manufacturer, we are required to have manufacturing floors that can respond promptly and flexibly to changes in the social environment. AI (artificial intelligence) and optimization technologies have enabled us to make decisions based on on-site conditions, such as optimizing work sequences and boosting work quality. By applying these technologies, we have successfully eliminated dependence on skilled workers and have raised productivity, including reducing lead times, through reforming work processes.

Introduction

Recently, uncertainty in business has been increasing due to rapid changes in the social environment. Given such circumstances, our manufacturing floors must be competitive and enable us to enhance productivity while responding promptly and flexibly to these changes.

1 Background

Thanks to improvements in infrastructure, an environment facilitating the accumulation of big data is being put into place. In addition, AI and data analysis technologies have advanced rapidly and can enable more sophisticated decision making. Many cases of utilizing such technologies to enhance productivity on the manufacturing floor have been reported 1). Data collection and accumulation are underway on our own manufacturing floor as well as those of other companies, and systems for visualization and work automation are being put into place.

2 Productivity enhancement with data utilization

Recently, we have become able to adopt data utilization technologies more easily thanks to improved, more affordable data analysis environments. However, there is no single data analysis technique that can be applied to solve every type of challenge on the manufacturing floor, so data analysts with a general knowledge of data analysis, including of topics such as statistics and machine learning, must propose solutions.

At the same time, to enhance productivity through data utilization, we must not only implement new systems but also deeply understand the current challenges, define the ideal work processes, and carry out reforms to realize such processes. To this end, the data analysts must have the ability not only to understand data science technology but also to work with manufacturing personnel to deepen our understandings of their work, to identify the actual challenges, and to propose solutions for the identified challenges.

In our company, for example, data analysts are working closely with manufacturing personnel to identify challenges and to use data to find solutions to such challenges in order to propose factory layouts and to optimize production plans 2). In addition, we are making various efforts to enhance productivity.

3 Examples of our efforts

As examples of our recent efforts to enhance productivity through data utilization, the following describes a detection system for preventing deviations from work standards in real time; a planning system for automatically optimizing the sequence in which different products are fed into an assembly line, and a production management technique for shortening lead times in large factories.

(1) Real-time prevention of deviation from work standards

(i) Challenge

Our Precision Machinery Business Division manufactures hydraulic equipment used mainly for construction machinery. On the manufacturing floor, we are working to enhance productivity while ensuring safety and quality by thorough work standardization. However, workers have been frequently shuffled in order to change the number of workers in response to rapidly fluctuating demand. As a result, new, inexperienced workers deviated from the work standards (abnormal work) in some cases, which caused accidents and quality issues; these in turn reduced productivity.

To prevent such deviation, we adopted foolproof systems on the manufacturing floor and installed cameras to record work. However, foolproof systems cannot be applied to work in which tools that cannot output signals are used. As for recording, abnormal work, which causes accidents and quality issues, cannot be detected in real time; instead, it can be addressed only after the fact.

In the workplace for assembling the joystick-type electric remote control unit (electric joystick) shown in **Fig. 1**, we have adopted the mixed production system, where multiple workers repeat a series of steps of standardized work, including mounting and screwing parts and applying grease, on the work stage. This process makes use of a work instruction system linked with tools[3)], whereby each worker executes, step-by-step, the standardized work specified in the work procedure presented by the system. However, in the grease application and adhesive application work, for which work completion cannot be detected mechanically, it is confirmed by pushing a button. Therefore, with this system, human error, such as omission of a necessary step or application of too much grease or adhesive, cannot be completely prevented.

(ii) Solution policy

We developed an automatic detection technology with AI that automatically detects deviations from work standards in real time based on videos taken by cameras placed on the manufacturing floor and output alarms.

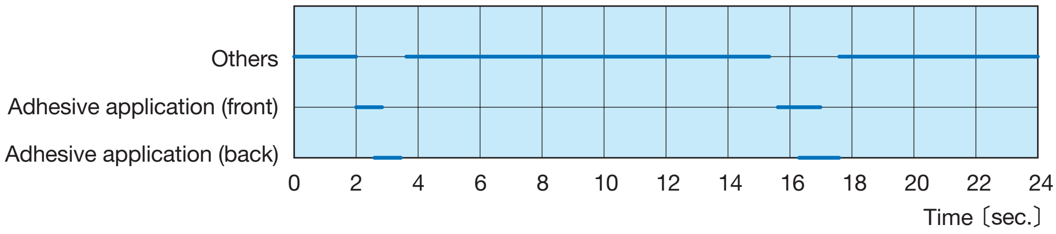
We extracted images from the video data; labeled them as "Adhesive application work (front)," "Adhesive application work (back)," and "Other work" to prepare training data; and created an AI model for image classification using a model trained in advance. We then sampled images from the work videos at 0.1-second intervals and classified them by work type with the developed model. **Figure 2** shows the time-series graph of the classification results. Based on the results, we found that it is possible to detect abnormal work in real time by performing a series of steps of standardized work in advance, defining trends by type of work (standard sequence), and monitoring whether the judgment result conforms to the standard sequence.

Next, we conducted a preliminary study and tuned the training data and model to improve the judgment accuracy. As a result, we achieved a false negative rate of 0% (the rate at which abnormal work is judged to be normal work) and a false positive rate of 5% or less (the rate at which normal work is judged to be abnormal work) for videos showing the handling by multiple workers of over 1,000 workpieces.

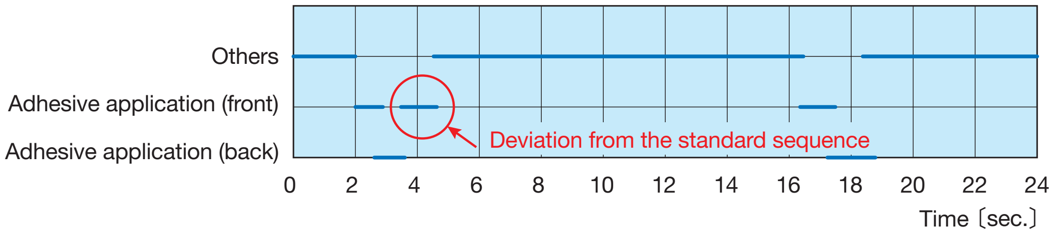
(iii) Results

We systematized this technology in April 2021, and it has now been in operation for more than a year. The system enables us to plan workpiece feeding sequences quickly even in the absence of experienced personnel, thereby contributing to stable production. In addition to

Fig. 1 Assembly of Electric Remote Control Unit



(a) Normal work



(b) Abnormal work

Fig. 2 Work classification by AI

enhancing quality through the detection of operational errors, this system is expected to improve the manufacturing floor by detecting deviations from standard work times, identifying causes, and facilitating response. Tests are underway for improvements. This system can be applied relatively easily to any standardized repetitive work. We are making efforts to apply this system to other divisions within the company.

(2) Automatic optimization of the sequence in which different products are fed into an assembly line

(i) Challenge

Our Robot Business Division offers a product lineup consisting of several hundreds of items to meet various market needs. Its assembly lines produce small quantities of various products through mixed production. On these mixed production lines, if workpieces are not fed in an appropriate order, the necessary equipment or jigs may not be available, and workers will be forced to wait until they become available, which causes delivery delays or leads to overtime work. Therefore, each day the optimal workpiece feeding sequence is planned by experienced planning personnel. However, planning the optimal workpiece feeding sequence requires consideration of various factors—including the workload, equipment configuration, and number of jigs—for each model to be produced on each production line. For this reason, at present only a limited number of personnel are capable of planning the workpiece feeding sequence, making such planning dependent on individuals, and many hours are spent each day to plan the workpiece feeding sequence.

(ii) Solution policy

To empower inexperienced personnel to plan the workpiece feeding sequence quickly so as to ensure stable production, we employed optimization technology to automate workpiece feeding sequence planning. This time, we achieved such automation in an assembly workplace where general-purpose large robots are used and mixed production is performed by connecting an assembly line and an operational inspection line in series as shown in **Fig. 3**.

The option configurations and specifications of the models handled in this workplace vary greatly depending on customer requirements; therefore, it is difficult to maintain or adjust the standard work time for individual models and tasks. Completing the work as fast as possible is not always the best approach, and the optimal solution cannot be calculated mathematically based on the standard work time master. Therefore, we studied a method that does not require meticulous maintenance of master data.

We conducted interviews with experienced planning personnel regarding the workpiece feeding sequence planning method and found that they had defined rules that must be observed in their heads in order to evaluate workpiece feeding sequences. We then made a list of these rules for workpiece feeding sequences (hereinafter, "feeding rules") and quantified the importance of each rule so that they could be processed by computer. In addition, we used a genetic algorithm to impose penalty points for violations of each feeding rule and to determine the workpiece feeding sequence that minimized the sum of the penalty points. This helped us reflect the ideas of the experienced planning personnel in the system's logic, enabling workpiece feeding sequences to be planned automatically based on experienced planning personnel's

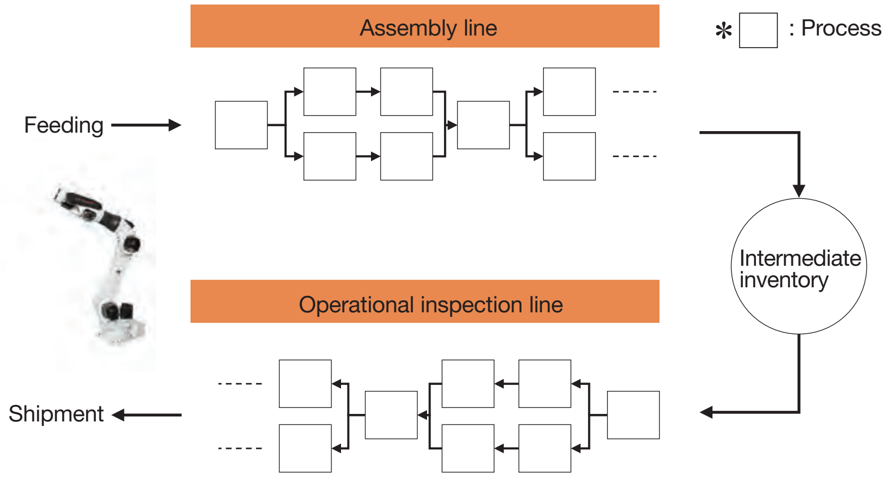


Fig. 3 Production line configuration using robots

ways of thinking.

At first, the calculated workpiece feeding sequence differed greatly from the workpiece feeding sequence planned by the experienced planning personnel, so we worked with the experienced planning personnel to set and review the feeding rules. As a result, we became able to calculate a workpiece feeding sequence that did not differ from that planned by the experienced personnel within five minutes, whereas such a sequence took the personnel one hour to prepare.

After establishing the system's logic, the experienced planning personnel modified the feeding rules according to changes in model specifications and other conditions. For systemization, we needed high flexibility to respond to changes in these conditions. Therefore, we again sorted out the feeding rules and found that the feeding rules could be classified into specific patterns, each of which could be represented in terms of parameters. We then abstracted the feeding rules and developed a product feeding sequence optimization system that enables flexible addition and correction of feeding rules by configuring settings on-screen. An overview of this system is shown in **Fig. 4**.

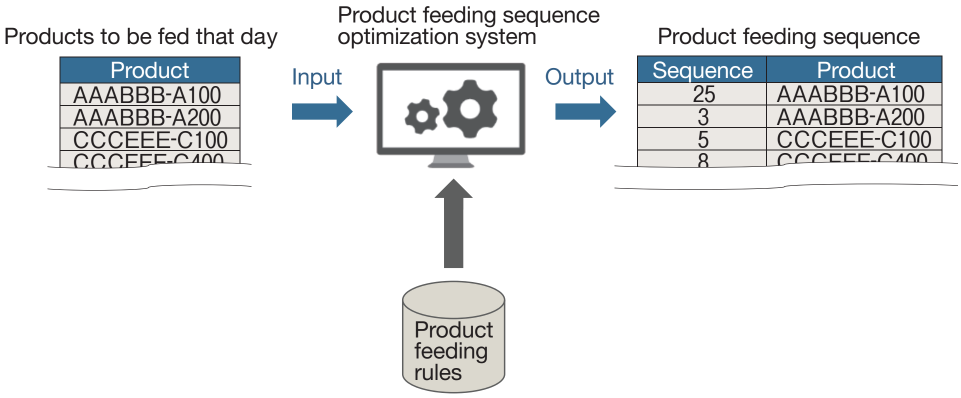
(iii) Results

We put this system into practical use in April 2021, and it has now been in operation for more than a year. The system enables us to plan workpiece feeding sequences even in the absence of experienced personnel, thereby contributing to stable production. In addition, we have improved the system so that feeding rules can be flexibly added and modified, which enables even personnel without specialized knowledge of programming to respond flexibly to changes, and moreover facilitates application of the system to the production lines of other divisions. We are now applying the system to other workplaces.

(3) Production management technique for shortening lead times in large factories

(i) Challenge

Our Aerospace Business Division produces various parts ranging from mass-produced parts to specialty parts



Product
AAABBB-A100
AAABBB-A200
CCCEEE-C100
CCCEEE-C400

Sequence	Product
25	AAABBB-A100
3	AAABBB-A200
5	CCCEEE-C100
8	CCCEEE-C400

Fig. 4 Production sequence optimization system

produced in quantities of a few pieces a year. Various parts of various sizes and quantities are manufactured using multiple processes, including machining, manual work, surface treatment, and coating; for this reason, it is difficult to build dedicated production lines. Under the job-shop production system, parts are manufactured by passing them between various workplaces as shown in **Fig. 5**. Parts pass through several hundreds of workplaces along several tens of thousands of routes annually, with over a hundred thousand production requirements during normal times, thus necessitating an extremely large, complex system. Therefore, we could not prepare detailed production plans that took into consideration the available resources, and we made daily work plans for individual workplaces by referring to an overall plan determined based on standard lead times that assumed unlimited capacity. However, we had insufficient or excessive intermediate inventory between workplaces, mainly because mass-produced parts, which have some repeatability, and made-to-order parts, which do not have repeatability, co-existed and because trouble and urgent orders frequently occurred.

(ii) Solution policy

A relatively easy method for shortening lead times and for ensuring delivery times are met in a large factory is to control parts feeding by controlling the amount of raw materials fed into the factory and specifying the priority for adjusting delivery lead times [4]. One such method is to set an upper limit on the number of workpieces in the factory (WIP: Work In Process) as shown in **Fig. 6** so as to limit the amount of raw materials fed into the factory; such an approach is known as the CONWIP (CONstant WIP) method. However, this method can be applied to mass-produced parts only. Thus, we improved the method. Parts are classified into a limited number of groups, and the amount of raw materials to be fed is controlled on a group

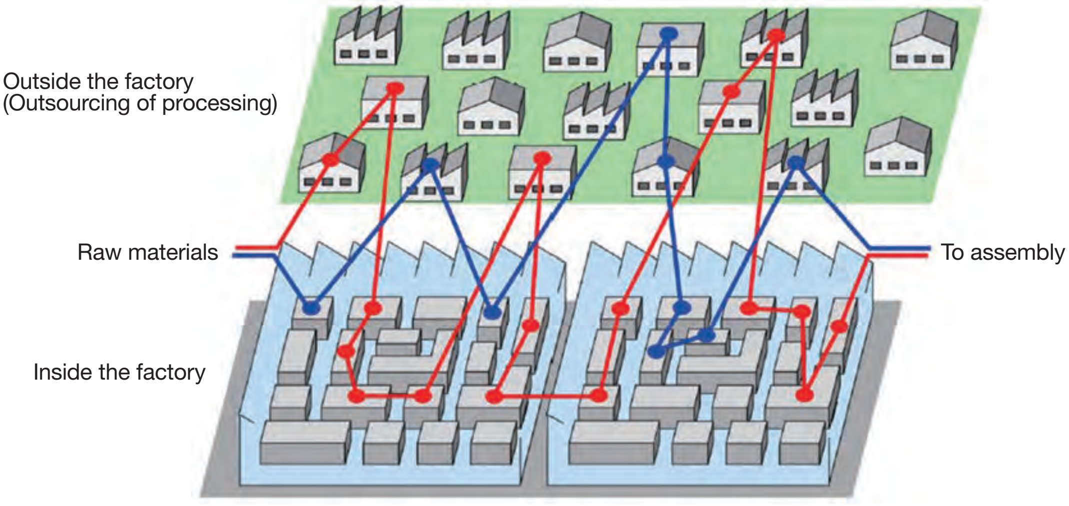


Fig. 5 Production system for aircraft parts

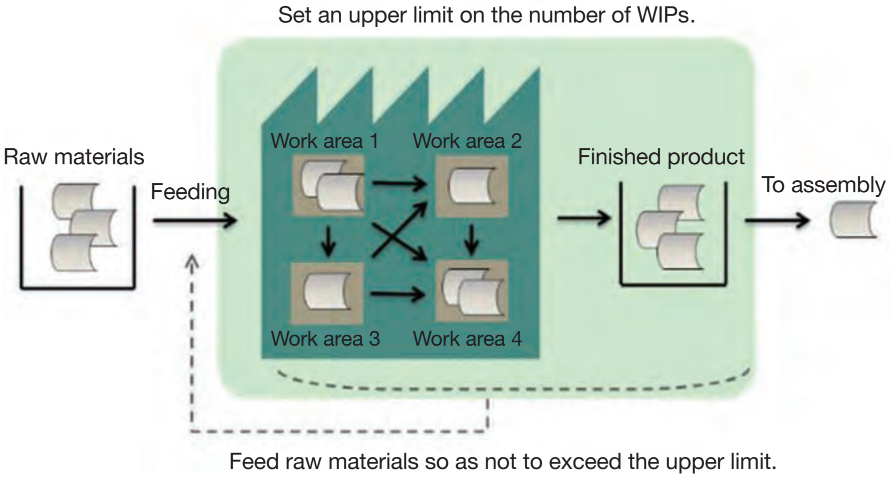


Fig. 6 CONWIP production method

basis. Priority is calculated based on the number of WIPs for mass-produced parts, and on lead times for made-to-order parts. In this way, we have successfully built a feeding logic that enables us to determine the feeding timing while handling mass-produced parts and made-to-order parts in the same manner.

(iii) Verification of effectiveness

We conducted a simulation with the logic we built and verified its effectiveness. We confirmed that when we decreased the number of WIPs by 20%, lead times could be shortened by 15% while output was maintained at the same level. We now plan to apply this logic to some factories on a trial basis in fiscal 2022 and to further verify its effectiveness.

As part of the Smart-K Project, our Aerospace Business Division is working to integrate work processes in the engineering chain and supply chain through digitalization and has realized Smart Factories, where various manufacturing floor data can be obtained. In the future, we will apply this feeding control based on such data to contribute to management through reduced lead times.

Conclusion

The waves of DX (digital transformation) are expected to propagate further and to digitalize every inch of manufacturing floors. To solve the challenges we face on the manufacturing floor with data utilization for reforming work processes and creating new value, we need to develop data utilization personnel who can appropriately apply data analysis technologies to the manufacturing floor. Therefore, we will continue to work with manufacturing personnel to tackle these challenges to develop data utilization ability. In addition, to make maximum use of data utilization, we should not merely make case studies out of successful cases but rather standardize them so that they can be applied to other areas. Thus, we will make full use of our knowledge for standardization and further development.

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XR Technology Brings about Innovative Changes in Manufacturing

As customer needs are diversifying, product specifications and manufacturing processes are becoming increasingly complicated, and at the same time, the passing on of skills by experienced workers has become an issue. Therefore, we are required to further promote the deepening of internal and external communication, as well as further improving interdivisional cooperation, quality assurance, cost reduction, and compliance with delivery dates. To solve this challenge, we are working to stimulate communication through the utilization of XR (Cross Reality) technology using 3D model data obtained through digitalization, with the aim of standardizing our work and eliminating the dependency on specific individuals.

Introduction

Recently, increasingly diverse customer needs have necessitated that we, as a manufacturer, offer products to meet such various needs.

1 Background

In response to increasingly diverse customer needs, we manufacturers must know our customers well, so communication with users is important. Our products encompass a wide range from mass-produced products to build-to-order products, and it is important to ensure quality (Q); to streamline work to reduce costs (C); and to ensure compliance with delivery dates (D) in each process. Therefore, we further must improve work processes (business process improvement) and standardize work. With regard to the passing on of skills by experienced workers, we need to ensure close communication between veteran and young workers as well as quantify, standardize, and digitalize veteran workers' tasks to eliminate dependency on specific individuals.

2 Policy and processes for solving challenges with XR technology

One way to solve such challenges is to utilize digital technology or to promote so-called DX (digital transformation). For example, if we can digitalize human movements and skills, which has been considered difficult, as well as product information, manufacturing information, and technical information, as data, it will become possible to represent them quantitatively. This will enable us to visualize our work processes and to improve them more deeply, thereby achieving standardization without depending on specific individuals. Also, using digital data in an integrated manner across diverse processes facilitates more active, deeper communication between departments as well as users. This will enable different processes to work in collaboration or to work concurrently.

3D model data is the type of digital data most commonly used in the field of manufacturing. 3D model data is created mainly by the design department with 3D CAD, and it is available throughout the value chain. Such data enables visualization of products, production equipment, and working environments, including jigs. Even at an early stage in which no actual product exists, 3D model data enables relevant personnel to share images of a product, making it quite useful for invigorating communication and improving work processes (business process improvement). XR (Extended Reality) technology is a means of utilizing information visualized with 3D model data with a high degree of realism.

XR technology is a generic term for VR (Virtual Reality), AR (Augmented Reality), MR (Mixed Reality), and other technologies. VR is a technology that enables users in a virtual space generated by computer graphics or other technology to feel as if they were in a physical space. AR and MR are similar technologies that present virtual objects and information in physical space. In particular, MR is characterized by the fact that a virtual object can be presented consistently at the same location in physical space by obtaining location information. XR is often used in the fields of entertainment, education, and virtual exhibitions, and it generally requires expensive hardware and software as well as large facilities. Recently, however, XR has become more readily available because of lower user interface prices and simplified operations.

XR enables us to verify work in advance and to issue accurate work instructions that can be understood intuitively. For example, when implementing a measure to reduce mistakes, improving a production process, or verifying in advance the actual work conditions, then effectiveness can be verified in advance through a virtual experience. Even when a product or service is in development, so long as 3D model data is available, an image of the product or service can be shared through visualization that involves not only the sales, design, manufacturing, inspection, and servicing departments but also the customer, thus facilitating communication. Previously, we developed an evaluation method that combines ergonomic assessment with VR and applied it to the design of train operator seats [1, 2]. At that time, both the hardware and software were expensive, so we could not apply the method to other divisions, but now their prices have fallen, making XR more readily available.

3 Example applications of XR

The following gives three examples of applying XR. The first example describes how VR was used in welding work to enable workers to verify their own work in advance, thereby reducing trouble during such work. The second example describes how MR was used to enable workers to carry out complex work without needing to hold the instruction sheet in their hands, thereby enhancing work efficiency and quality. The third example describes how XR was used in upstream processes, thereby enhancing design efficiency.

(1) Advance verification of welding work with VR

(i) Background

The Production Division of the Energy Solution & Marine Engineering Company develops production technologies to manufacture various products, including gas engines, steam turbines, aerodynamic machinery, and propulsion machinery. Among others, welding work is an important process for forming an enclosure that supports the product structure. In the past, we studied work details by imagining finished products based on 2D drawings issued by the design department. We were sometimes forced to start production while still unconfident about work feasibility. In fact, we experienced a problem in piping installation work in which a part could not be inserted due to insufficient space, and accurately simulating work in advance was a challenge. In addition, when we wanted to request a design change to the design department while studying the details of the work, we had difficulty communicating with the design department because we had no good way to share images.

(ii) Actions

We came up with a method to assess and improve work feasibility and to alleviate difficulties in advance by viewing the product's 3D model data in VR as shown in **Fig. 1** and verifying the workability of the work areas we were concerned about in a VR space that provides an environment similar to the actual one. We received positive feedback from field workers that they could work at ease because they could experience the work in advance.

By applying this method several times on a trial basis, we received helpful improvement proposals from workers and VR verification took off. This led to the establishment of a dedicated room for VR so that workers could easily verify their work at any time.

For example, we verified piping welding work in a narrow space in a steam turbine as shown in **Fig. 2**, and

Fig. 1 Advance verification of welding work with VR technology

Fig. 2 Steam turbine (for power generation)

we used VR to confirm that during such welding work, visibility was lower than expected. The manufacturing side then proposed to the design department a modification to the structure around the piping, and VR was used to explain this proposal. Use of VR enabled the engineers to understand the actual welding work and led them to judge that the design change was necessary. Also, the piping was originally planned to be divided into several parts before welding, but this proposal eliminated the need to divide the piping in advance. This department works on many made-to-order products, so workers are often forced to do work that they have never done before. Verifying such work in advance with VR enables high-level work planning and is highly effective in rectifying production processes and eliminating the need to plan work with actual products as was done previously, thus contributing to reducing costs and stabilizing quality.

Advance verification with VR has been well-received by design and manufacturing departments. We are working to establish it as a standard process in work planning, including recording of VR verification's purpose, timing, procedure, and judgment results as a work process.

(2) MR work instruction system

(i) Background

The Aerospace Business Division manufactures major commercial aircraft parts such as front fuselages. One of its many production processes is drilling holes necessary to mount parts. Most holes are drilled with automatic machines, but those that cannot be drilled by automatic machines are drilled manually by workers. Hole drilling work employs drill jigs to ensure the location accuracy and quality of each hole. Drill jigs are secured with index pins in the reference holes drilled in advance on the fuselage. Template sheets made of semitransparent polyester film are used to set multiple drill jigs on the fuselage's side. Template sheets have a height of 4 m and a length of 10 m, and their cutouts have the same shape as the jig. The worker aligns the jigs with the cutouts. Making a template sheet costs a lot, and the sheet must be modified if a design change is made or repaired if it gets damaged Also, setting a template sheet requires several people and 20 to 30 minutes. For these reasons, we wanted to improve this work, but we could not find an alternative to template sheets.

(ii) Actions

XR has become more readily available, so we studied a method to use MR to issue instructions on how to set the jigs without using template sheets.

We used Microsoft's HoloLens as a head-mounted display (HMD) for MR. HoloLens projects images onto a permeable screen and enables the user to see virtual objects in physical space. It has cameras and sensors to measure the areas around the HMD to obtain self-location information. This makes it possible to superimpose virtual objects on physical objects. We developed an MR work instruction system that tells workers where to set the jigs with HoloLens as shown in **Fig. 3**.

We conducted an element test in 2017, and we developed a prototype system in 2018. With the prototype system, we found that with respect to HoloLens's display location accuracy, error increases as the distance from the reference position increases, and the error is about 1% of the distance from the reference position. Many users commented that they felt uncomfortable when wearing HoloLens because of the poor weight balance of the first

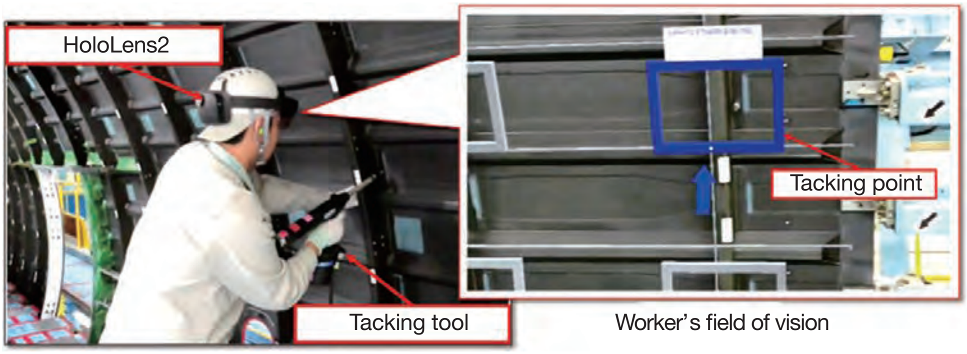


Fig. 3 Tacking work using MR work instruction system

version, which we used initially. In addition, the battery lasted only about two hours, which was a concern for practical use. However, the prototype system was well-received by the users, or field workers because instructions were displayed directly on the fuselage and could be understood easily and intuitively.

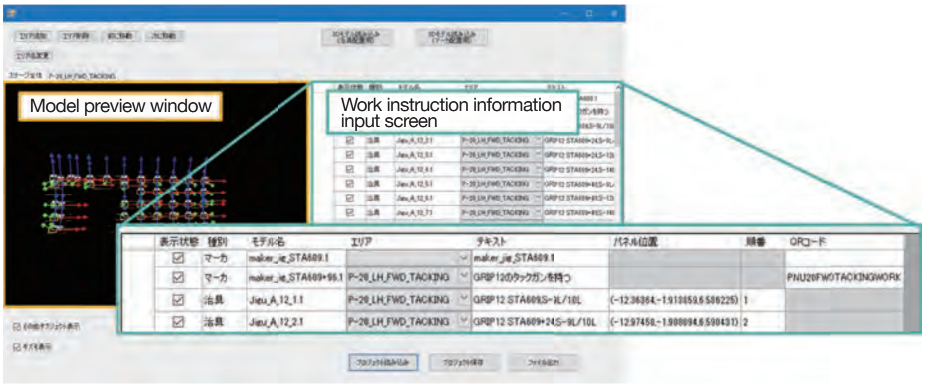
In 2019, we worked to solve the aforementioned problems. To improve accuracy, we set markers indicating the reference position, thereby achieving the display location accuracy required to set the jigs. Also, late 2019 saw the release of HoloLens 2, which featured a modified shape to improve wearing comfort. As for the battery life problem, we concluded that it could be addressed by improving usage and using multiple batteries. At the same time, we developed the MR work instruction editor shown in **Fig. 4**, which enables manufacturing engineers to create instructions. The MR work instruction editor does not require programming skills, and new work instructions can be created as usual.

The completed MR work instruction system supports HoloLens 2 and uses QR codes as markers. Field workers commented that with the wider viewing angle and improved wearing comfort, using the system in place of template sheets is no problem.

Though this system was developed for setting jigs, we studied its applicability to other types of work. In tacking work for temporarily joining frames, tacking is performed from inside the fuselage in the specified sequence. The MR work instruction system eliminates the need to view the instruction sheet during the work. This makes the work easier to perform because the worker only needs to hold the tool. In addition, HoloLens 2 displays each instruction directly on the outer surface of the fuselage, and the next tacking position is indicated by an arrow, preventing the worker from making a mistake in the work sequence. Also, this system has a check function that prevents the worker from proceeding to the next task until the specific task is completed, thus preventing omissions. We will apply this system to inspection and machining processes as well as other models. In addition, we are considering linking this system with the system for registering work records in the core system. We are also applying this MR work instruction system to other divisions throughout the company.

(3) Co-creative design with XR

To create products that meet diverse customer needs, we must verify various ideas, including original ones, not



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☑	マーカ	maker_ie_STA609+96.1	P-20_LH_FWD_TACKING	GRP12のタックガンを持つ			PNU20FWDTACKINGWORK
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☑	治具	Jigu_A_12_2.1	P-20_LH_FWD_TACKING	GRP12 STA609+24S-9L/10L	(-12.97458,-1.908094,6.590431)	2	

Fig. 4 MR work instruction editor

only in the design and development stages but even in the planning stage. Such activities should not be constrained by location, and we must proceed with verification even if there is no actual product yet. We are working to utilize XR to promote "co-creation," which refers to collaboration between customers and other external stakeholders and internal stakeholders in order to create new value. With XR, we will invigorate communication to strengthen our design capabilities.

In motorcycle development, for example, the rider's operations are input into a digital model of the vehicle from the riding simulator by the riders themselves, and the behavior of the running vehicle can be obtained through numeric simulation. Use of XR enables riders to experience motorcycles as if they were actually riding them as shown in **Fig. 5**. In addition, various data, including vehicle deformation and stress, can be obtained by executing multiple simulations simultaneously. With XR, the results of such simulations can be visualized and presented to the user in real time. This enables us to quickly obtain feedback during idea verification and decision making. Also, if it is possible to visualize information from the sensors incorporated into a product with XR even after the product is put on the market and to share actual product usage with development personnel, it will become possible to improve the product and to develop follow-up products based on customer usage.

To realize co-creation, we are also using XR to develop autonomous delivery robots. We are considering various operating scenarios to determine the specifications of these autonomous delivery robots. At this time, verifying all operating scenarios takes significant time and money. In addition, for market-oriented development, there is a need to share usage scenarios with users and to obtain comments directly from such users to quickly assess customer needs. We are using XR to do this.

Fig. 5 Co-creative design

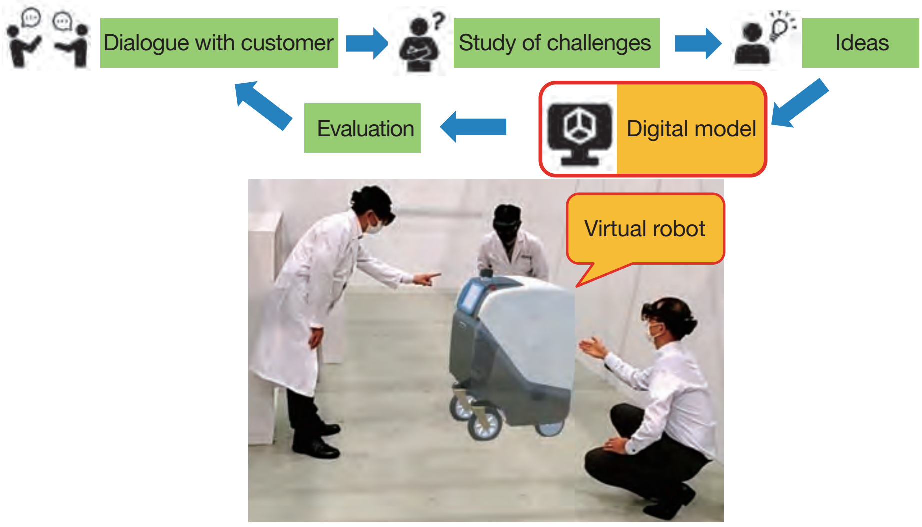

Fig. 6 Market-oriented development using XR

If a delivery robot is developed for use in hospitals, operational simulation must be carried out in a space in which the delivery robot and humans co-exist. Therefore, with MR, the delivery robot is superimposed onto the space as shown in **Fig. 6** to reproduce the co-existence of the delivery robot with humans. The delivery robot's behavior is then computed by simulation, and the behavior is reproduced with MR. This enables the evaluator to verify the behavior of the humans and the virtual robot in physical space with a high degree of realism. Since the robot is virtual, even if the hardware or software is modified, new behavior can easily be reproduced. This activity enables us to promptly confirm customer specification requirements, thereby knowing actual customer needs. Currently, we are verifying the utilization of delivery robots in hospitals.

Conclusion

We will further enhance QCD (Quality, Costs, and Delivery) by utilizing XR technology while promoting internal and external communication to meet diverse customer needs. Through such activities, we will offer products and services more speedily.

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Automation of Visual Inspection with Measurement and Image Processing Technologies

Customers are increasingly demanding product quality not only from a functional aspect but also from a visual aspect, including flawless, beautiful surfaces. To ensure quality, we are conducting a full inspection through a visual check by operators. To achieve more stable quality and deskilling, we are working to develop inspection automation technologies by combining photographing technologies using high-resolution cameras and robots, image processing and artificial intelligence (AI), and other technologies.

Introduction

Customers are increasingly demanding product quality not only from a functional aspect but also from a visual aspect, including flawless, beautiful surfaces. A common practice to ensure quality of appearance is to conduct a full inspection of products through a visual check.

1 Background

Our company, like others, has many visual inspection processes. We check the statuses of attached parts and check the appearance and surfaces of welded sections for any foreign substances, contamination, scratches, deformation, or cracks. Some of these can be judged clearly by visual inspection, while others are judged based on a sensory evaluation according to the perception and experience of the operator making the judgment, which means that such judgments are variable and cannot be quantified. In addition, since the inspection work imposes a high burden because it requires a high level of concentration and stresses operators' eyes, some hard-to-judge objects can only be judged by highly skilled operators.

2 Development plan

To eliminate such variance in judgment based on sensory evaluation and high-burden work as well as to ensure stable quality, automation of human-dependent inspection has arisen as a common need at a variety of our products' manufacturing sites.

Among our products, motorcycles, which are required to have not only advanced functions but also to look beautiful, are often inspected visually by human resources in mass-production processes, including those performed overseas. Therefore, we have decided to start by establishing an inspection automation technology for motorcycles and then are advancing development to gradually expand its use throughout the company.

Among the visual inspections for motorcycles, we consider the three inspections shown in **Fig. 1** (① assembly inspection, ② weld bead inspection, and ③ appearance inspection for scratches) to be needs in common with those of our other products (e.g., jet engines, hydraulic equipment, and railway carriages) [1]. All of these have many inspected objects and inspection items, and moreover they must be performed in a very short amount of time in mass-production processes.

To address such challenges, we aim to achieve high-speed automated judgment by photographing and taking measurements using high-resolution cameras and 3D sensors as well as categorization or detection processing using advanced image processing and AI technologies. By accumulating the obtained data, we can also apply such technologies to traceability and process improvement.

3 Development status

(1) Visual inspection in the engine assembly process

(i) Background

A motorcycle engine is an important component

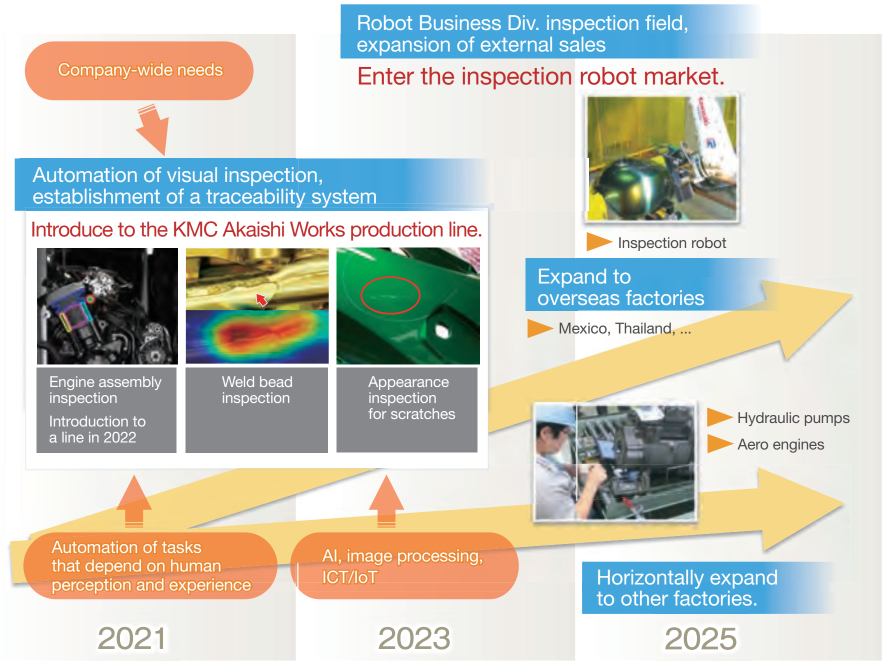


Fig. 1 Roadmap for automating visual inspection

involved in traveling. After assembly, special inspectors perform a full inspection of each engine. Over 100 types of inspection items such as the failure to attach parts, direction of attachment, attachment of incorrect parts, and degree of screw tightening are inspected visually or by direct manipulation with the hands per engine.

(ii) Response

Since 2020, we have considered the automation of 117 inspection items for the Z900RS engine and developed an appearance image photographing system using a camera and pass/fail judgment software that employs image processing. We completed development of the system and software during the first half of 2022 and began trial application to an on-site assembly line.

The appearance image photographing system is equipped with a high-resolution camera that photographs the top and side of the engine, illumination sources, and rotating machinery as shown in **Fig. 2**. Meanwhile, **Fig. 3** shows an example of judgment by image processing in which a pass/fail judgment is made by means of processing logic, such as the degree of matching and color identification according to preregistered part shapes. This has enabled speedy, accurate judgment of various shapes and colors. Currently, 44 items can be inspected; these are processed by the camera's plane recognition. We will improve the performance evaluation and processes while comparing against the visual inspection results. We aim to expand its application to inspections of other models and assembled bodies.

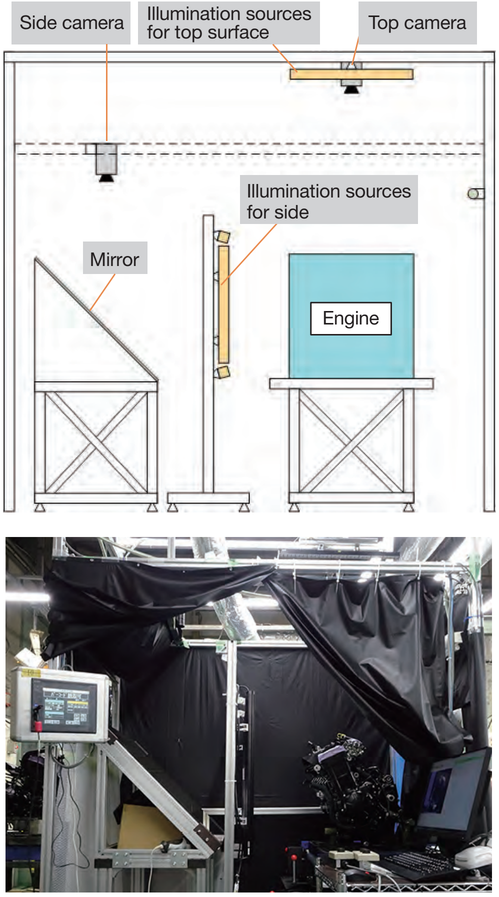
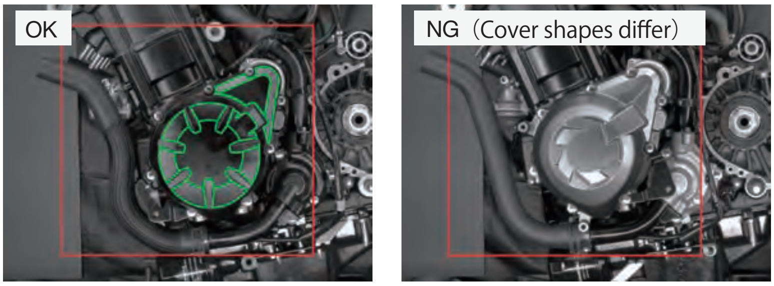
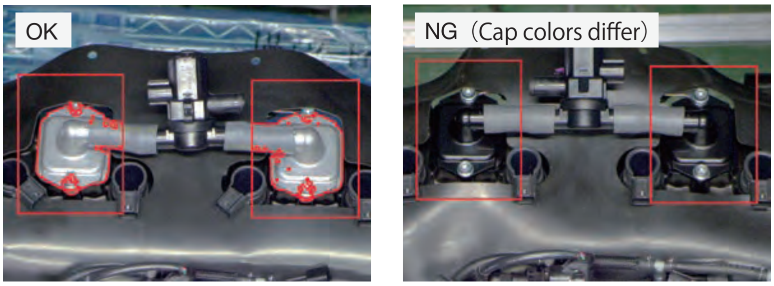


Fig. 2 Automated photographing system for engine appearance



(a) Example of judgment by part shape matching



(b) Example of judgment by color identification

Fig. 3 Inspection of engine assembly with image processing

(2) Bead appearance inspection of welded structure frames

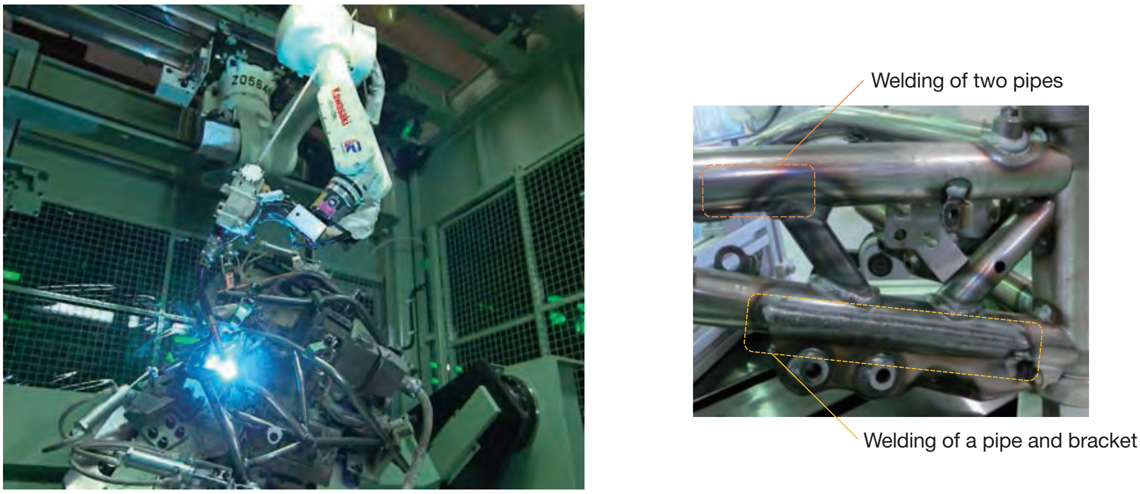
(i) Background

Motorcycle frames are manufactured by welding pipes and small parts such as brackets by the three-dimensional movement of a robot as shown in **Fig. 4**. Since the frame is an important part that functions as a bony structure of the body, welded parts must have sufficient strength and stiffness. Furthermore, in recent models, attractive frames have come to be associated with product design, which in some cases necessitates that the beads be beautiful.

Each frame has over 100 welded sections. Even normal weld beads vary greatly depending on the combination of materials and surface status. Defects are judged instantly by visual inspection conducted by skilled inspectors at a predetermined cycle time. However, it has become difficult to secure inspectors, and thus automation is demanded.

(ii) Response

Welding defects errors vary widely. Some are relatively easy to judge (e.g., displaced beads and perforations), while others are minute and require skill to judge (e.g.,



(a) Robot welding of a frame structure

(b) Frame structure

Fig. 4 Frame structure of motorcycle and robot welding undercuts). In considering how to automate bead appearance inspections, we are working to achieve image judgment using AI because it is difficult to detect variation among beads and various other defects by rules-based image processing, which is used for engine assembly inspections and other inspections.

We have developed a system that automatically photographs a specific weld bead using multiple high-resolution cameras and illumination sources attached to a mount after robot welding. By accumulating images from mass production and using AI to calculate the abnormality level, we are working to achieve image judgment as shown in **Fig. 5**.

(3) Appearance inspection for scratches on fuel tanks and plastic cowls

(i) Background

Parts for motorcycles such as fuel tanks and plastic cowls are elaborate, and they are fully inspected visually for scratches, dents, and other blemishes by operators under special illumination sources conditions. Because such defects are very small and their locations on a large workpiece cannot be predicted, only skilled inspectors can find them. In addition, since part surfaces are complicated and feature curves, they must be inspected by examining the extent of light reflections from various angles, which makes automation extremely difficult.

(ii) Response

To photograph a surface thoroughly such that defects can be clearly seen, it is necessary to keep constant the angles of the camera, illumination sources, and inspected workpiece surface so that light always reflects under the same conditions. Because the inspection targets are fuel tanks and plastic cowls that have curved, complicated surfaces, we decided to use a scanning photography method that employs a line scan camera, which obtains images of one line only. A photographing system that combines a line scan camera with an illumination source is held by a robot in order to continuously scan and photograph the object such that the distance from the surface and its angle are always constant. Judgment is made by processing such images.

Technologies that employ a line scan camera and photograph the surface conditions by moving a photographing system or targeted workpiece already exist. However, it has been difficult to apply these to inspections of parts having complicated shapes due to reasons such as being limited to linear operation or being limited to operating at a constant low speed.

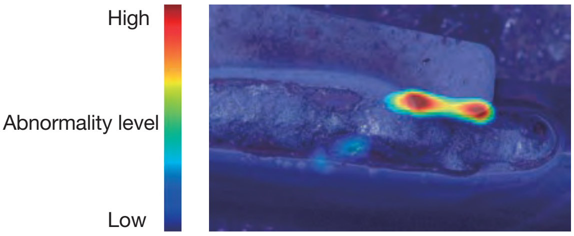
(iii) Development of high-speed curve photographing technology

To solve such challenges, jointly with the Robot Business Division, we have developed a new technology for our robots, the tool tip movement output function, to realize high-speed photographing along complicated curves.

This tool tip movement output function enables the robot controller to automatically output a signal pulse for photographing according to the movement of the tool tip (line scan camera photographing position), which is attached to the robot arm, as shown in **Fig. 6**. A complicated scanning movement along the curves is generated using KCONG [2], which is offline teaching software for robots. As shown in **Fig. 7**, KCONG generates a movement path that places the line scan camera and illumination sources at appropriate positions

(a) Normal bead

(b) Abnormal bead



(c) Abnormality map calculated by AI

Fig. 5 Evaluation example of weld bead image by AI

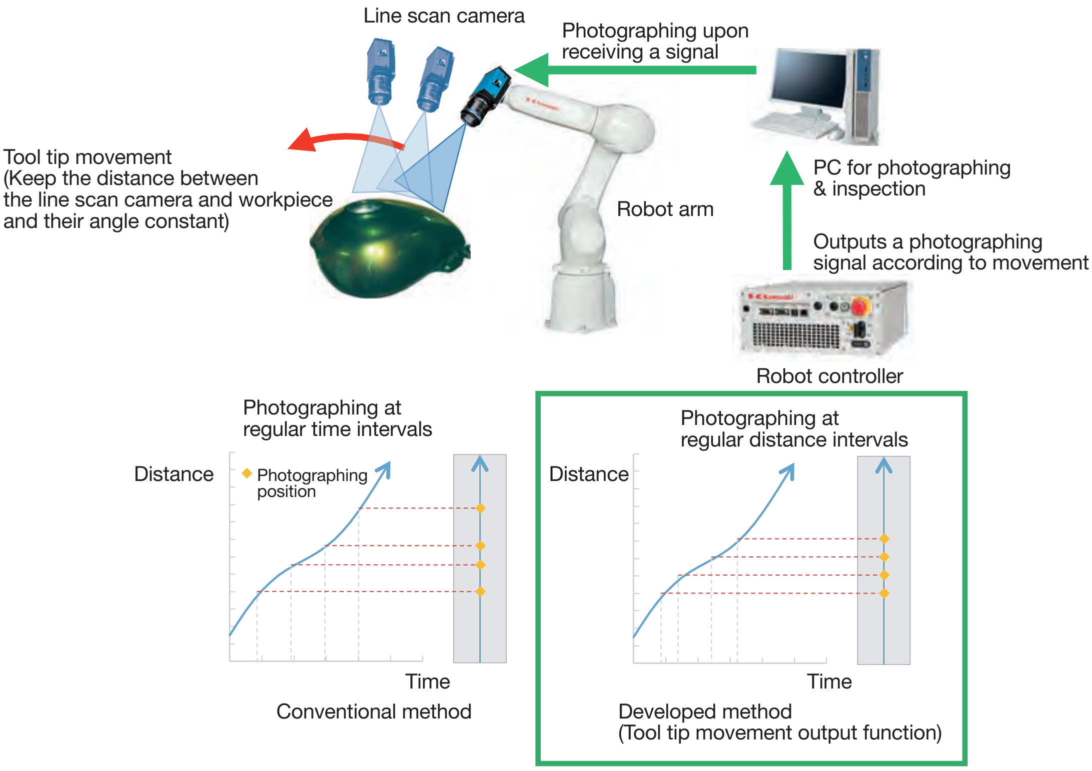


Fig. 6 Tool tip movement output function

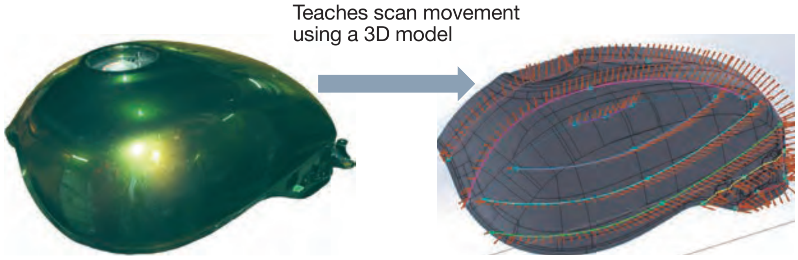


Fig. 7 Offline teaching of scanning points of fuel tank

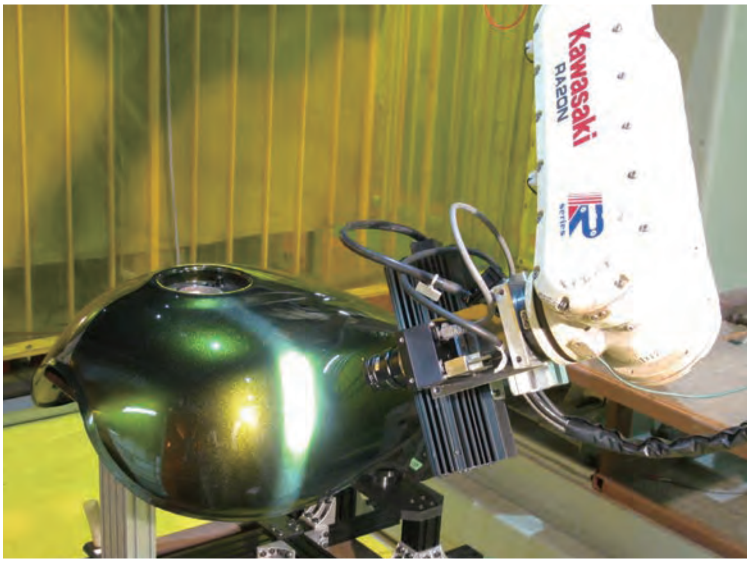
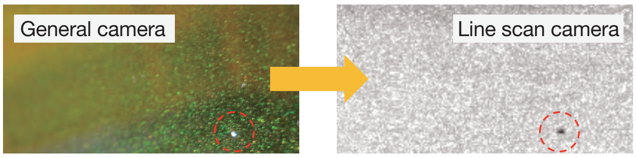
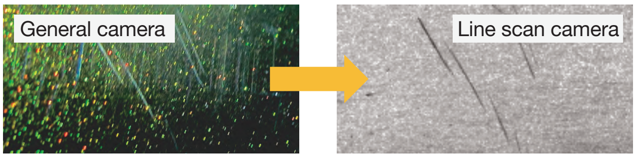


Fig. 8 Scanning of surface appearance with robot



(a) Results of photographing of a bump



(b) Results of photographing of line scratches

Fig. 9 Results of photographing of defects with line scan camera

in appropriate postures with respect to the fuel tank 3D model. In this way, highly accurate continuous photographing of a complicated workpiece can be realized at high speed.

Fig. 8 shows continuous photographing of a curved surface using a robot, while **Fig. 9** shows images of photographed defects. If a glossy fuel tank with a complicated shape is photographed using a general camera, part of the photographed image develops blurs, and the surface gloss affects the image as shown in the left photo in **Fig. 9**. However, by using a line camera to scan along the curve, we succeeded in clearly photographing minute defects of approximately several hundred μm. Going forward, we will develop image processing that performs defect detection and validate it with various workpieces.

Conclusion

To respond to the decrease in the number of skilled operators and to ensure stable quality, including that of products manufactured overseas, we are developing inspection automation technologies using state-of-the-art cameras, sensors, image processing, and AI technologies. We are first establishing such technologies for motorcycles and putting them into practical use. We will expand their use to domestic factories and then overseas factories as well as expand their applications horizontally to our various products. We will actively apply inspections using new robot technologies to our own factories as well as externally.

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Development of Remote Control Technology That Offers a Flexible Working Style

Because of the declining birthrate and aging population, there are serious labor shortages in so-called "3D" (Dirty, Dangerous, and Demeaning) jobs such as manufacturing, and the improvement of working environments is an urgent task. As one of the solutions to this problem, remote control of manufacturing work is required.

Basically, a wired LAN is used to connect to different pieces of factory equipment because Wi-Fi cannot provide adequate responsiveness and reliability. However, there are physical and cost constraints to connecting many pieces of equipment by wire; therefore, it is difficult to realize remote control using wired networks. However, the emergence of private 5G has changed these constraints dramatically. We have carried out development to realize remote control of robots by making networks wireless using private 5G.

Introduction

Japan's population has continued to decline since 2011, and labor shortages due to the declining birthrate and aging population are an issue. Labor shortages are especially serious in so-called "3D" (Dirty, Dangerous, and Demeaning) jobs, and the improvement of working environments is an urgent task.

1 Background

Recently, much attention has been drawn to Smart Factories, where data on workers and equipment in the factory is collected by IoT (Internet of Things) technology, and then analyzed and used effectively to create new added value. Realizing a Smart Factory requires wireless communication, which enables flexible, efficient factory networking; one option for doing so is private 5G.

2 Remote manufacturing

During the COVID-19 pandemic, with regard to office jobs, remote working has become increasingly common, and web meetings have also become widespread. However, for manufacturing jobs, materials are basically processed with machine tools and assembled on site. Therefore, remote working is difficult.

To perform typical manufacturing jobs remotely, including transport, processing, assembly, inspection, and shipment, one option is to automate such jobs as much as possible using AGVs (Automatic Guided Vehicles) and robots and to operate such machines remotely. To do so, there is a need to transmit a control command to equipment via communication while monitoring the shop floor by communication, transmit the next command based on the received operation result, and then repeat these steps. This requires the equipment to be connected to a network, and connecting many pieces of factory equipment by wire requires the installation of a huge number of LAN cables, network switches, and other network devices inside the factory. In addition, if the shop floor layout is changed to manufacture a different product, these numerous cables must be rerouted. Developing a remote environment involves making a large number of arrangements. Therefore, wireless communication is highly beneficial in controlling factory equipment remotely.

Many factories have adopted wireless LAN, but wireless LAN is susceptible to noise and it is difficult to ensure stable communication. In addition, data is transmitted at high speeds between different pieces of equipment, and if data communication suffers delays, the equipment cannot operate normally. Therefore, wireless communication requires high reliability, high speed, and low latency. For these reasons, the 5th Generation Mobile

Communication System (5G) is now attracting attention.

In addition to wireless communication, robots that can be controlled remotely to do jobs that have heretofore been done by humans are necessary, and we have already put Successor [1)] into production as a robot system for controlling such robots. Successor uses a dedicated controller called Communicator to control robot arms remotely. Because of the aging of society, passing down the skills of experienced engineers, who are the successors of advanced manufacturing technologies, is a common issue in many developed countries. Successor is a new robot system developed to solve this issue.

Thus, we worked to outfit remote control robots with wireless communication in order to realize remote control of the shop floor.

3 Technical challenges in making factory communication wireless

5G is a communication system standard for which commercial service began in Japan in spring 2020. 5G is characterized by its ultra-high speed transmission, massive connected devices, and ultra-low latency. There are two types of 5G: carrier 5G and private 5G. While mobile operators provide carrier 5G, private 5G is used by private companies, local governments, and other organizations to build 5G networks on their own as shown in **Fig. 1**. This system was newly introduced for 5G to enable flexible development and operation of optimal 5G networks regardless of the service provision status of carrier 5G.

5G communication is expected to be applied for industrial purposes, but conventionally, information has mainly been communicated wirelessly. Therefore, the following performances, which are required to apply wireless communication for industrial purposes, must be verified.

① Transmission speed

To monitor the progress of processing statuses and other information in remote locations, transfer of high-definition video (HD video, 4K video, etc.) is required.

② Latency

The most important factor in controlling equipment by 5G communication is latency. Production equipment and robots in factories are controlled to an accuracy of milliseconds, and if there is even a slight delay in communication between pieces of equipment, they may not operate normally.

③ Coverage area

Millimeter waves, which enable 5G's high speeds, greatly attenuate in the air; therefore, they can travel only a very limited distance. It must be verified how far these millimeter waves travel on the shop floor.

④ Environmental tolerance (noise immunity)

Various working machines, including large cranes and forklifts, operate in factories. These may be sources of noise or obstacles for radio waves. Therefore, communication stability must be verified while the factory is running.

4 Overview of verification

To tackle these technical challenges, we introduced a 5G facility at the Harima Works on a trial basis from November 2020 to January 2021 and conducted a Proof of Concept (PoC) to verify 5G performance.

This test utilized 5G NSA (Non Standalone), while 4G was utilized for the core network (equipment having

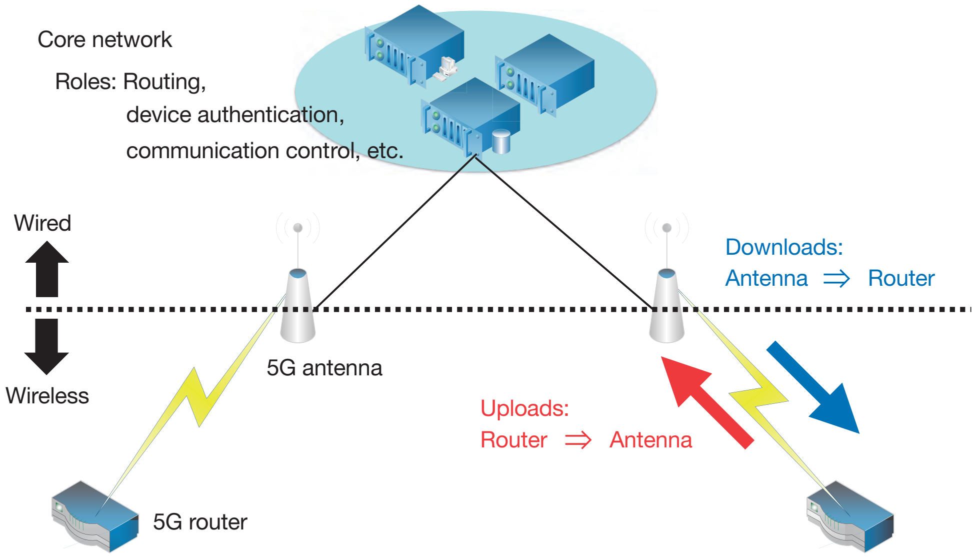

Fig. 1 Private 5G system

authentication, data packet transfer route configuration, mobility management, and other functions). Normally, however, 5G SA (Standalone) should be used, and all base station equipment, from the wireless communication equipment to the core network equipment, should be designed exclusively for 5G, but products for doing all of this are not yet available. Among 5G's three features, only high speed and high capacity can be achieved with the NSA system; with this system, 5G's latency is almost the same as that of 4G.

Successor-G [2)] in the Harima Works was used as the remote control robot. Successor-G is a robot system for grinding, deburring, and surface finishing. The worker operates the communicator, which eliminates the need to perform heavy work and relieves the worker from working under adverse conditions, such as in a hot and dusty environment.

Remote control with the current Successor-G assumes that the operated robot is located within line of sight, and the communicator and robot are connected via wired LAN. This time, as shown in **Fig. 2**, private 5G was used to establish wireless communication and to verify whether the robot could be operated remotely by monitoring the 4K video, and whether remote control was possible.

The test steps are shown in **Fig. 3**. First, we set up a 5G antenna on the first floor of the skills training facility at Harima Works and conducted a basic performance test and remote control test with Successor-G. Next, we moved the 5G antenna to the tank manufacturing factory at Harima Works and verified the communication area and noise immunity. We set up the core network in the administration office of Harima Works.

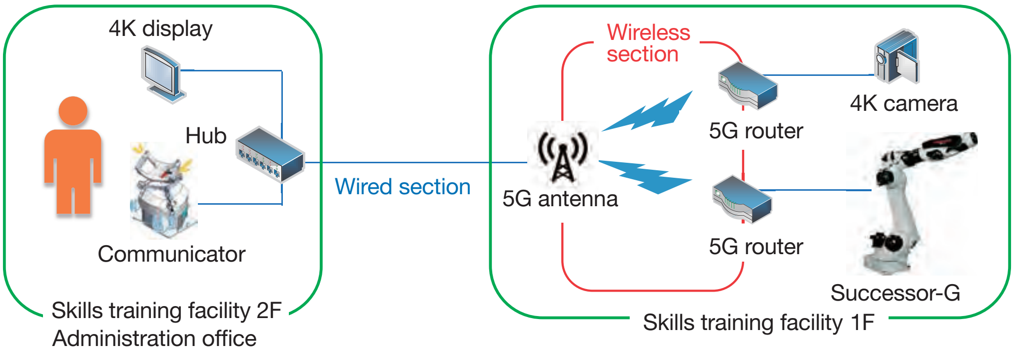

Fig. 2 5G system configuration for Successor

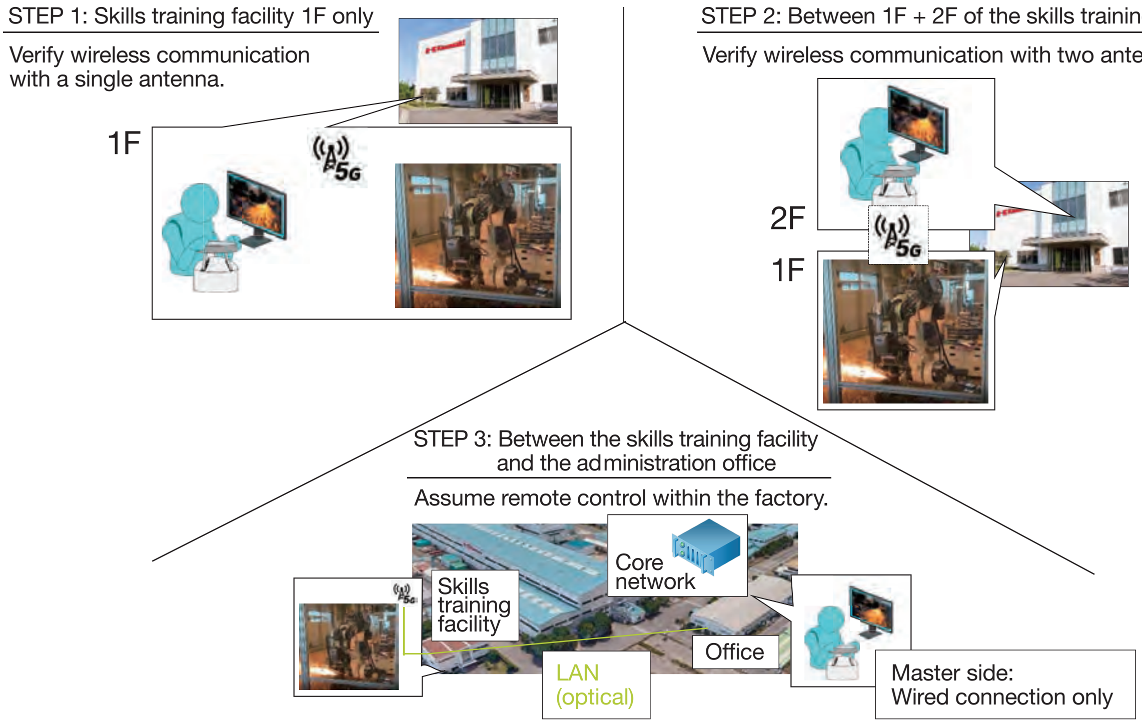

Fig. 3 Test steps

5 Details and results of verification

(1) Basic performance test for private 5G

We measured the transmission speed, latency, and radio field intensity with a network tester while changing the position of the 5G antenna in the skills training facility and in the tank manufacturing factory.

①② Transmission speed and latency

The maximum download and upload speeds were 650 Mbps and 120 Mbps, respectively, and these were as specified. The average latency was 6 ms. In terms of 5G NSA performance, 6 ms was a lower latency than expected, suggesting high performance.

Next, we conducted a high-definition 4K video transmission test. The results indicated that video could be transmitted from three 4K cameras at the same time, and we could transmit video of the shop floor to the administration office while patrolling the factory. Remote control via high-definition 4K video makes it possible to significantly reduce the amount of monitoring work performed under adverse working conditions.

③ Coverage area

We measured the radio field intensity and transmission speed at various points while moving around inside the tank manufacturing factory, which is 300 m deep. The results indicated that the upload speed exceeded 25 Mbps, at which 4K video can be transmitted, when the distance from the antenna was 50 m or less, and performance decreased when the distance was 100 m or more. In particular, visibility from the antenna is important, and without any obstacles, the upload speed reached 30 Mbps, at which 4K video can be transmitted, even at a distance of 260 m. Since factories have various working machines of differing sizes, where to set up the antenna should be considered. Regarding the area for millimeter wave communication, we were concerned that communication would be greatly affected by the surrounding environment, but when the antenna was set up on the first floor of the skills training facility, communication was possible from the second floor of the same building.

④ Environmental tolerance (noise immunity)

No noise was generated intentionally in the test, but the factory was running as usual during the test, so noise was generated by working machine operation and welding. Even in such an environment, communication during the test was not interrupted or unstable. Thus, adequate noise immunity can be expected even in a factory environment.

(2) Successor-G remote control test

We conducted verification of steel grinding. A grinder is a tool that causes a disk-shaped grinding stone to rotate at high speed and is used for grinding work. Each grinder weighs 2 to 3 kg, and it must be kept flush against the workpiece during grinding work as shown in **Fig. 4 (a)**, which is heavy work. In addition, noise is generated and grinding swarf flies into the air during grinding work, which subjects the worker to severe working conditions.

Successor-G has a force feedback function, with which, when the communicator is operated to bring a robot with a grinder into contact with a steel material, the reaction force is transmitted to the communicator. This function enables the worker to sense the actual force pushing the grinder flush against the steel material during grinding work as shown in **Fig. 4 (b)**. This provides the same level of operability as holding the grinder in one's hand without requiring the worker to hold a heavy grinder. This system has been realized by feeding back the output of the force sensor attached to the robot to the communicator with low latency. However, if there is a delay in communication between the communicator and the robot, the sense of contact cannot be reproduced correctly, leading to poor operability.

The robot was located on the first floor of the skills training facility, while the communicator was set up in the administration office, from which the grinder work was performed remotely.

Massive 4K video data and robot control signals were transmitted simultaneously via 5G, so the worker could operate the grinder based on force feedback from the communicator while monitoring how the steel material was being ground according to the high-definition 4K video displayed on a 50-inch display.

Multiple workers performed the grinder work, and some said that they could not operate the grinder smoothly and felt some resistance. This is presumably because ultra-low latency could not be achieved with the private 5G NSA system used for this test, resulting in an operational feeling that is inferior to that obtained by wired communication. If 5G SA is put into practical use, we can expect the same level of operability as that obtained by wired LAN. Although further verification is required as to the safety and reliability of wireless communication, if wireless communication can be used, robots that move freely within a factory can be operated remotely, so jobs done on the shop floor can be done remotely. Workers relieved of the burden of heavy work and adverse working conditions thanks to Successor-G will then be relieved from working on-site thanks to 5G.

In this test, the robot was operated from the administration office, which is located at a linear distance

(a) Manual work

(b) Successor-G

Fig. 4 Grinder work

of approximately 200 m from the skills training facility, but if the robot is operated remotely from another factory, or from a worker's home, the distance between the factories or the distance between the factory and the home will be an issue. Such a distance can be covered by a wired connection that employs optical fiber. The latency with optical fiber is 5 μs/km, and the round-trip latency is 1 ms when the one-way distance is 100 km. In the test, operability decreased at a latency of 6 ms. Even if an ultra-low latency of 1 ms can be achieved with 5G SA, the latency will be 6 ms if the wired section is 500 km long. If the latency can be decreased to 2 to 3 ms, the current level of operability can be achieved when the distance is 100 to 200 km. In addition, network devices, such as routers, are installed midstream in the communication path. Considering the latency of these devices, the distance at which force feedback is possible is expected to be 50 to 100 km. This means that even factory workers could work remotely from inside the factory's commuting area.

6 Future development

The distance at which force feedback is possible with a remote-controlled robot is estimated to be 50 to 100 km, and if the robot is operated from a more distant location, the work is expected to be done in a virtual space with a simulator. Although accurate simulation is required, digital twin technology, which seamlessly connects virtual and physical spaces, is attracting attention, and this field is expected to grow. Another approach is to operate a remote-controlled robot with a simple device such as a game controller, and operational precision is attained with the help of the AI onboard the robot.

In addition, we will link this system with, for example, operation data and production schedules with the aim of offering products to customers that have the optimal quality, cost, and delivery schedule in the factories of the future.

Conclusion

Although there are challenges in operating private 5G, such as the need to obtain a license for operation and the high cost, it will make it possible to do various kinds of work remotely via wireless communication, and in combination with other solutions, such as Successor-G, private 5G is expected to contribute to addressing the labor shortage due to the declining population, relieving workers of the need to do 3D (Dirty, Dangerous, and Demeaning) jobs, and passing down experienced workers' skills to the next generation.

We would like to thank OPTAGE Inc. for supporting this PoC.

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Kawasaki Heavy Industries Group
Main Products and Production Bases by Business Segment

Business Segment	Main Products	Main Production Bases
Aerospace Systems	• Aircraft (fixed-wing aircraft and helicopters), missiles, electronic equipment, space systems and peripheral equipment, simulators	Gifu Works (Kakamigahara, Gifu Prefecture) Nagoya Works 1 (Yatomi, Aichi Prefecture) Nagoya Works 2 (Tobishima-mura, Aichi Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.)
	• Aircraft components, rocket components, space equipment, target systems • Aircraft servicing, remodeling	NIPPI Corporation • Yokohama Plant (Yokohama, Kanagawa Prefecture) • Atsugi Plant (Yamato, Kanagawa Prefecture)
	• Aircraft engines • Aircraft gear boxes	Akashi Works (Akashi, Hyogo Prefecture) Seishin Works (Kobe, Hyogo Prefecture)
Rolling Stock (Kawasaki Railcar Manufacturing Co., Ltd.)	• Train cars, integrated transit systems	Head Office & Works (Kobe, Hyogo Prefecture) Harima Works (Harima-cho, Hyogo Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.) Kawasaki Rail Car, Inc. (U.S.A.)
	• Rotary snowplows, deicing material spreaders • Railway motor cars, heavy-lift cars	NICHIJO CORPORATION. • Akebono Plant (Sapporo, Hokkaido) • Inaho Plant (Sapporo, Hokkaido)
Energy Solution & Marine Engineering	• Cement, chemical, conveyers, and other industrial plant systems • Industrial boilers for land and marine use • Waste treatment facility • LNG tank and other storage facilities	Harima Works (Harima-cho, Hyogo Prefecture) Anhui Conch Kawasaki Energy Conservation Equipment Manufacturing Co., Ltd. (China)* Anhui Conch Kawasaki Equipment Manufacturing Co., Ltd. (China)* Shanghai Conch Kawasaki Engineering Co., Ltd. (China)*
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