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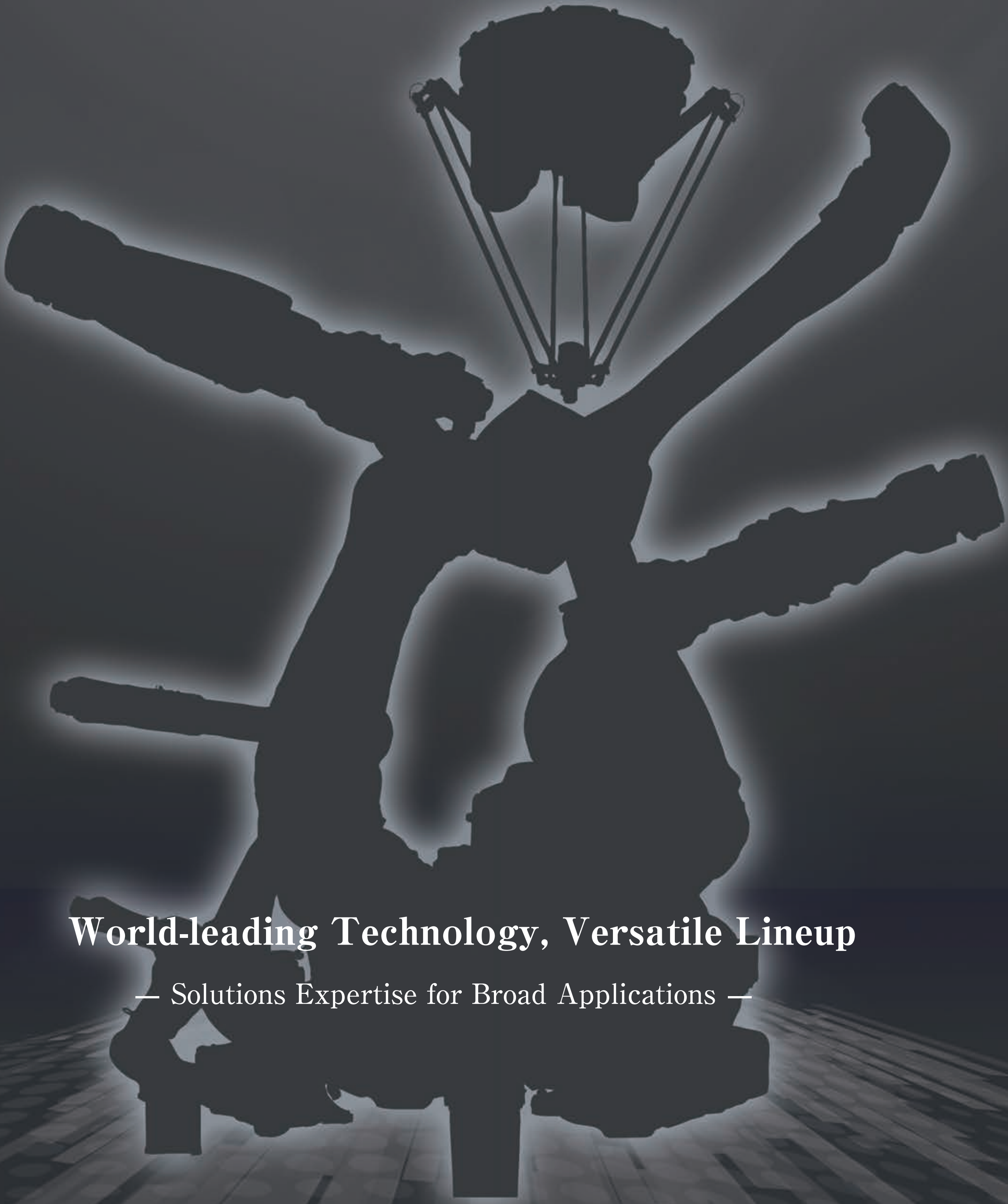

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Simple and friendly

Kawasaki Robot

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Lead Article

Technical Description

A Conversation with the President of the Precision Machinery Company

Current status and future prospects of the robot business

Makoto Sonoda
Senior Vice President
President, Precision Machinery Company

It has been two years since the launch of the Precision Machinery Company.

In October 2010, we merged the hydraulic equipment division and robot division to form the Precision Machinery Company. After the launch, interaction between the divisions has continued to grow, creating synergistic effects. In the manufacturing department, robots have been introduced at a faster speed than ever at the Nishi-Kobe Works (hydraulic equipment division), steadily moving toward automation. This has boosted production efficiency at the works and enabled the robot division to promote new application development on actual production lines, revealing the effectiveness of having both users and the manufacturer within the same company. In addition to the manufacturing department, the procurement department and the quality assurance department also engage in close information exchanges that are facilitating mutual growth.

Furthermore, we intend to actively promote information exchanges among the engineering and development departments as well. While robots were originally hydraulically driven, we moved in the 1980s to electric drives. Nevertheless, hydraulic drives also have many advantages. For example, most construction equipment operates on hydraulics. We are hoping that the recent trend toward hybrids will result in the appearance of innovative products that combine the power of hydraulics and controllability of electric drives.

Tell us about the latest robot topics.

The International Robot Exhibition was held in Tokyo in November 2011. The event was a success, with more exhibiting companies and visitors than in 2009. What was particularly noticeable among the exhibits was the trend toward downsizing and faster motion speed. Robots are becoming slimmer and more compact so that more robots can be placed on a single stage to realize shorter spot welding lines. In addition, by increasing the motion speed, the welding points of each robot can be increased to boost productivity. This compactness and higher speed contribute to the reduction of facility costs for automobile production lines. With our BX series robots, we reduced the installation area by approximately one-half and greatly reduced the time required for each welding spot compared to existing models, and we are confident that our robots are of the highest standard compared with other companies.

The next thing that attracted attention was the parallel link-type robots. The same type of robot developed by Kawasaki is called the picKstar, which is targeted at the food, medical products, and cosmetics industries. These three industries, unlike the automobile and electrical industries, are not greatly affected by business fluctuations, so relatively stable sales can be expected.

Cooperation between humans and robots appears to be increasing.

We are currently developing technology to bring humans and robots closer. The international standards (ISO) have been revised to allow software-based safety monitoring of robots. In response to this change, we have developed Cubic-S, a robot motion monitoring safety unit. Cubic-S will enable safety fences to be placed closer to the robot since they will only need to be placed according to the actual motion range of the robot. In addition, monitoring of the robot's motion range and speed has made it possible for humans to come closer to robots. These functions will also make it easier for human and robots to collaborate.

What is the recent trend in the robot market?

In 2009, China became the largest automobile producer in the world by volume, and production is expanding, with the parts industries benefiting from the boom as well. The same trend can also be seen in other emerging countries. Demand for robots has been surging as a result, and the emerging countries are growing in importance as a market for robots. In response, we are also strengthening our sales and service systems in emerging countries. Due to the economic growth in emerging countries and expansion of new markets such as smartphones, the market for semiconductors is growing as well. We have earned high marks from the manufacturers of semiconductor production equipment for the proposals we put forward, and we intend to respond aggressively to development requests from our customers and further boost our market share. Furthermore, we also plan to leverage our know-how cultivated in the area of clean robots for semiconductors to expand into clean environments in other fields.

A few words in conclusion?

Robots are now a fixture in a wide range of industries, spanning from automobiles and electronics to semiconductors. In addition, demand for robots has recently been rising fast for relatively new applications, such as the food, medical products, and cosmetics industries. In response to these market trends, we would like to expand our existing customer base by cultivating new customers and applications in new fields. Toward this end, we need to accelerate development of vision systems, sensors, and other technologies not seen before. We will continue promoting these developments, and providing new robot products that will benefit our customers.

Kawasaki's distinctive lineup of robot products

Yasuhiko Hashimoto
Associate Officer
General Manager, Robot Division, Precision Machinery Company

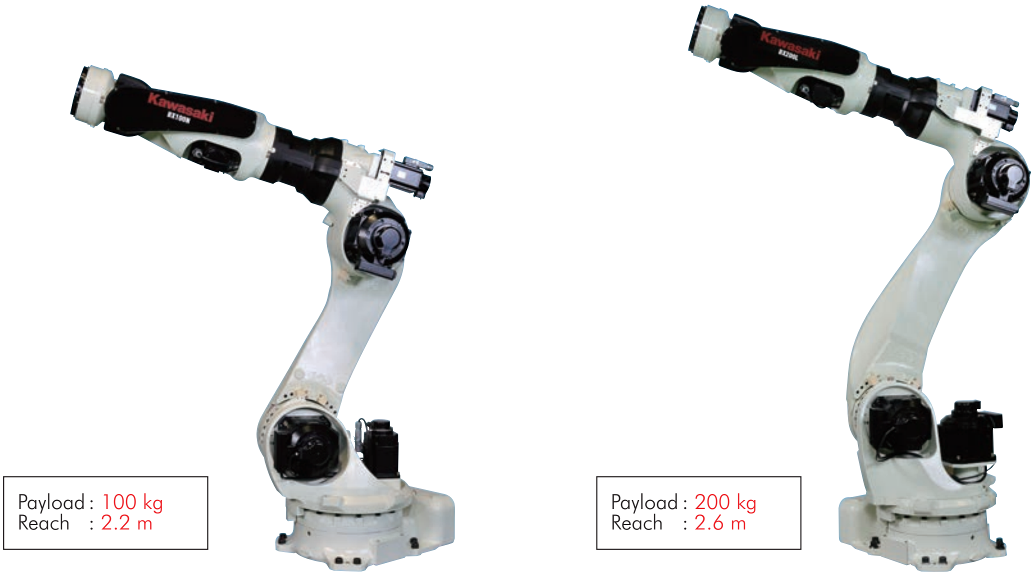
Preface

Kawasaki sells a wide variety of robots to industries such as automotive, general machinery and semiconductor. From an application point of view, we provide robots for spot welding, painting, assembly, handling, and arc welding etc. In addition to industrial robots, we also provide automation cells including peripheral equipment. In this paper, we would like to introduce Kawasaki's latest robot and automation cell lineups.

1 Robots for automotive and general machinery industries

In 2011, we launched the BX series robots for spot welding application (Fig. 1). This new BX series features a more compact and slimmer arm which realizes higher motion speed compared with our existing ZX series. In addition to these features, a new structure is employed that enables external cables to be housed inside the robot arm and wrist, realizing a neat and slim design. We also launched the NC locater robot designed for flexible part (workpiece) positioning previously conducted by dedicated jig tools. By combining the BX series robot and the NC locater robots, we can provide very compact and flexible car body assembly lines to customers.

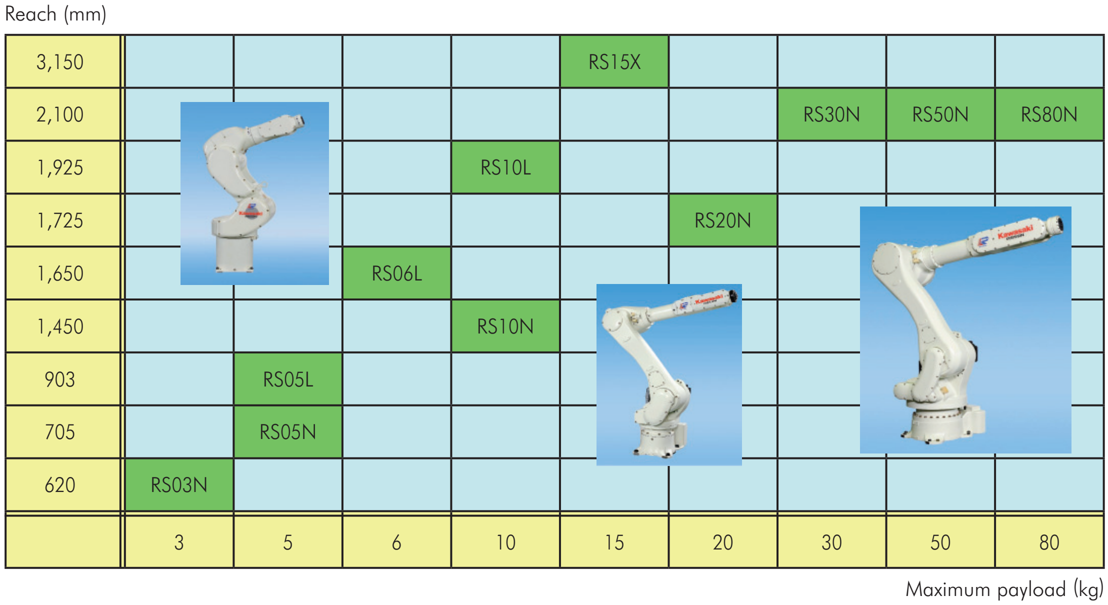
For the general machinery industries, we offer the RS series robots (Fig. 2). The RS series robots feature a slimmer arm structure that enables robot motion within a narrow working space and has a wider motion area and higher speed compared with our former robot model the FS series. The RS series lineup covers a wider range of



BX100N

BX200L

Fig. 1 BX series



Reach (mm)

3,150					RS15X				
2,100							RS30N	RS50N	RS80N
1,925				RS10L					
1,725						RS20N			
1,650			RS06L						
1,450				RS10N					
903		RS05L							
705		RS05N							
620	RS03N								
	3	5	6	10	15	20	30	50	80

Maximum payload (kg)

Fig. 2 RS series (representative example)

payload from 3 kg (RS03N) up to 80 kg (RS80N). We also launched RS series robots for dedicated purposes, such as palletizing (RD80N) and sealing (RS15X). Thus, the RS series covers a wider range of application—handling, assembling, transferring, and sealing etc.

2 High-speed pick and place robot

For high-speed pick and place application, we developed the picKstar robot with a parallel link mechanism (Fig. 3). This robot is used for parts aligning and box packing of small parts in food, pharmaceutical, and cosmetics industries. Our picKstar demonstrates an extremely high speed and a wider motion range.

In many picKstar applications, we use vision systems. Because picking parts are delivered by the infeed conveyor in random orientations, we use a vision system to detect the orientation, and based on this information, the robot can pick the parts accurately, and then execute the box packing action. Kawasaki already developed a vision system named K-VFinder for 2D application and LSC (Laser Slit-scan Camera) for 3D application. In the case of picKstar, we use the vision system K-VFinder for 2D, and realize high-speed and accurate pick and place action.

Fig. 3 picKstar

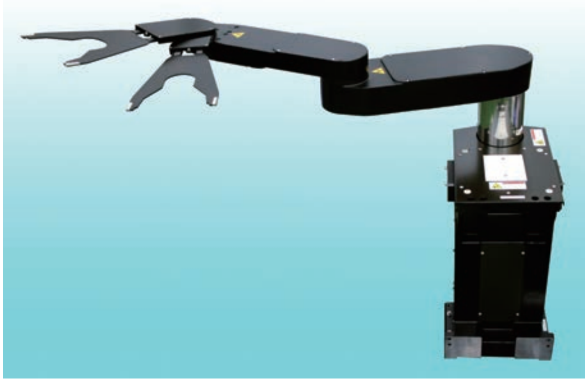


Fig. 4 NT series

3 Semiconductor Robot

Our lineup for the semiconductor industries includes the NS series, NX series, and NT series (Fig. 4) as semiconductor wafer handling robots. The newly launched NT series provides a common platform solution from 2 FOUP up to 4 FOUP applications without a track. Kawasaki wafer handling robots demonstrate minimal vibration and high accuracy in high-speed motion because of the high-stiffness arm and high-performance controller. These robots are highly evaluated by high-demand customers and shipped to many semiconductor equipment customers and end-users. Recently, we are proceeding with development activities for the coming new standard 450 mm wafer.

*FOUP (Stands for Front Open Unified Pod. A type of closed wafer cassette.)

4 Automation Cell

To cover a wider range of customer requests, Kawasaki also offers robot automation cells in addition to a lineup of industrial robots. In this section, we would like to introduce our representative automation cells.

(i) DANBOT

DANBOT is an automation cell that is specially designed for cardboard manufacturing customers, and consists of not only a robot, but also an end-effector, a conveyor, a stacking device, and slip sheet extraction devices etc. By applying the DANBOT cell, automated cardboard palletizing lines can be very easily set up. No dedicated slip sheet machine is required, which enables space-saving installation for the customers.

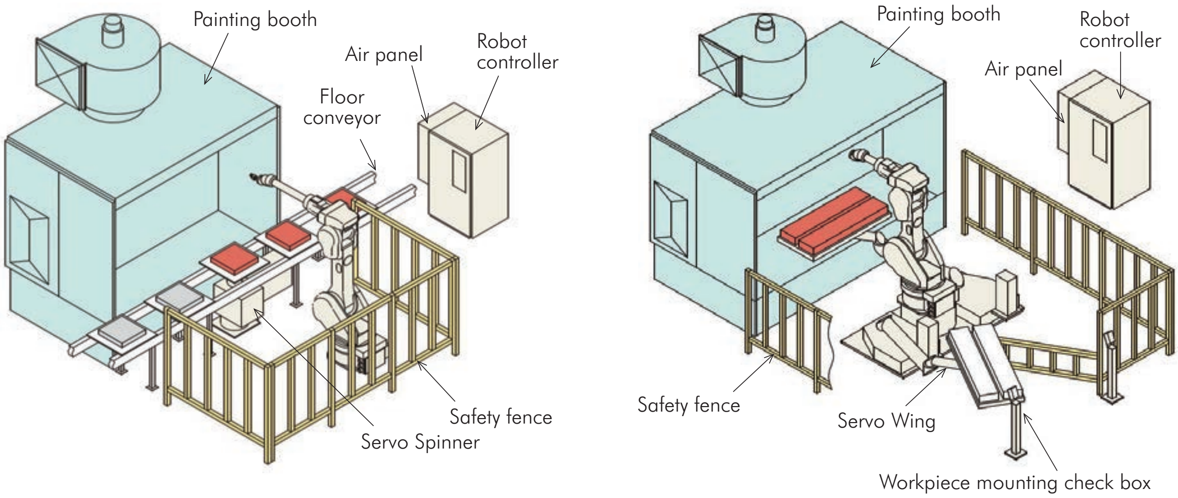


Fig. 5 Example of painting automation cell

(ii) Painting Automation Cell

Kawasaki prepared six types of painting automation cells that can be selected according to the size and shape of the painting parts (Fig. 5). Because we can provide these cells as an integrated set, these can contribute to shortening the startup time for the customers.

5 Controller

The controller is a very important unit for a robot to perform high-speed and high-accuracy motion stably. Our newly launched controller is the E series, and it is now already applied to the BX series, RS series, and picKstar robots. According to the global region, we prepared Asian and Japanese version, North America version, and EU version E controllers. We also prepared small size E series controllers E7X/9X for small robot application.

In the case of the Asian and Japanese version E series controller, we realized a 40 percent volume downsizing, and 25 percent footprint downsizing compared to our former D series controller (Fig. 6). As for the Teach Pendant, the operation method has not been changed from the current model, but a new GUI delivers a more user-friendly operation. A USB port—now a global standard—is incorporated. And the main CPU processing capacity has been greatly improved, thus enabling advanced control.

Closing

Kawasaki is now developing peripheral equipment, support tools, vision systems, and end-effectors as well as industrial robots and automation cells. We are also developing the offline teaching software K-ROSET, which makes simulation on PCs very easy. From now on, we would like to promote these developments and also provide user-friendly and productivity-boosting products.

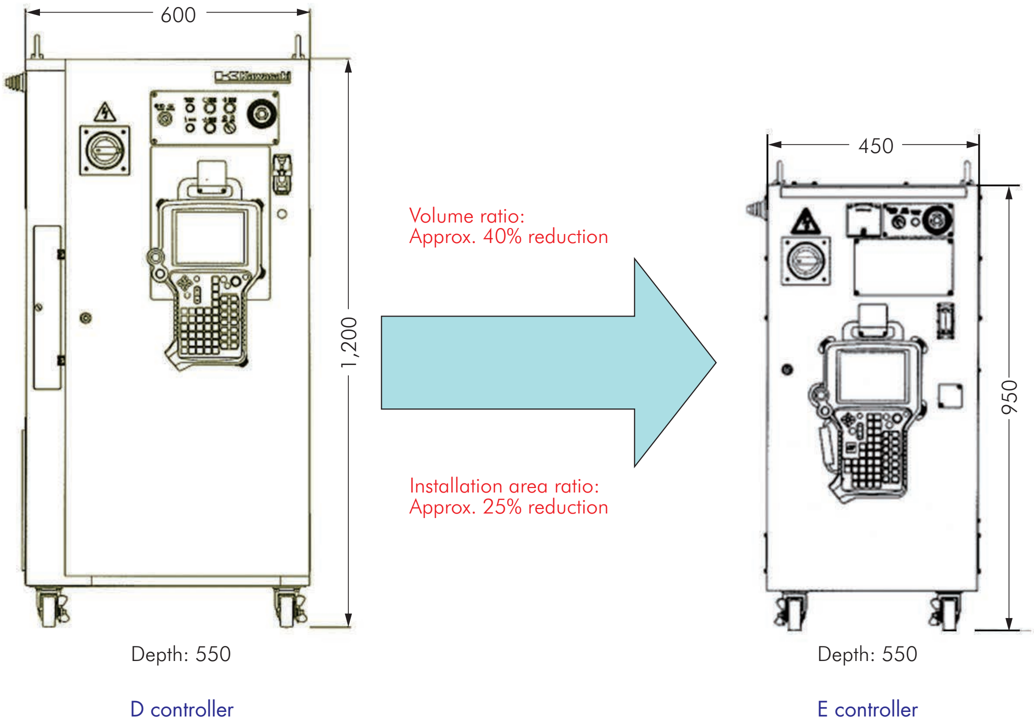


Fig. 6 Major downsizing achieved with E controller
(Example of Asian and Japanese version)

BX series new spot welding robots that innovate production lines

Spot welding robots have shown their capabilities in automating production and in raising product quality in automobile manufacturer where the leading users are found. The needs for increased efficiency of facilities and reduced costs have been growing recently. This paper presents the BX series of new spot welding robots that will serve these needs by enabling "space-saving," "concentrated layout," and "increased speed."

Preface

In automobile production facilities, reduction of total facility costs is one of the most important issues. Today, there is considerable demand for slimmer and more compact robots that take up less space, as well as robots with higher operating speeds for greater productivity.

At Kawasaki, we have used the large general-purpose Z series robots for spot welding applications. The Z series has a wide operating range and is capable of mounting a wide range of peripheral equipment, allowing it to be used for assembly and handling applications as well. For spot welding applications, however, the robots only require a set of specified equipment and a limited operation range, and operations mostly involve moving between short-distance teaching points while repeating acceleration and deceleration.

Therefore, we have developed a new series of spot welding robots called the BX series, which features improved robot and welding movements, to enable space-saving, concentrated layout, and increased speed. The BX series consists of the BX100N and BX200L, with a payload capacity of 100 kg and 200 kg, respectively.

1 Achievement of space-saving and concentrated layout

An effective way to reduce costs for automobile production facilities is to shorten the length and narrow the width of the production lines to create a compact facility. This requires reducing the space occupied by robots for a more concentrated layout. The following discussion describes the design features added to realize a smaller footprint and a concentrated layout.

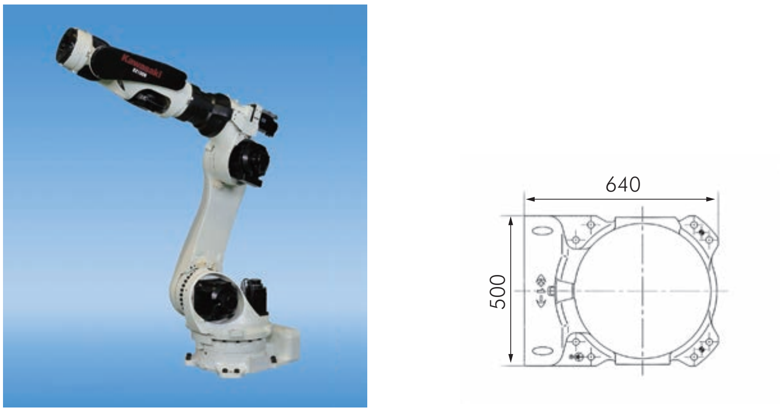
(1) Reduced layout area

The Z series model has additional space for optional wiring and tubing at the robot base to provide expandability for various applications. On the other hand, the BX series is limited to the wiring and tubing sufficient for spot welding, and they are routed through a hollow tube located at the center of the rotation axis. By making this design change, we were able to reduce the installation area to about 52% of the original size. The external view and layout of the BX100N and the existing model ZX165U with similar capabilities are shown in Fig. 1.

(2) Arm length suitable for spot welding application

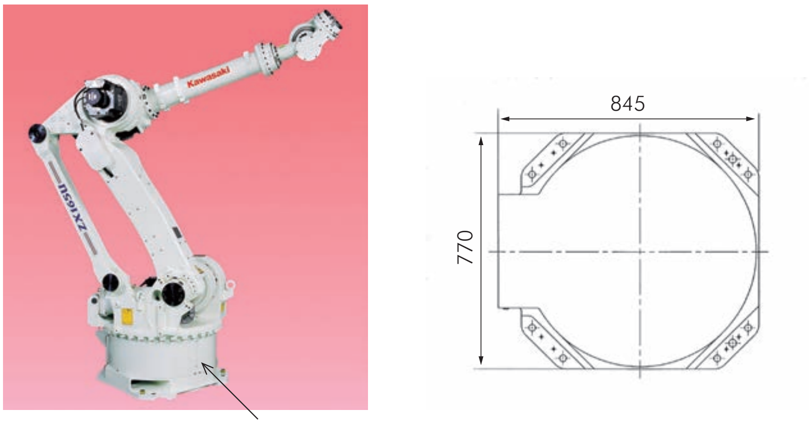
The BX100N has a 2,200 mm reach (maximum reach distance from the center of the robot's rotation axis to the center of its wrist area), and the BX200L has a 2,597 mm reach.

While a longer robot arm length can ensure a broader operating range, it also increases the overhang in the rear side when the arm is folded up. This enlarges the interference area, which makes it difficult to achieve a high-density layout. Therefore, we analyzed the teaching points in past spot welding operations to determine a



Wiring and piping housed in the hollow section at the center of the rotation axis

(a) BX100N



Optional wiring and piping space

(b) Existing model ZX165U

Fig. 1 External view and layout of BX100N and ZX165U

suitable arm length.

The BX100N covers over 90% of the teaching points created for the various spot welding programs developed to date, which means most of the spot welding operations can be handled with this model. In addition, the arm length was shortened and the spring for power assistance on the forward and backward axes was removed to reduce the interference area (Fig. 2).

On the other hand, the BX200L has the same reach as the existing ZX series model and covers virtually all the teaching points, making it a viable replacement for the existing model. At the same time, the interference area of the arm rotation axis has been reduced in the BX200L by replacing the large coil spring for power assistance on the

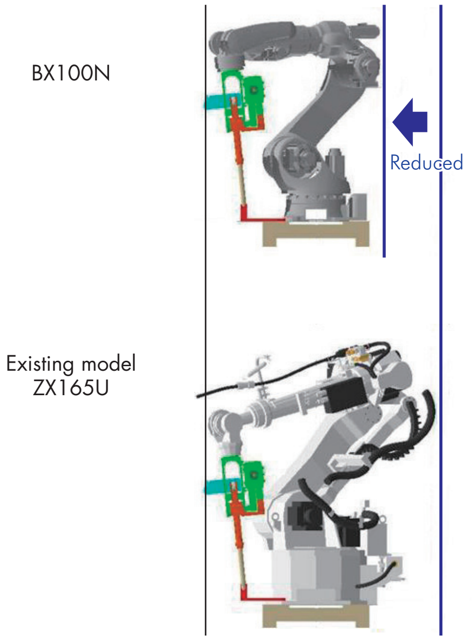


Fig. 2 Reduction in interference area

forward and backward axes with a gas spring. A comparison of operating ranges is shown in Fig. 3.

(3) Built-in spot welding cables/hoses

In spot welding, cables and hoses must be installed from the robot base area to the welding gun mounted at the end of the wrist. Previously, the cables were hung on a hook that was attached to a pole on the arm, or they were taken along the arm (Fig. 4(b)). With these methods, however, a certain distance must be secured between the arm and the cables to avoid interference between them, resulting in a wider interference area when the cables were included. Moreover, since the cables swing when the robot moves, it is difficult to predict cable behavior, particularly in offline teaching, so an even wider interference area had to be assumed.

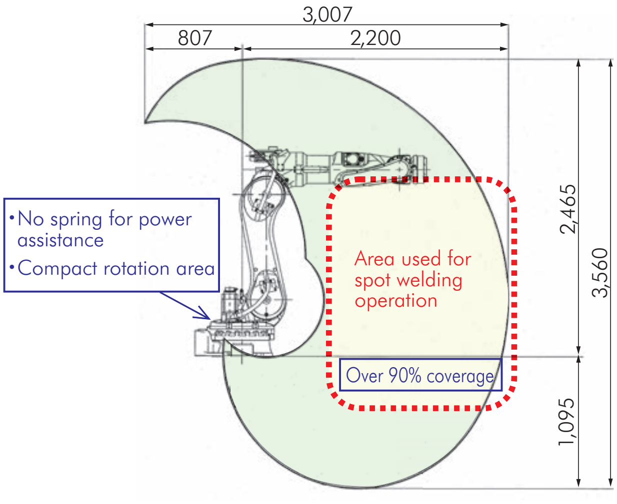
In the BX series, the cables are housed inside the arm to reduce the interference area and eliminate the need to take cable behavior into consideration (Fig. 4(a)). This enabled reducing the distance between the robots and the workpiece, as well as the distance between the robots themselves. It also reduced the amount of corrections required by offline teaching, reducing the amount of time required for line setup or changes.

(4) Compact, lightweight arm

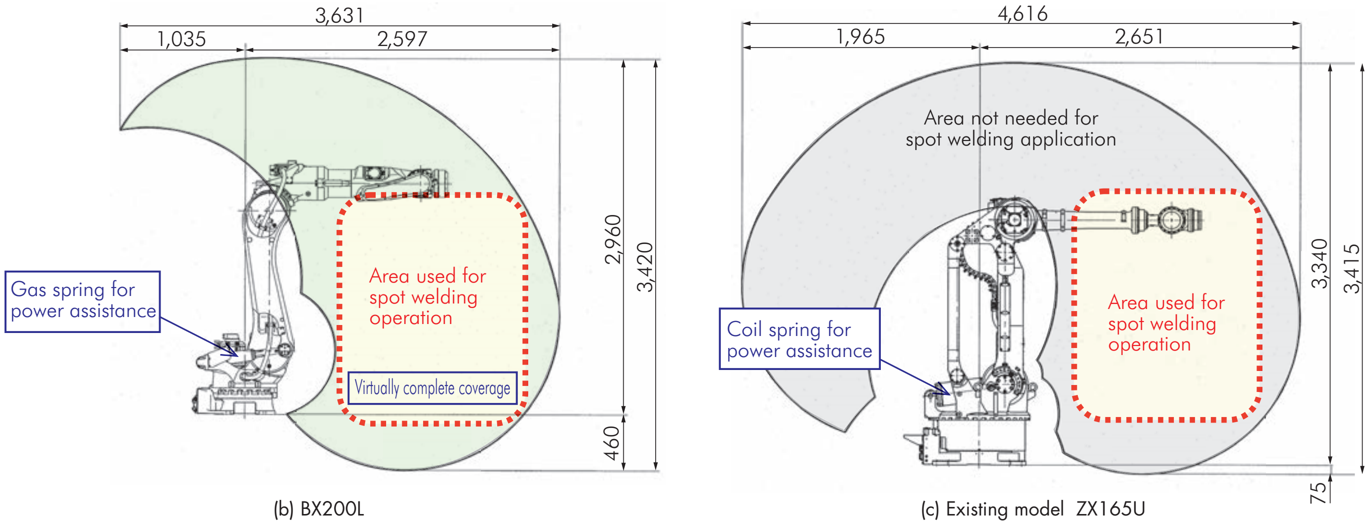
In the BX series, weight reduction was achieved by reducing the number of parts and using strength analysis to reduce part sizes to a necessary and sufficient level. As a result, we managed to reduce the weight of the BX100N by over 45%, and the BX200L by over 30%, compared to existing models.

2 Increasing operating speed

By increasing the operating speed of robots, the amount of workload handled by each robot will also increase. As a result, fewer robots will be required to perform the same amount of work, thus making a shorter production line a possibility. The following discussion describes how we achieve increased operating speed.



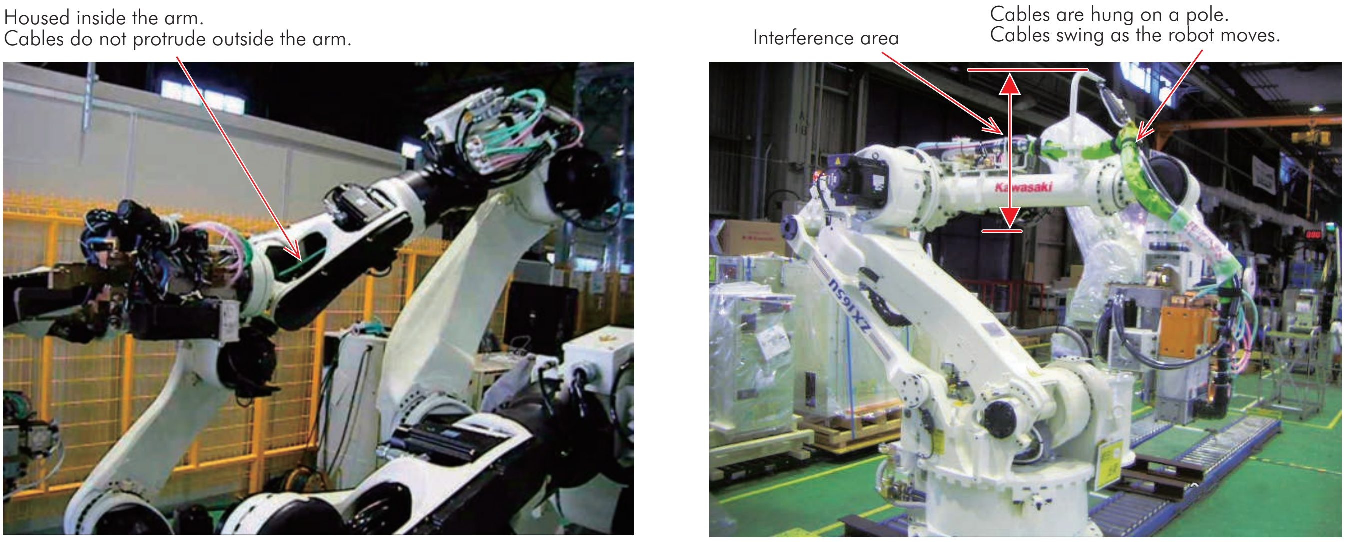
(a) BX100N



(b) BX200L

(c) Existing model ZX165U

Fig. 3 Comparison of operating ranges



(a) BX series

(b) Existing model

Fig. 4 Cable and hose processing

(1) Increased robot operating speed

The BX series robots achieve faster operating speeds by using the “variable acceleration and deceleration function” and “variable maximum speed function” described below.

(i) Variable acceleration and deceleration function

Forces such as gravity, inertia, centrifugal force/Coriolis force, and friction act on the robot arm in variable strength, depending on the arm's position, speed, and acceleration. When the robot operates, these variables are calculated to obtain the optimal acceleration and deceleration so that the motor force can be utilized to the maximum extent. While this is not a new function, improvement in the controller's calculation speed has enabled more efficient use of the motor force in the BX series.

(ii) Variable maximum speed function

Servo motors produce less torque in the high speed range due to the back electromotive force generated internally. In addition, reduction gear in each axis increases the resistance torque as the speed increases. As a result, even if maximum electrical power is supplied, the torque available for the robot becomes smaller as the speed increases, so the robot's acceleration and deceleration speeds also decrease. When operating over a certain distance, whether it is better to increase the speed or to keep the speed low and raise the acceleration and deceleration speeds depends on the operation distance. Therefore, the optimal combination of speed and acceleration for achieving the shortest possible operation time is calculated based on the relationship between the speed and the output torque of the robot.

(2) Increased speed in spot welding operations

Robot operations involved in spot welding operations can be divided into “moving between continuous welding points” and “application of pressure on welding points”. The new spot welding control employed in the BX series achieves high speed in relation to these operations.

(i) Moving between continuous welding points

In conventional operations for moving between continuous welding points, the gun axis moves to the clearance position after welding is completed, and then the robot moves to the next welding point, tracing a so-called “wedge-shaped” locus. While this is close to the air gun operation locus and thus makes it easy to track the gun movement, it includes unnecessary movement paths and is not conducive to reducing the cycle time (time required for performing the desired operation). In the BX series, therefore, the robot movement to succeeding welding points is performed simultaneously with the gun axis movement for applying pressure to the welding points, tracing a so-called “arc” locus. This tracing of an “arc” locus enables shortening the movement path between continuous welding points and results in reduced cycle time.

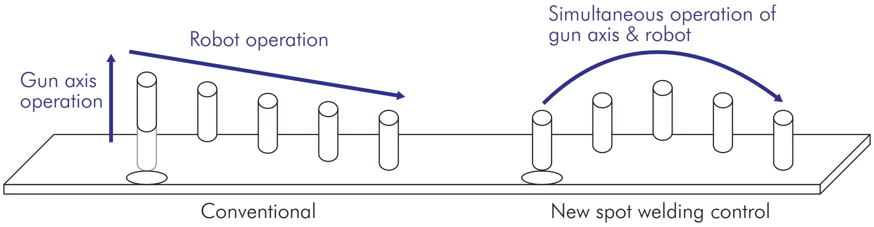
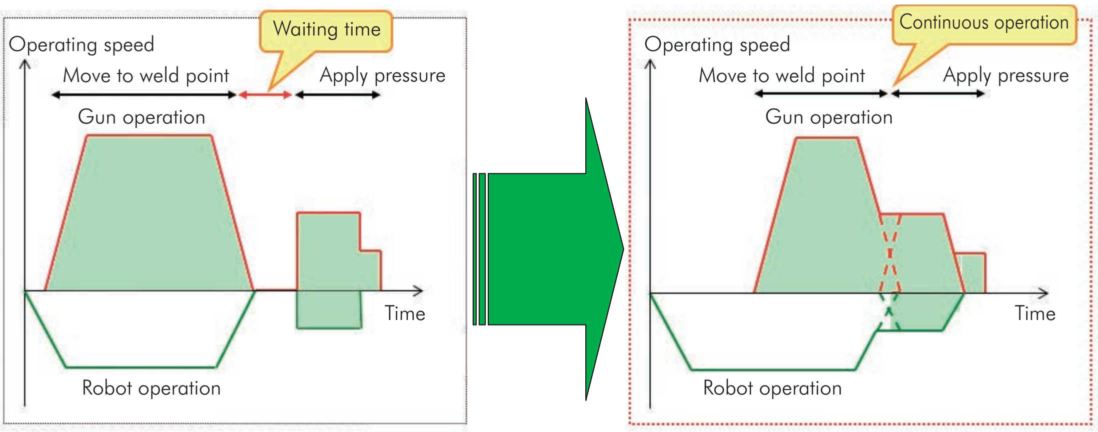


Fig. 5 Operational locus in conventional and new spot welding controls



(a) Conventional

(b) New spot welding control

Fig. 6 Comparison of operational locus between conventional and new spot welding controls

A comparison of operational locus between conventional control and new spot welding control in traveling over continuous welding points is shown in Fig. 5.

(ii) Application of pressure to welding points

In the conventional spot welding control, the robot pauses at the workpiece contact position before applying pressure in order to obtain a stable welding pressure. While a stable welding pressure can be obtained with this method, there is a slight waiting time at the workpiece contact position.

For the new spot welding control in the BX series, the pause at the workpiece contact position was eliminated to enable applying pressure at a constant speed, for a continuous and smooth operation that reduces the cycle time while maintaining a stable welding pressure.

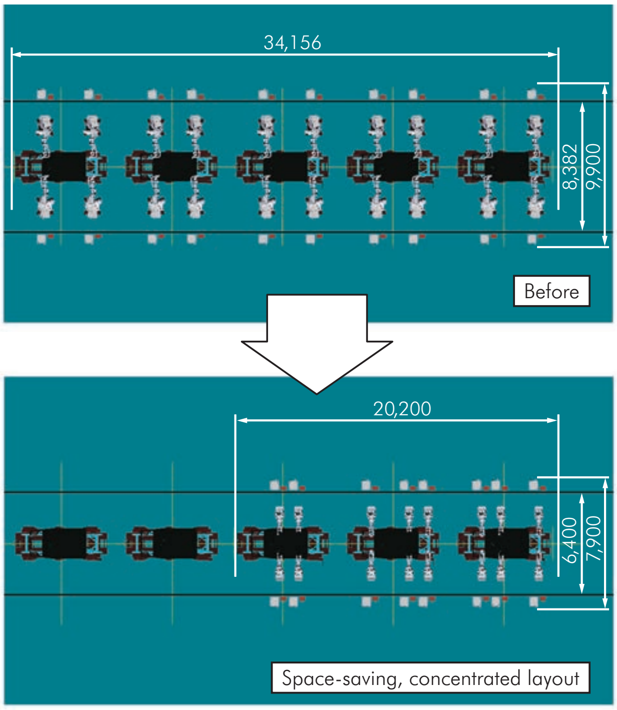
The change in gun axis and robot operation speed during pressure application between the conventional and new spot welding controls is shown in Fig. 6.

(3) Higher speed through optimization of gun axis acceleration and deceleration

In the conventional method of gun axis acceleration and deceleration, the maximum acceleration time presented by the gun manufacturer was used as a fixed parameter. However, this value makes an allowance for a certain margin, and a certain amount of motor torque margin is known to exist even when the gun axis is operated at the maximum acceleration time. For the BX series, the

Table 1 Reduction rate of the cycle time in the BX series

	BX100N	BX200L
Maximum load	24% reduction	20% reduction
100 kg load	23% reduction	21% reduction



Item	Conventional		After adoption	
No. of robots	20	100%	16	80%
No. of stations	5	100%	3	60%
Area (m^2)	286	100%	129	45%

Fig. 7 Effect of space-saving, concentrated layout, and increased speed

optimum gun axis acceleration and deceleration speeds are determined to make full use of the allowed gun axis motor torque, thereby achieving further reduction in the cycle time during pressure application.

(4) Effects of increased speed

Table 1 shows the rate of reduction in the cycle time achieved in the BX series as compared with the existing ZX165U model, which is not equipped with this function, for a continuous welding operation involving 10 welding points pitched at 50 mm intervals.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3 Effect of space-saving, concentrated layout, and increased speed

An example of the effect of space-saving, concentrated layout, and increased speed is shown in Fig. 7. Increased speed has enabled greatly reducing the number of robot units than before, and the installation space has been considerably reduced through space-saving and concentrated layout.

Concluding remarks

By leveraging the know-how and experience cultivated over the years, we at Kawasaki intend to continue developing new technologies and new products that help achieve labor savings, improved product quality, and greater efficiency in production facilities.

High performance pick and place robot "picKstar"

Delta-type parallel link robots targeting the food, medical products, and cosmetics industries have in recent years been released in rapid succession, intensifying competition. This paper presents Kawasaki's high-speed, high-rigidity pick and place robot "picKstar", which offers superior performance compared to other competitor products.

Preface

Facility investment in the manufacturing sector was suppressed by the global economic recession of 2008, and the number of industrial robots installed declined sharply at automobile and semiconductor-related companies, which make up our main customer base. While the market has slowly recovered since 2009, we determined that new industries should be cultivated in addition to automobiles and semiconductors in order to generate a stable income not affected by economic fluctuations.

We turned our attention to solar power, which is attracting interest as a renewable energy, and to the food, medical, and cosmetics industries, where demand is solid and not easily affected by economic fluctuations. With a focus on pick and place operations, where automation is most in demand, we developed the proprietary delta-type parallel link picKstar robot (Fig. 1), which achieves the industry's top performance for high speed and high reliability.

1 Characteristics

The three processes most representative of automated facilities for food, medical products, and cosmetics are the picking, packing, and palletizing operations (Fig. 2). We

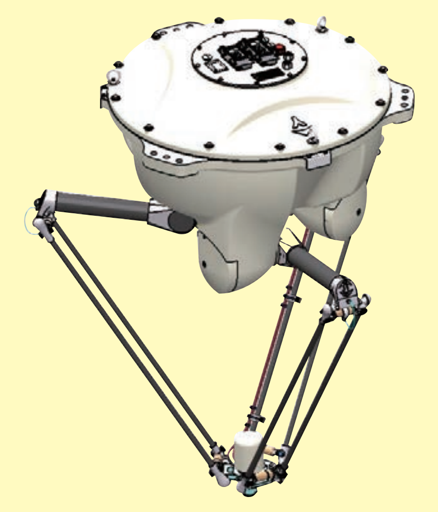


Fig. 1 picKstar

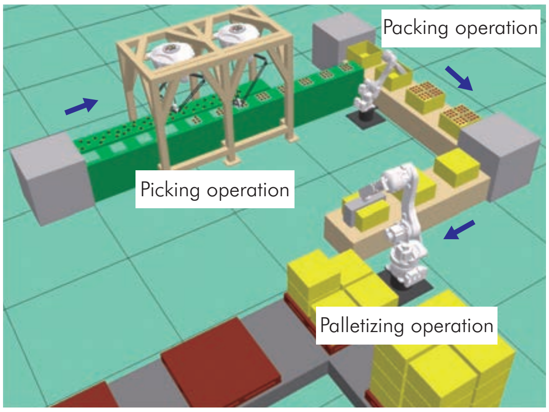


Fig. 2 Picking, packing and palletizing

developed picKstar for the picking process, which comes at the top of the three operations, and it features the following characteristics.

(1) High-speed performance

One major characteristic of the delta-type parallel link robot is the placement of the motor, reduction gear, and metal frame, etc., in the base area, and the use of lightweight CFRP (carbon fiber reinforced plastic) arms in the movable part, to achieve high-speed motion. However, since force applied to each of the robot's mechanical elements near the outer edge of the motion range increases by a greater proportion than in the center of the motion range, achieving high-speed motion over a wide range required that we both lighten the structural members of the movable part and ensure strength capable of handling loads at the outer edge. Therefore, we optimized in various combinations the motor power, drive system structure and strength, robot arm rigidity, elastic force of the spring unit, and strength of the mechanical parts at the end of the robot arms which move at high acceleration and deceleration rates, to achieve high-speed operation over a wide range.

(2) High rigidity

The second characteristic is high-speed operation. In general, high rigidity is required to maintain vibration damping while operating at high speeds. Therefore, we performed detailed studies into the types, direction, and laminated structure of fiber in CFRP used in the robot arm (Fig. 3), and ensured sufficient rigidity in the structural members of the moving parts other than the robot arms, thereby achieving levels of stopping performance and vibration damping unseen in this type of robots. As a result, we were able to reduce overshoot and vibration to enable highly reliable picking, earning high marks from customers in solar-cell-related wafer picking applications that require extremely high positioning accuracy and low vibration.

(a) Upper part of the arm

(b) Lower part of the arm

Fig. 3 CFRP arm

(3) Reliability against lubricant leaks

The markets where picKstar is utilized are industries handling solar cells, food, medical products, and cosmetics, etc., where lubricant leaks are not tolerated. Therefore, we have taken two main measures for picKstar's gearbox to achieve superior reliability in regards to lubricant leaks (Fig. 4).

(i) Internal pressure relief mechanism

When the robot performs continuous operations, the pressure inside the gearbox rises, increasing the risk of lubricant leaks from parts mating faces as well as rotating and sliding parts, etc. Therefore, we incorporated a mechanism into picKstar for relieving the rise of internal pressure, reducing the risk of lubricant leaks.

(ii) Double seal structure

The locations with the highest frequency of lubricant leaks are the rotating and sliding parts. We installed two layers of oil seals in these parts to reduce the risk of lubricant leaks.

(4) Tolerance to chemical washing

Since the robot is used for food, medical products, and cosmetics picking operations, we expect that it will be subjected to spray washing and chemical washing for sanitary requirements. For this reason, advanced sealing performance, and chemical tolerance for the exposed parts, are required. For sealing, we use a seal structure at the boundary between the robot interior and exterior to achieve IP67 waterproof and dust-proof protection, and also designed a curved frame structure for the robot exterior that leaves few bumps and protrusions for particles to become trapped in during washing. In addition, for chemical tolerance, we have designed the coating for the base section of the robot's main body and surface processing for the movable parts to give tolerance to the strongly alkaline sodium hydroxide cleaning agents commonly used in the industry for washing, and also to some weakly acidic cleaning agents.

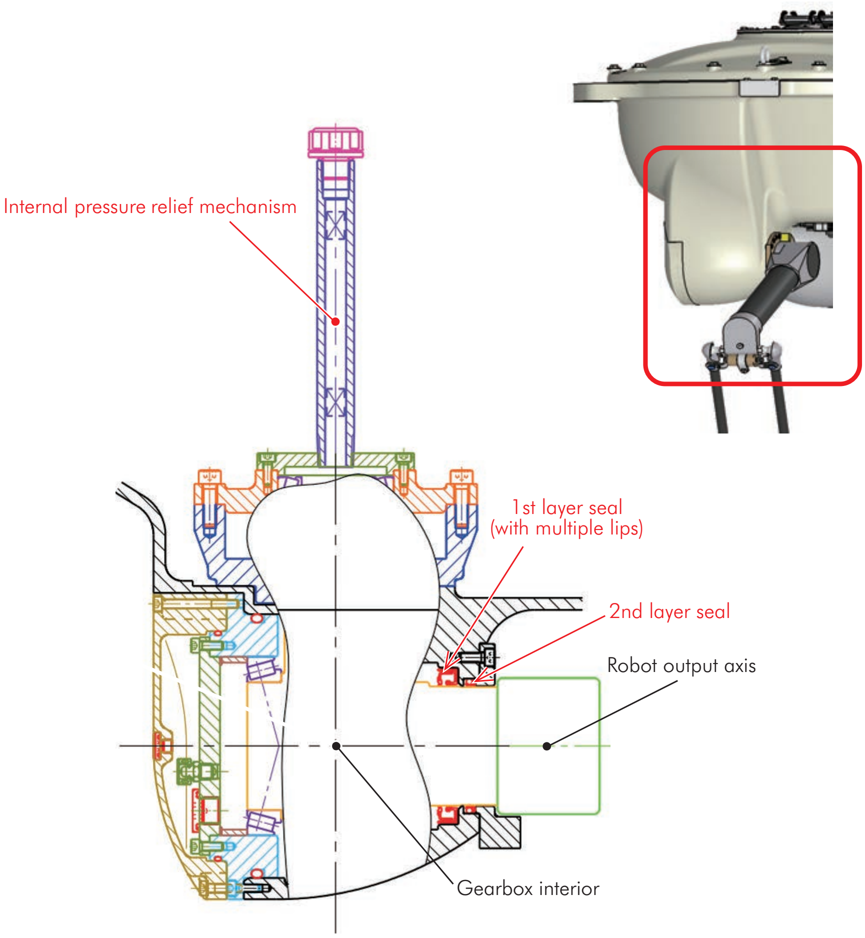


Fig. 4 Measures against lubricant leak (gearbox configuration diagram)

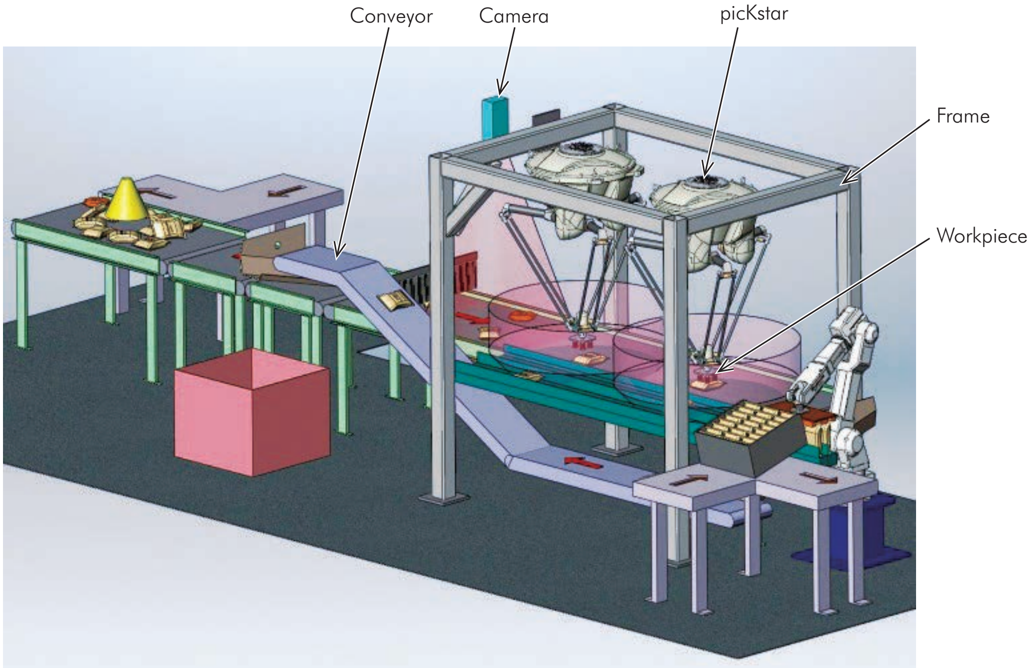


Fig. 5 System layout example of picKstar

2 System configuration

In this section, we introduce an example using an image processing system with multiple robots and conveyors. A system layout example using picKstar is shown in Fig. 5, and a system configuration example is shown in Fig. 6. The following discussion describes an image processing system and data management in a picKstar system configuration.

(1) Image processing system

The image processing system operates as follows.

① The target object (workpiece) to be processed is fed to the robot.

② An upstream camera detects the workpiece position and orientation, and transmits this information to the robot.

③ When the workpiece arrives, the robot picks it up and transfers it to the transport conveyor in the predetermined alignment.

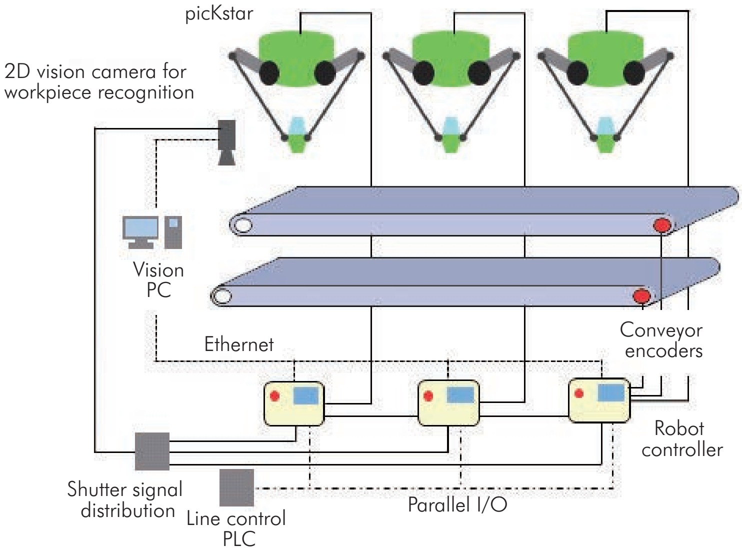


Fig. 6 System configuration example for image processing system

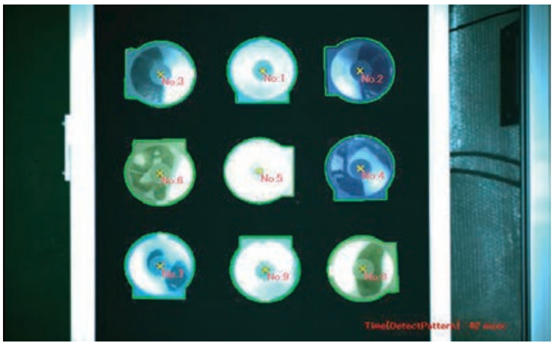


Fig. 7 Example of pattern matching screen

Fig. 8 Example of image binarization screen

④ An image recognition camera captures the image of the workpiece fed to the robot to discern its position and orientation.

At this time, if lens distortion correction is needed for the incorporated image, the distortion is corrected and detection is performed. The detection process can be performed with the following two methods.

① Pattern matching method, which uses edge information to recognize the workpiece against model registration (Fig. 7).
② Method using binary images to compare and detect area, circumference, and other characteristics (Fig. 8).

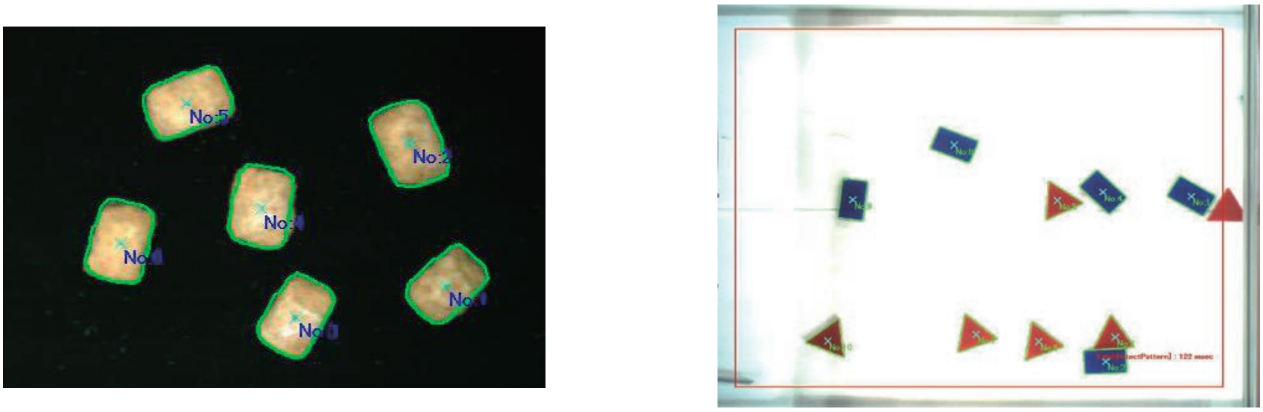
In some cases, these processes can also be used in tandem. New detection methods could also be added. The system also features an interference check function for checking for obstructions when the detected workpiece is removed by clasping, a color discrimination function, and a local shape detection function, etc. The workpiece information detected with these functions is converted into the robot's real coordinate system and sent as measurement results to the robot. The measurement results can be sent at the same time to multiple robots in accordance with specified distribution settings.

(2) Data management between robots

An external interface unit can be used to send between the robots such information as the placement patterns and the number of workpieces to be placed on the discharge conveyor. Moreover, even if one robot has stopped for some reason, the other robots can be used as backup for the operations of the stopped robot, enabling a flexible response to unexpected situations.

(3) Example of practical image recognition

As examples of actual applications of work image recognition, Fig. 9 shows processed images of frozen food items (deep-fried food) and plastic pieces with different shapes and colors. The system takes in the workpiece



(a) Frozen food items (binarization process)

(b) Plastic pieces (pattern matching)

Fig. 9 Example of work image recognition

Fig. 10 Example of gripper

image to recognize the shape of the workpiece, and then detect the center of gravity and orientation. Size discrimination is also possible, enabling operations such as sorting fed workpieces by size.

In addition, we have developed hands (grippers) that can be applied to various workpieces (Fig. 10), and we have earned high marks from customers for their performance as well.

Concluding remarks

Since commencing development of this robot and peripheral systems, we have obtained much technical knowledge through various application evaluations including projects involving actual customers. We intend to continue development toward satisfying potential customer needs, and to pursue further performance improvements.

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KJ series common platform type painting robots

Painting robots are used in a wide variety of industries including automobile manufacturers. This paper presents the KJ series painting robots, capable of being used in all types of painting applications, as well as painting system solutions we provide as a painting robot supplier.

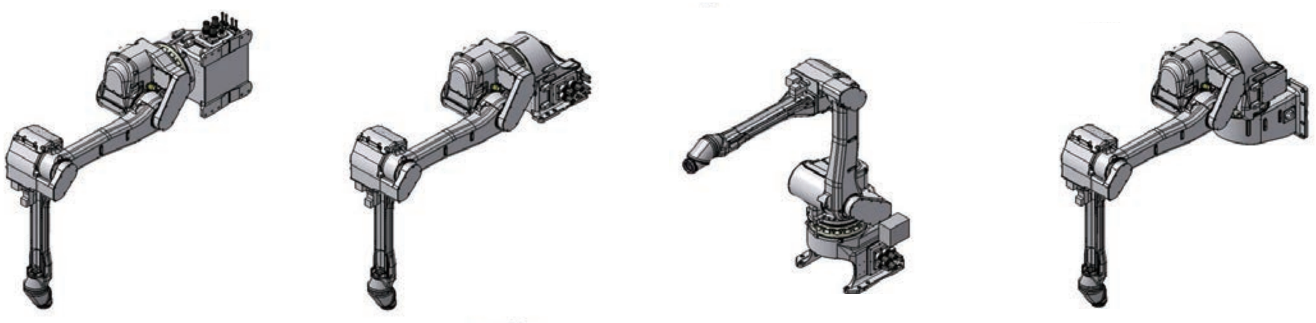
Preface

Painting robots are used in a wide variety of fields including the automobile industry. The robots are used for such purposes as reducing the manufacturing cost through manpower saving, relieving operators or workers from the so-called "3D" (dirty, dangerous, and demeaning) work, reducing manufacturing cost by reducing the usage of paint, and stabilizing painting quality. In addition, it is rare to use the painting robots standalone; they are normally used as a system in combination with a variety of equipment such as painting booth or painting equipment.

At Kawasaki, we are developing standalone robots and robot systems in response to the efforts and needs of the end users and painting-related manufacturers, while also pursuing development and improvement efforts from the standpoint unique to a robot manufacturer.

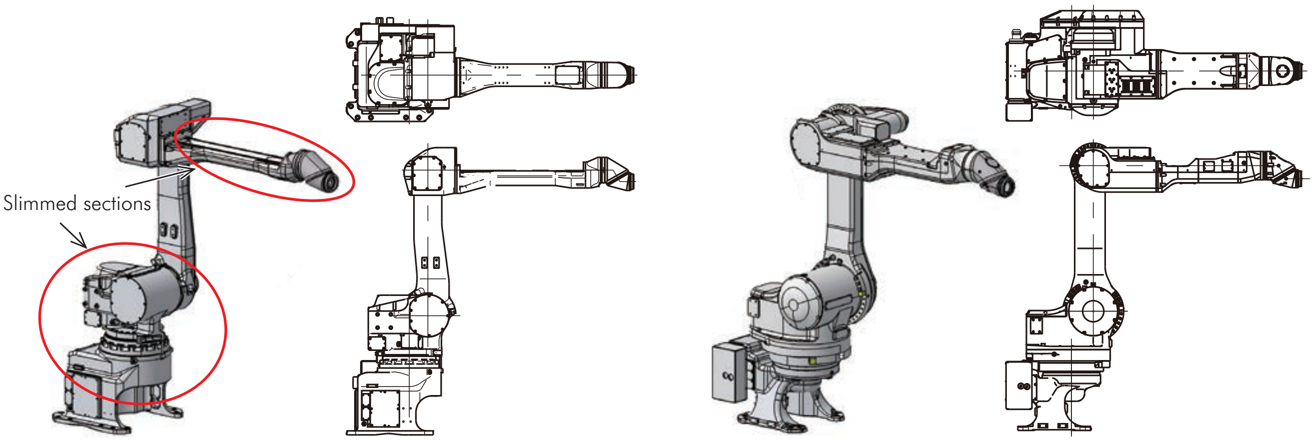
1 New KJ series painting robots

We are lining up the K series as explosion-proof painting robots that can be used in combustible gases including paint solvents. We have developed the KJ series as a line of common platform type painting robots designed to improve functionality and integrate existing models, with efforts to launch the KJ264 and KJ314 currently underway.



KJ264 (wall mounting) KJ264 (shelf mounting) KJ264 (floor mounting) KJ314

Fig. 1 KJ264 and KJ314



(a) KJ264 (floor mounting)

(b) Existing large model KG264

Fig. 2 Comparison of new model with existing models

Common platform type refers to the type compatible with various application conditions of the robot, and it is aimed at eliminating the necessity of model selection that used to be required depending on the usage condition. The KJ264 has only six axes as with existing models, but the KJ314 has seven axes including one axis newly added to the base section to widen its application range. Fig. 1 shows external views of the KJ264 and KJ314.

(1) Support for various installation conditions

Since the painting robot is used in combustible gases, it is used mainly in a dedicated booth. Also, in recent years, the trend has been for the robots to be installed on the wall of the booth or on the shelf inside the booth to make effective use of their motion range, and also to prevent the robots from getting dirty from paint blowing back. Existing robots are designed mainly to be installed on the floor (floor mounting), and when they need to be installed on the wall (wall mounting) of the booth, a cradle is added in the booth to make this possible. There have also been requests to install the robots on a shelf-shaped cradle (shelf mounting), which have been addressed by creating a special model for that. In contrast, as shown in Fig. 1, KJ264 can support all installation conditions just by changing the base section.

(2) Making the robot body slimmer and lighter

Demand for smaller painting booths is very high since a reduction of maintenance costs. A problem that may occur by reducing the size of the painting booth is the interference with the robot, but slimming of the robot body is one way to prevent the interference. Also, the wrist section and the upper arm section of the robot must be slim so that they can be inserted from the opened door of an automobile body to paint the inside of the door.

As such, the structure of the new KJ series painting robot was fully reexamined, and the robot was made to have the exterior slimmer than the existing models (Fig. 2). Since the existing KG264 robot for automobile painting is large, it is not suitable for interior painting. However, with the KJ series featuring a slimmer body, interior painting has now become possible with a large robot for automobile painting. Also, since the KJ series is now as slim as the medium-sized KF264, it can now be used for the general industries as well.

In addition to slimming the robot, the material of the robot structure was changed to aluminum from steel, achieving drastic reduction of weight from 800 kg or more (the weight of existing robots) to 550 kg. This reduction in weight produces various advantages. For example, it makes it easier to install the robot at an upper portion of the painting booth, and the booth structure can be built with less materials because the required strength of the booth wall can be reduced.

(3) Slimming by integral construction of the paint hose

The painting robot is used by attaching a painting device such as spray gun at the tip of its wrist, and tubes for supplying paint or thinner to the painting device have to be placed along the body of the robot. These tubes also cause interferences, so how to place these tubes along the robot also becomes an issue. To address this issue, a reducer having a hollow structure is used at the rotating axis in the base section, and in addition to the tubes, a harness for supplying the power and communication is passed through

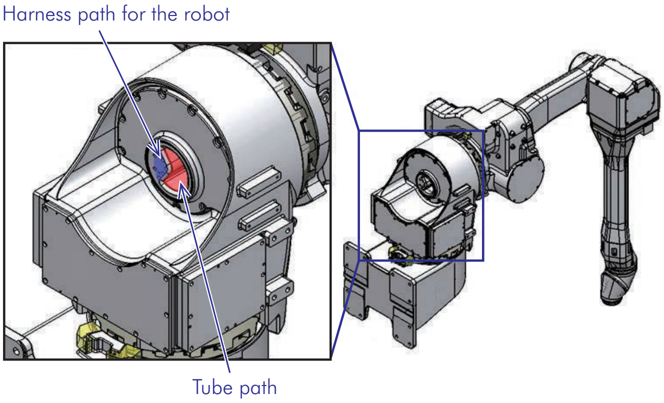


Fig. 3 Harness and tube path at the base section

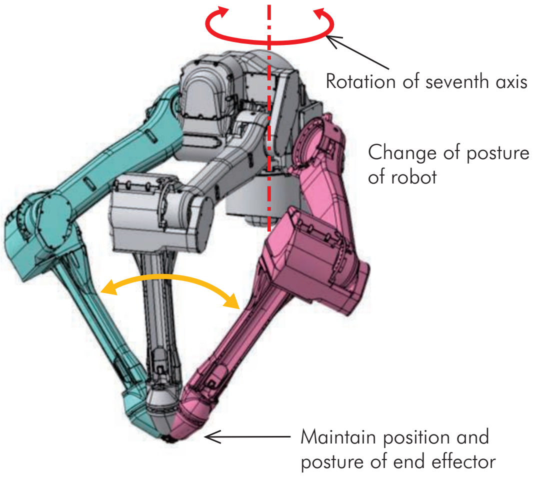


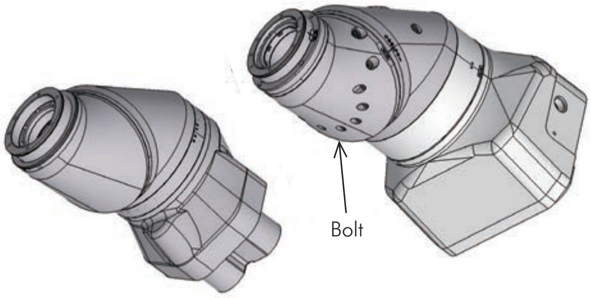
Fig. 4 Posture changes by seventh axis

the hollow part (Fig. 3). Such a hollow structure was also used with the existing models, but it was only possible to pass either the harness or the tubes, so it was getting in the way for slimming.

When the harness or tubes are passed through the center of the rotating axis, they will be twisted by the movement of the robot, so it is required to prevent damage by decreasing the amount of twist per unit length. Coexistence of harness and tubes was enabled by employing a structure that partially relieves the twisting force on the harness outside the hollow section.

(4) Space-saving with the seven-axis KJ314

To save the space while maintaining the range of movement of the robot, it is required to prevent the interference between the robots, interference between the robot and the object to be painted, and interference between the robot and the painting booth walls. Also, with the six-axis robot, the number of postures of the robot is limited to one when the position and posture of the end effector of the robot are specified with six degrees of freedom. This disables changing of the posture of the robot to clear the interference. Previously, space-saving was limited because of these problems, but it has now become possible to give a degree of freedom for changing the posture of the robot by adding a seventh axis (swing axis) as a redundant axis, enabling it to clear the interference (Fig. 4). It increases the cost to add the redundant axis, but by limiting the function by conditioning the seventh axis to be actuated only when changing the posture, the increase of the cost is minimized.



(a) KJ264 (floor mounting)

(b) Existing large model KG264

Fig. 5 Comparison of wrists of new and existing models

(5) Enhancement of cleanability by flattening of wrist

The wrist is the closest part to the painting device, and it easily gets dirty with the blow back of the paint. The object to be painted will be rendered defective if the paint attached to the wrist peels off and attaches to the object. Therefore, it is necessary to make the wrist hard to get dirty, and easy to clean. With the existing type of wrist, bolts are used on the surface of the wrist, making it easy for the paint to accumulate and hard to clean. By modifying the assembly procedure and placement of the bolts, the KJ series is structured using no bolts on the surface of the wrist (Fig. 5).

Fig. 6 Explosion-proof type teaching pendant

2 Robot controller

This section describes the features of the robot controller E25 used to control the KJ series, and new features added for the KJ series.

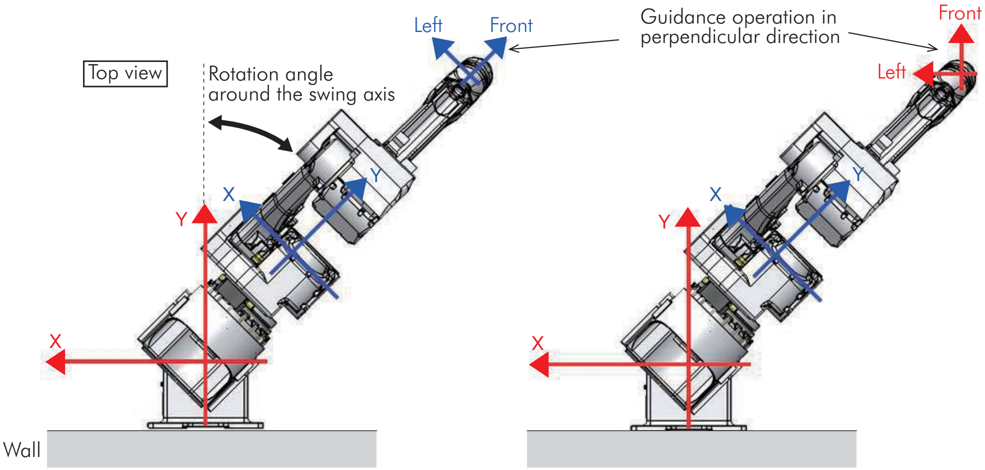
(1) Explosion-proof E controller

The new KJ series painting robot uses the cutting edge explosion-proof E controller E25 as its robot controller. The E25 has a teaching pendant with color LCD panel (Fig. 6), and in addition to performing various settings and monitoring the status of the robot using the LCD panel, it also can adjust the setting values for the painting device using the graph display. The program instructions and teaching operation procedure are compatible with the older version explosion-proof C controller, making it easy to replace with the older version controller.

(2) Swing axis control – using the world coordinate system

Normally, the guidance operation perpendicular to the robot is performed along the coordinate system referenced on the robot base section (base coordinate system), but the coordinate axis direction changes depending on the angle of the swing axis on the system with the swing axis. Therefore, the guidance operation in perpendicular direction is made possible using the fixed coordinate system with the rotation center of the swing axis (world coordinate system) instead of the base coordinate system (Fig. 7).

The coordinate value in the teaching data and the



(a) Base coordinate system

(b) World coordinate system

Fig. 7 Coordinate system for KJ314

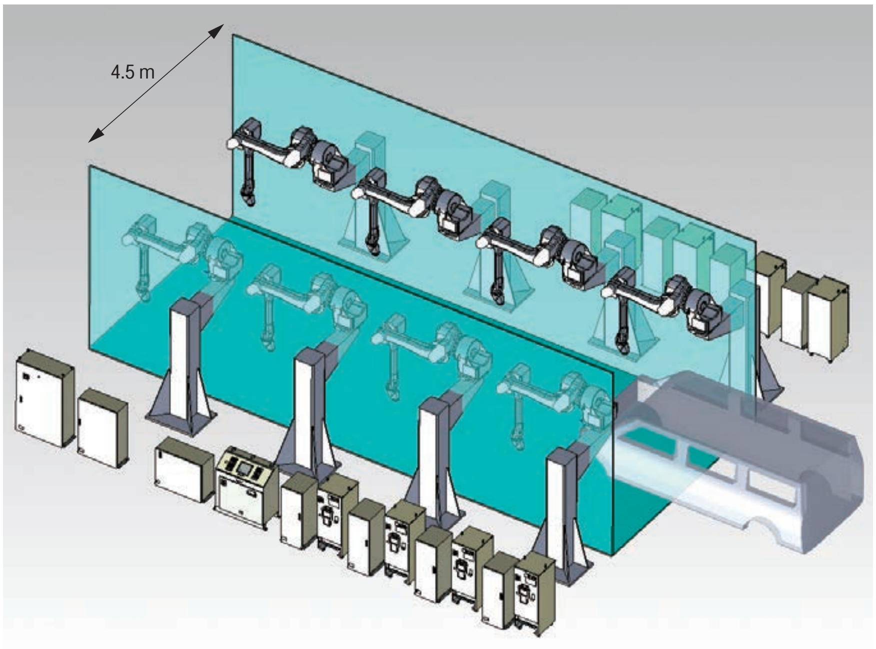


Fig. 8 Painting system for outer body of automobile

direction of the following operation to the conveyor are also set using the world coordinate system, eliminating the difference of operation due to existence of the swing axis.

(3) Variable acceleration and deceleration control – speeding up the posture change

The painting robot performs operation to change the posture drastically while almost keeping the tip of the tool stationary when switching the discharge direction of the paint. With this operation, it is necessary to perform the posture change as fast as possible within the tolerance of the motor torque for each axis. The KJ series determines the optimal acceleration and deceleration at the time of posture change by considering the posture of the operation start point and the end point using the improved variable acceleration and deceleration formula.

3 Painting system solution

(1) Painting system for outer body of automobile

With the painting for outer body of automobile, which is the most popular application for KJ series, it is becoming common to adopt the robots to reduce the usage of paint and improve painting quality. The floor-mounting type robots were used for painting the top side of the automobile body when the robots were first adopted, so a booth width of 6 m was required. However, in recent years, placing the wall-mounting or shelf-mounting type robots higher than the automobile body has made it possible to reduce the booth width to 4.5 m (Fig. 8).

The part that requires the most energy in the painting process is intake and exhaust of the painting booth, so reduction of the booth width and the booth length results in reduction of energy cost, which in turn is contributing to a reduction in CO_2 emissions.

(2) Painting system for inner body of automobile

It is required to shorten the booth length by narrowing the spacing between the robots, while avoiding interference with the narrow opening of the automobile body or between the robots when painting the engine compartment, trunk room, and the inside of the doors. For this reason, the use of robots for inner body painting applications is delayed compared to the painting of outer body of automobile. Featuring a slim arm and a large hollow wrist, and leveraging the interference check and prediction functions enabled with the offline programming simulation function, the KJ264 can be used to construct an optimal painting robot system for inner body painting (Fig. 9).

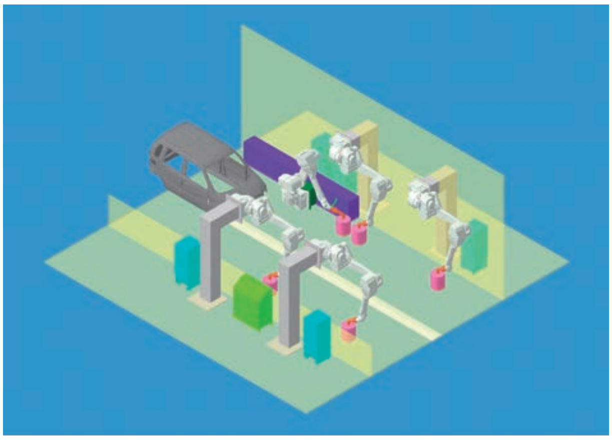


Fig. 9 Painting system for inner body of automobile

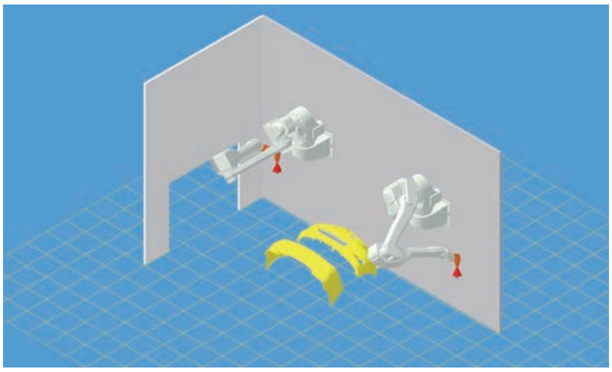


Fig. 10 Painting system for automobile bumpers

(3) Painting system for automobile bumpers

Currently, floor-mounting type painting robots are adopted for painting of the automobile bumpers, requiring a booth width of 5 m, but by placing the KJ314 above the bumpers and utilizing the swing axis, we have made it possible to narrow the booth width to 3 m (Fig. 10).

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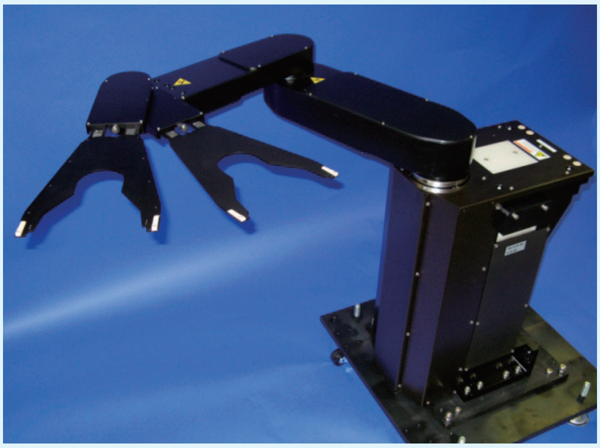
Concluding remarks

We believe the important mission for suppliers of robots and robot systems is to relieve as many operators as possible from painting work, while enabling cost reduction and high-quality painting. Also, reduction of VOCs (volatile organic compounds), CO_2, and other factors that impact the environment is a global challenge that needs to be tackled continuously and in close partnership with the paint, painting equipment, and painting facility manufacturers. Although the amount of contribution that robots alone can make toward reducing environmental impact is limited, the impact will be large when taking into consideration the positive effects that can be had on an entire facility as a system solution.

We hope to contribute to the society by continuing to provide better products and systems.

NT & NV series advanced semiconductor-transferring robot achieving both high speed and ease of use



Since the start of development in 1995, our semiconductor-transferring robot has met many customer needs, including high-speed transfer, high positioning accuracy, and automated teaching, and holds the top share in the industry at present. Moreover, our efforts have gone beyond standalone robots to offer integrated robot solutions at a higher level, and further expansion of our business can be expected. This paper introduces system models of the Kawasaki clean robots and auxiliary functions, focusing on the NT and NV Series.

Preface

In recent years, customers have been demanding improved throughput in semiconductor manufacturing equipment, necessitating an increase in the number of semiconductors transferred per unit of time. Customers have also been demanding the following:

① Improved maintainability via automation of robot position teaching

② Simplification of operations simulations performed before actual robot operation

③ Reduction of downtime (time during which the robot is shut down) for maintenance, etc.

Ever since developing the semiconductor-transferring robot in 1995, Kawasaki has provided clean robot solutions optimized for the customers' semiconductor manufacturing equipment. The culmination of our efforts has been the development and market introduction of the NT series, to wide acclaim. The NT series delivers high speed, high accuracy, and ease of use, and by combining the vacuum robot NV series, it can offer transfer capabilities in both atmospheric and vacuum environments.

1 NT Series

(1) Broad motion range and compact design

The NT series is a robot used in silicon wafer transfer mechanisms such as FOUP (Front Opening Unified Pod), a container that seals for transport silicon wafers to be used as semiconductor substrates, and EFEM (Equipment Front End Module), which transfers wafers between semiconductor manufacturing equipment processes. The NT series meets the Class 1 cleanliness requirements of the International Standards Organization (ISO). Furthermore, while in the past a traveling device was required for systems with four FOUPs lined up, we have now positioned the arm rotation center to be offset within the EFEM, enabling a longer arm length, and a broad motion range using upper and lower link arms (Table 1). This configuration frees up the space previously occupied by a travel device for use by a controller etc., enabling more effective use of space (Fig. 1).

Table 1 NT Series standard specifications

Model		NT420	NT520	NT620
Basic structure		Horizontal articulated type		
Motion range	θ 1 axis (rotation) (°)	340	340	340
	Z axis (up-down)(mm)	400	470	600
	θ 2 axis (rotation) (°)	340	340	340
	H1 axis (rotation) (°)	340	380	380
	H2 axis (rotation) (°)	340	380	380
Position repeatability (mm)		±0.1	±0.1	±0.1
Maximum reach (mm)		1,280	1,280	1,250.7

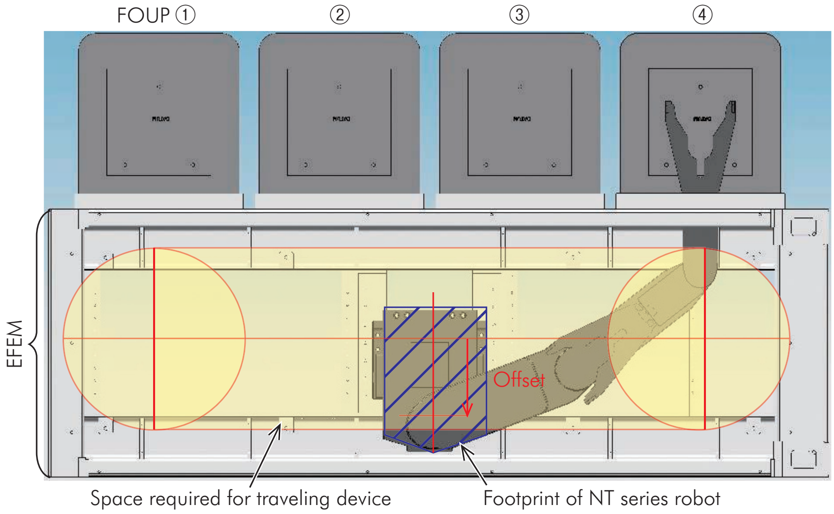


Fig. 1 Comparison with footprint of robot with traveling device

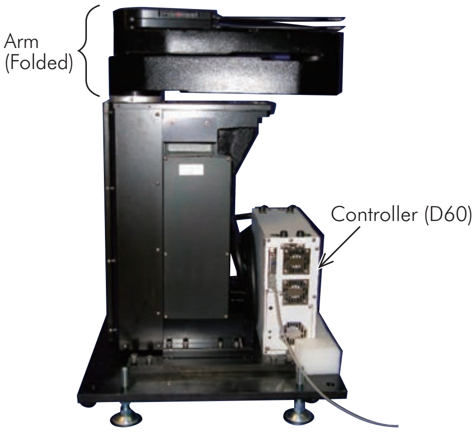


Fig. 2 Robot with arm folded and controller

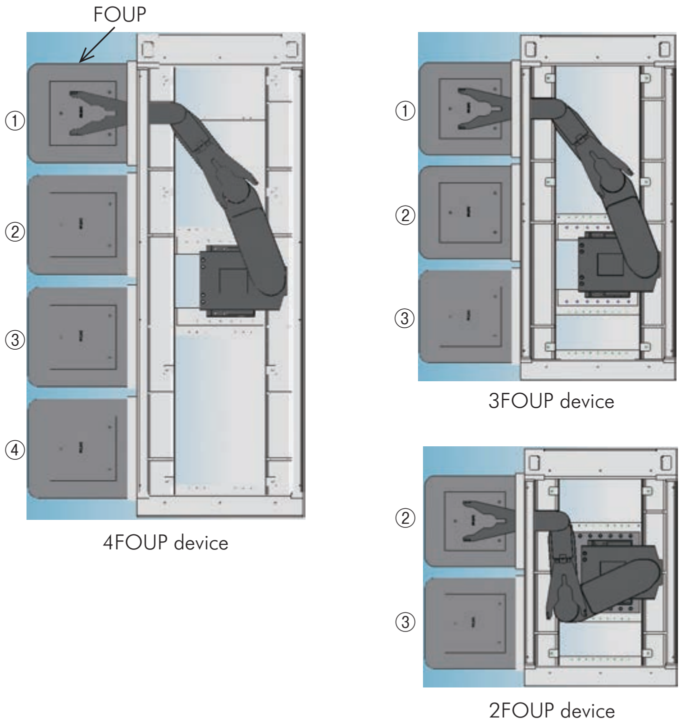
In addition, we reduced the size of the robot when its arm is folded, enabling easy access from the front in case replacement is needed due to a breakdown. Furthermore, we made the controller itself smaller, so it fits easily in the space previously required for the traveling device (Fig. 2).

(2) High-speed, high-precision operation

The NT series has extended the arm length per robot unit to improve wafer transfer speed without boosting the relative angular speed between arms. While this configuration appears to result in smooth, stable operation, in reality it enables high-speed wafer transfer. For example, while it took robots with traveling device 1.2 seconds to move from FOUP ① to FOUP ④ (1,515 mm), the NT series can cover the same distance in 0.9 seconds. This high-speed operation was achieved through an arm drive based on our proprietary gear train configuration. The NS and NX series also uses a gear mechanism to transmit motive power from the AC servomotor to the arm.

For the NT series, however, we positioned a gearbox at each joint, for a configuration consisting of an AC servomotor and gears only. This arrangement boosted rigidity and simplified the configuration of the transmission mechanism, reducing the opportunities for error due to the transmission. It also contributed to improved positioning accuracy, achieving an accuracy of within ±0.1 mm.

In addition, we used a newly designed gearbox for the NT series. Gearboxes need to be free of backlash with a long operating life and high rigidity. Based on the latest component technology developed through years of experience, we have realized a wear-resistant design and high gear precision that achieve both compact size and reduced gear number while maintaining the reduction gear ratio. This gearbox is extremely smooth for a backlashless type, with little mechanical loss and characteristics close to those of a direct drive mechanism. However, unlike direct drive, it does not require a high-performance positioning detector or large-current amplifier, enabling more layout freedom and compact size. This design also contributes to improved precision of the automatic teaching function.



4FOUP device

3FOUP device

2FOUP device

Fig. 3 Layouts of 2/3/4-FOUP devices

(3) Layout freedom

We designed the NT series for use in EFEM. EFEM offers layout variations of two to four FOUP units, with a standard program available for each.

As shown in Fig. 3, even if the number of FOUP units varies, the same operation program can be used for access to each FOUP by positioning the robot at the 4FOUP position. This will enable accessing each FOUP only by specifying the FOUP numbers—FOUP ①, ②, ③ for a 3FOUP device, and FOUP②, ③ for a 2FOUP device, for example.

(4) Simple structure and easy maintenance

Of the two arms, the lower arm has two sets of built-in gear deceleration mechanisms and motors for the arm drive. In addition, the upper arm has built-in gear deceleration mechanisms and motors for the wrist drive, for up to a maximum of two axes. This positioning of a drive system at each joint results in a simple configuration (Fig. 4).

The cover to the arm joint can easily be removed to access gears inside the arm for adding grease, reducing the downtime required for periodic maintenance. In addition, we constructed the arm drive and wrist drive as modules (Fig. 5) so that maintenance locations can be identified with ease.

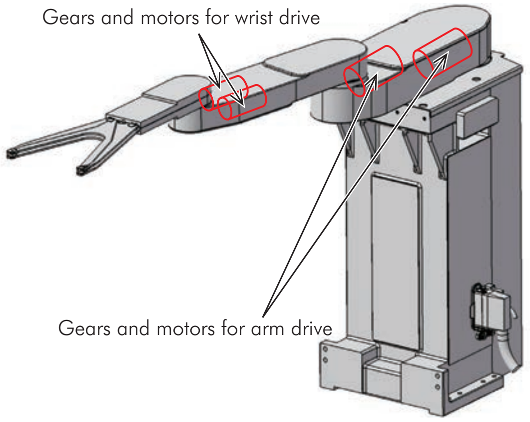


Fig. 4 Locations of gears and motors

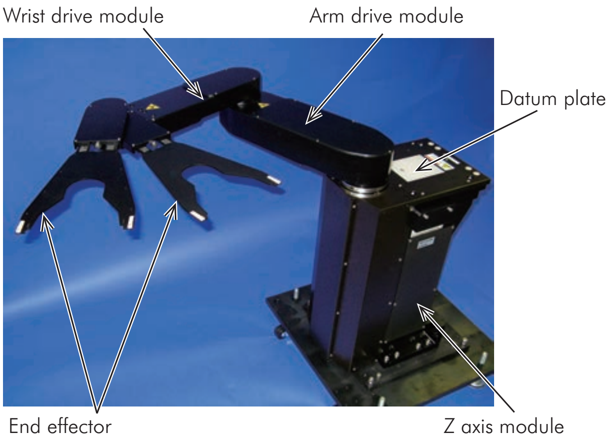


Fig. 5 Drive system for modular configuration

Table 2 Controller specifications

Control type	D60 controller	D61 controller
Dimensions (mm)	W320×H300×D130	W445×H429×D130
Weight (kg)	12.5	18.5
Number of control axes	Max. 7 axes (2 robots, total 6 axes, aligner 1 axis)	Max. 12 axes (2 robots, total 11 axes, aligner 1 axis)
Drive system	Full digital servo	
Teaching method	AS language program	
Cooling method	External air intake and forced cooling	
Dedicated external signals	External emergency stop, external stop, safety fence	External emergency stop, external stop, safety fence, 2 systems each
Communication I/F	RS-232C×1	RS-232C×2
	Ethernet×1	Ethernet×1
General purpose input/output signals	Maximum input signals 16, output signals 8	Maximum input signals 32, output signals 16
Power requirements	Specifications: AC208V±10%, 50/60Hz, single phase	
	Voltage drop: Conforms to SEMI-F47	
	Grounding: dedicated grounding, 100Ω or less	
Exterior facing	SUS304	

(5) Highly rigid body

The drive system for modular configurations is shown in Fig. 5. With a highly rigid structure for the arm and Z axis module, we perform shipping control so that errors in the Z axis direction (height direction) are held to within the standard value during movement (250 mm movement in the front-back direction for wafer placement in relation to 1 to 4 FOUP units) at the access port, including depression during arm operation, and vertical hand position adjustment error.

In addition, we perform shipping control so that the levelness can be recreated on the end effector placed at each access port position by using the datum plate for leveling (Fig. 5) when installing the robot. This has sharply cut the time required for level adjustment on access ports, reducing the robot installation time.

(6) Controller

Controllers driving the robot include the D60 controller and D61 controller. The D60 controller features a compact design, while the D61 controller is capable of driving two multi-axis robots by increasing the number of control axes. The controller specifications are shown in Table 2.

2 NV Series

(1) Compact body and stable operation

The NV series, developed as a vacuum robot for use in semiconductor manufacturing, uses a drive unit based on our NS series and features a compact design with a reduced body diameter and shortened body length (Fig. 6, Table 3).

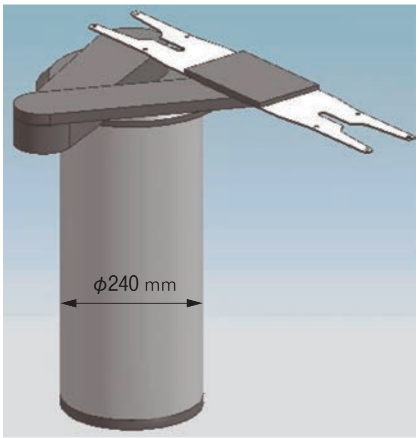


Fig. 6 External view of NV111

Table 3 NV111 standard specifications

Model		NV111
Degree of freedom		3
Structure		Horizontal articulated type
Motion range	θ axis (rotation: JT2) (°)	−180 to +180
	Z axis (up-down: JT3) (mm)	0 to +30
	X axis (front to back: JT4) (mm)	−686 to +686
Repeatability (mm)		±0.1
Degree of vacuum (Pa)		1.33×10^{-4}

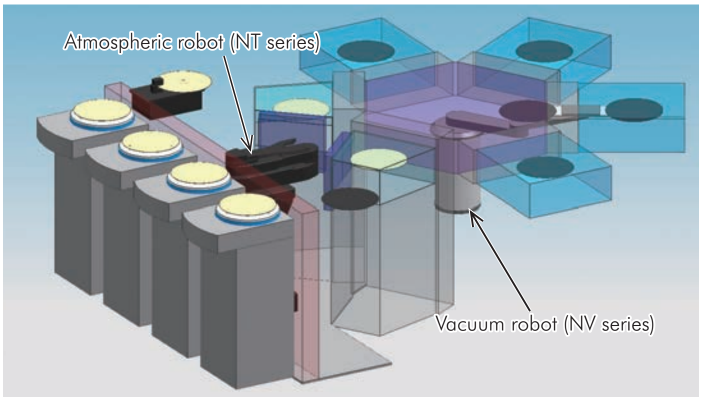


Fig. 7 Combination of atmospheric robot and vacuum robot

For the atmospheric side, we used cast aluminum parts that maintain rigidity while achieving compact size and light weight. Since the component parts are taken from drive systems with a long history of use, they are highly reliable and can maintain stable operations over long periods.

(2) Use of same AC servomotor and gear as NS410

For the drive mechanism, we used an AC servomotor and gear already used on the atmospheric robot NS410, to ensure a reliable drive configuration. As a result, we are able to use the same spare parts to ensure availability in case of a breakdown. Furthermore, with the drive system shared with the atmospheric robot, we use the same D61 controller for the NT series, NV series, and prealigner, enabling space savings and effective use of available space.

Moreover, use of a common AC servomotor and gear ensures that many functions previously developed for the atmospheric robot, including various software and collision detection and other functions, are available for general use. An example of D61 controller usage is shown in Fig. 7.

(3) Vacuum seal and in-vacuum drive transmission mechanism

Since we used the same drive system as the atmospheric robot, drive transmission from the atmospheric side to the vacuum side is necessary. In the NV series, we used a magnetic flow seal on the area where the rotation drive force is transmitted to the vacuum side, and a bellows on the vertical Z axis. These serve to maintain a stable seal and enable a vacuum of 1.33×10^{-4} Pa as a usable vacuum environment.

We used such materials as aluminum and stainless steel for the arm and other parts used in vacuum, to reduce the amount of gas emitted from the parts surfaces. Moreover, for the drive inside the arm, we used a timing belt or stainless steel belt. The belt material varies depending on the semiconductor manufacturing device process, and the selection depends on the gas emission performance demanded for the transfer system.

(4) Wafer detection

With the NV111, a fiber sensor for wafer detection can be attached to the tip of the hand, and the sensor amplifier used is shared with the atmospheric robot. We used a Teflon material to cover the fiber sensor, in order to reduce emitted gases. The AC servomotor and sensor amplifier are shared with the atmospheric robot, enabling wafer sniffing (wafer detection at each stage) just as with the atmospheric robot. Going forward, we will also look at using this sensor for automatic teaching.

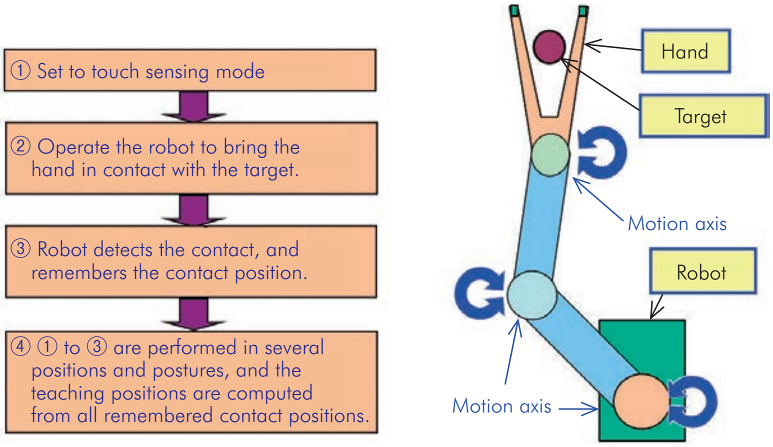
3 Contact type (touch sensing type) automatic teaching function

(1) Summary

In robot position teaching, which must be performed accurately and in a short time inside the limited space available within the increasingly complex semiconductor manufacturing devices, operators must have highly advanced skills. To address this situation, we have developed a contact-type automatic teaching function that can easily perform teaching without relying on the skills of the operator.

The contact-type automatic teaching function features the following characteristics, which are attracting attention from customers.

① Teaching can be performed in a short time in cramped spaces.
② Since teaching is not dependent on operator skills, there is little variance in teaching accuracy.
③ Expensive sensors or special sensor tools are not required.
④ Sensing is not dependent on environmental factors


① Set to touch sensing mode

② Operate the robot to bring the hand in contact with the target.

③ Robot detects the contact, and remembers the contact position.

④ ① to ③ are performed in several positions and postures, and the teaching positions are computed from all remembered contact positions.

Fig. 8 Touch sensing operation

(water droplets, corrosive gases, high temperatures, etc.).

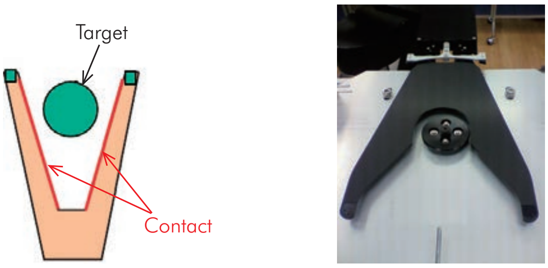
(2) The position detection method

The teaching operation requires registration of the X, Y, Z coordinates for performing the wafer capture/placement operation. The basic position detection operation using touch sensing is shown in Fig. 8. In touch sensing, since the position detector (encoder) normally required for robot operations is used for touch position judgment, there is no need to add a new external sensor. The NT robot uses our proprietary highly rigid gear train configuration, enabling operation with virtually no hysteresis or backlash on the motor/encoder side even when driven from the load side. As a result, unlike the belt drive or the differential gear reduction drive, detection on the motor axis is possible even with the slightest deviation due to touch from the load side. Moreover, with the force limited to 1 to 2N, it does not cause any damage to the target.

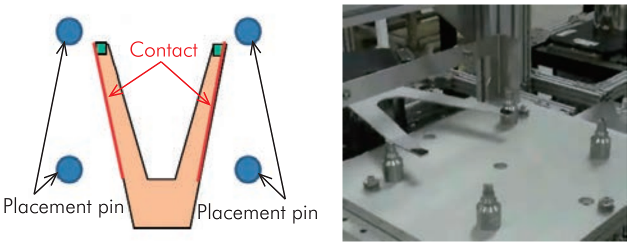
(3) Example of position detection method

An example of a target (tool positioned in place of a wafer for teaching) being used is shown in Fig. 9(a). The teaching position is found by computation based on multiple positions detected by sensing, the target dimension and mounting position, and the hand dimension. The target may be pre-mounted on the device side, or it can be mounted when the teaching operation is performed.

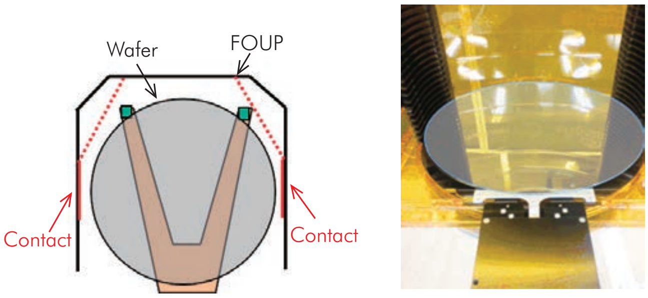
In Fig. 9(a), position detection is performed by bringing the inside of the hand into contact with the target, but the location or object to be contacted is not necessarily determined beforehand. Fig. 9(b) shows an example of position detection when the outside of the hand is brought into contact with the placement pin for placing the wafer. In addition, Fig. 9(c) shows a FOUP example, with position detection performed by bringing the wafer held in the hand into contact with the side walls.



(a) Example using target



(b) Example of placement pin



(c) Example using wafer

Fig. 9 Example of position detection method

With the semiconductor-transferring robot, the hand shape or wafer holding method (edge grip, vacuum chuck, etc.) can vary depending on the customer or device, and the wafer capture/placement position structure can also vary. If the contact-type automatic teaching function is used, and if pre-determined points for position, shape, and dimensions, etc., exist near the teaching position, these can be used to perform teaching. Since most variations in contact points (location, number) or direction can be addressed with a change in software, installation is easy even when adding as an additional function to existing equipment.

(4) Application technology

With the high rigidity of its motion transmission system, and its ability to transmit position changes in the detection axis during touch sensing to the motor or encoder with minimal loss, the NT series enables high-precision sensing. In addition, use of this touch sensing technology can be applied as follows to the robot self-diagnosis function. By periodically sensing specified points within the equipment to confirm their position, changes to the robot status can be monitored over time, with warnings sent to the equipment side whenever threshold values are exceeded to prevent the occurrence of troubles.

Table 4 Main functions of simulator

· Interference check	· Operation trajectory display
· Cycle time verification	· TP simulation
· I/O simulation	· External communication connection
· Operation waveform display	

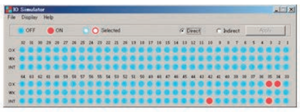
4 Semiconductor-transferring robot simulator

(1) Summary

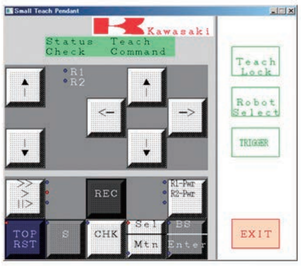
We also actively pursue development of a simulator specially designed for the semiconductor-transferring robot, which can be broadly utilized all the way from the order placement stage to robot installation and after the equipment begins operation. This is a simulator that runs on a computer, with functions as shown in Table 4. The simulator consists of an I/O screen, a teach pendant screen, an operations screen for inputting AS language (robot language), a graph display screen for waveform display of speed and position, etc., and a 3D drawing screen for the robot. The screen configurations are shown in Fig. 10.

(2) Simple robot application examination

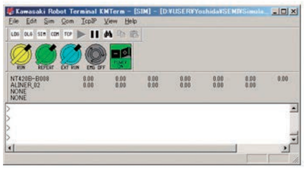
The simulator uses special tools to simplify such operations as setting the robot motion range or drawing target parts at access positions, etc. based on the equipment layout drawing. In addition, it sets the operations parameters (robot posture, and various offset values for operations) and operations sequence to automatically generate data read with standard operations software, and it performs interference checks, operations trajectory examination, operations sequence checks, and cycle time measurements (Fig. 11). Since these operations do not require special software technology and can be performed in a short time, this is a tool that can be widely utilized to give new customers a clear idea of what to expect.



I/O screen

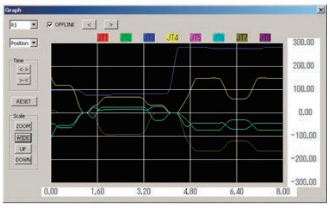


Teach pendant screen

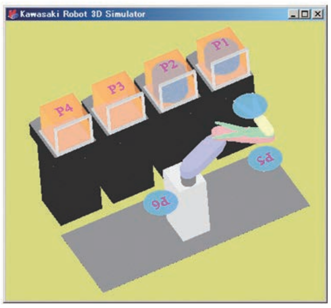


NT420B-B008 0.00 0.00 0.00 0.00 0.00 0.00 0.00
ALINER_02 0.00 0.00 0.00 0.00 0.00 0.00
NONE
NONE

Operations screen

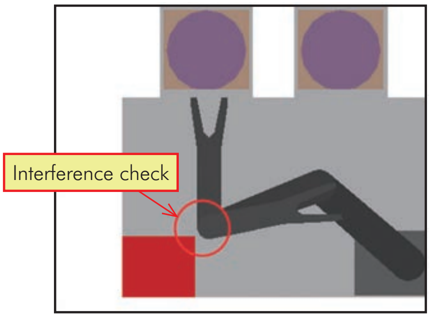


Graph display screen

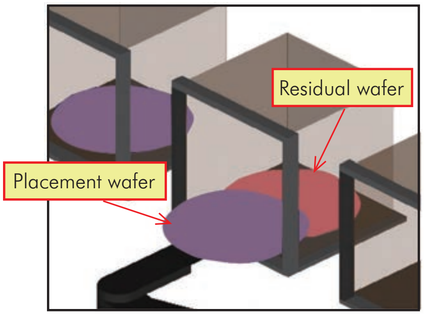


3D drawing screen

Fig. 10 Simulator screen configuration



(a) Interference check



(b) Operations sequence check

Fig. 11 Simulator functions

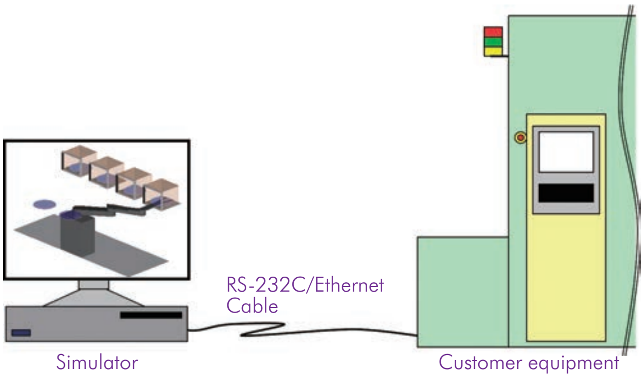


Fig. 12 Connections with equipment

(3) External communication connections

This simulator can be connected to external equipments through a computer's Ethernet port or RS232C port. As a result, the simulator can be connected with equipments (Fig. 12) before the robots are delivered to the customer, and the communication interface and robot operations can be checked. In the past, linkage checks with software on the equipment side could not be performed until after the robot has been delivered and connected with the equipment, including wiring and piping for electrical power and air. By contrast, since the robot software used in our simulation can be directly installed and used on the robot controller, the linkage checks can be performed offline, reducing the evaluation time required on the actual robot. Furthermore, we use highly reliable software that has already undergone a rigorous debugging process, reducing the risk of interference accidents during evaluation on the actual robot.

(4) Troubleshooting

If trouble occurs at the delivery site, data saved at that time is read into the simulator where the trouble can be recreated, enabling quick investigation of the cause and early resolution of the trouble.

Concluding remarks

Semiconductor-transferring robots with faster operating speeds will continue to be developed, and silicon wafers will continue to grow in size as well. We will continue efforts to refine our technology so that we can continue to provide products that earn the satisfaction of our customers.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E series evolutionary robot controller

Recently, further productivity improvements, quality improvements in each specific application, and improved maintainability have been required of the industrial robots. Among such conditions, the E Controller was developed with the latest electronic and information technology so as to offer easier operation and maintenance, higher basic performance and enhanced safety features. This paper provides an overview of the E Controller.

Preface

It has now been 44 years since Kawasaki commenced production in 1969 of the first industrial robots in Japan. Industrial robots introduced a level of flexibility not seen in earlier automation equipment, reducing labor requirements in spot welding, arc welding, painting, handling, semiconductor and liquid crystal substrate transport, and other fields of application, and improving productivity at manufacturing sites in Japan and overseas. However, the role played by industrial robots at manufacturing sites has continued to increase in importance, and further improvements in productivity, quality in the respective application, and maintainability are demanded.

Meanwhile, there has been remarkable technological progress in the electronic and information sectors, and early incorporation of that progress into robot technology has been the determining factor in the evolution of industrial robots. With this background, it is essential that the latest hardware and software be incorporated into robot controllers to improve basic performance and functionality, together with timely provision of added values that respond to diverse user needs.

To meet these demands, we have developed the E series controller as a new offering in our line of robot controllers. In addition to improved operation performance, this controller delivers greater operability and maintainability as well as enhanced safety functions.

1 Development concepts

In developing the E controller, we placed particular emphasis on the following items based on demands from users regarding existing controllers.

(i) Smaller size

Make the controller more compact to reduce the footprint for a leaner production line.

(ii) Improved basic performance

Use a powerful CPU to achieve more accurate trajectory control, faster program execution, and more convenient saving and loading, etc.

(iii) Improved maintainability

To reduce the maintenance time during operation and reduce the system setup time before operation, improve the replaceability of parts that require periodic replacement, and strengthen various monitoring functions.

(iv) State-of-the-art safety functions

Make full use of functional safety technologies to realize state-of-the-art safety functions such as software control of the robot's operating space.

2 Specifications

The specifications of the E controller are shown in Table 1. The enclosure consists of five types, including the newly developed E9X compact enclosure (for an arm with a payload capacity of up to 20 kg), as well as the E2X standard specification model, E3X/4X standard specification model, E2X/3X/4X explosion-proof specification model, and E7X compact enclosure (for an arm with a payload capacity of up to 10 kg). The enclosure to be used is determined according to the application, arm size, and applicable standard (UL certification/European standards compliance). The enclosure features a smaller footprint than the existing types and components that are organized into units by function for improved maintainability and reduced wiring.

Table 1 Specifications of controller

Item		Specifications
Enclosure structure		E2X/3X/4X Std/Ext, E7X: Enclosed structure E9X: Open structure
Size		E3X/4X Std: W550×D550×H1200 E2X Std: W450×D550×H950 E2X/3X/4X Ext: W500×D550×H1400 E7X: W500×D420×H259 E9X: W500×D580×H270
No. of control axes	Standard	6 axes
	Enclosure internal extension	E2X Std, E7X: (2 axes added) E3X/4X Std, E2X/3X/4X Ext: (3 axes added)
Drive system		Full digital servo system
Operation method		Coordinate systems: Joint, base, tool Types of motion control: Joint, Linear, Circular interpolated motion
Programming		Point to point teaching or language based programming
Memory capacity		8 MB/Approx. 80,000 steps equivalent
I/O signal	External operation signal	Emergency stop, external hold signal, etc.
	Universal I/O	E2X/3X/4X Std/Ext: 32, (64, 96, 128) points E7X, E9X: 32, (64, 96) points
Auxiliary storage device		(USB memory)
Communication function	PC, network communication	Ethernet 100BASE-TX, RS-232C
	Fieldbus	(CC-Link, DeviceNet, PROFIBUS, Ethernet/IP, CANopen, etc.)
Cable length	Teaching pendant	5 m, (10 m, 15 m)
	Robot/controller	5 m, (10 m, 15 m)
Power specifications		E2X Std/Ext: AC200-220V 3φ, 50/60 Hz E3X Std/Ext: AC440-480V 3φ, 50/60 Hz E4X Std/Ext: AC380-415V 3φ, 50/60 Hz E7X: AC200-240V 1φ, 50/60 Hz E9X: AC200-230V 1φ, 50/60 Hz
Environmental condition		Ambient temperature: 0-45℃, for E7X standing installation only, 0-40℃ Relative humidity: 35-85%, no condensation

Figures in parentheses show options.
Std: standard specifications
Ext: explosion-proof specifications

In particular, the E2X standard and explosion-proof specification enclosure enables the replacement of all components including the fan from the front, eliminating the need for maintenance space in the back and side areas. Also, the E7X and E9X use a compact enclosure and single-phase 200V power source, enabling installation in any environment.

The interior of the controller is divided largely into a card rack unit, a servo amplifier unit, and an MC unit (Fig. 1). The features of each unit are described below.

(1) Card rack unit

The card rack unit consists of ① a DC power source for supplying control power, ② a main CPU board for managing the execution of the operating system and user programs and generating position commands, ③ a power sequence board for monitoring and controlling safety circuit conditions, and ④ an I/O fieldbus board for sending and receiving signals with external equipment. In addition, use of a PC-based architecture forms a configuration for flexible functionality expansion.

(2) Servo amplifier unit

The servo amplifier unit consists of ① an amplifier for controlling the motor current driving the robot, and ② a servo CPU board for performing the servo control to track the encoder values with the position commands sent from the main CPU board. In the amplifier, we used the latest power device (power conversion element) and a current sensor for detecting the motor current, to achieve downsizing and improved reliability.

(3) Magnetic contactor (MC) unit

The MC unit consists of ① a magnetic contactor for shutting off power supplied to the robot during an emergency stop, etc., ② a converter for converting AC voltage to DC voltage, and ③ a bleed circuit for limiting the rise in voltage during power regeneration. We placed the converter and bleed circuit on a printed circuit board, for downsizing and reduced wiring.

3 Performance improvement

(1) Faster robot operation—improved vibration control

In the E controller, we enhanced the robot model for vibration control computed internally by the software, making it closer to the operating conditions of the actual robot and improving vibration control performance. This enabled minimizing delays in robot operations and increasing operating speed. As a result, we reduced the average cycle time for a typical operation by about 10% compared with existing models.

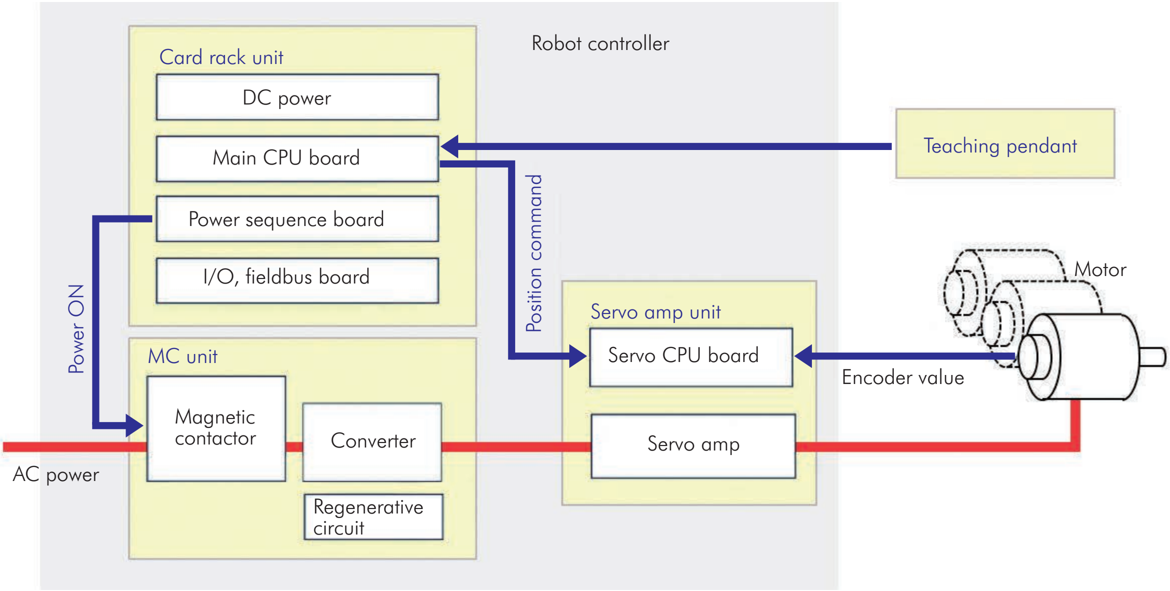


Fig. 1 Configuration diagram of controller

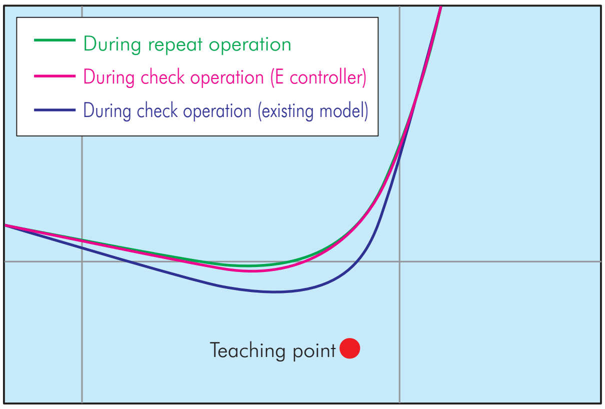


Fig. 2 Examples of trajectory error reduction

(2) Reduced check/repeat trajectory errors

In the past, there were large trajectory errors between check operations and repeat operations, and in some cases teaching correction was performed while monitoring the trajectory in repeat operations. In the E controller, this was improved by separating the trajectory errors into command values, delay elements, and dynamics. As a result, we were able to reduce the average trajectory errors for a typical operation to about 1/7 of existing models. Since only check operations are required to check the interference between the robot and tool in spot applications and the sealing position in sealing applications, the teaching time can be greatly reduced. Examples of robot trajectories before and after the improvements are shown in Fig. 2.

(3) Faster software processing speed

We used the latest high-performance CPU and also modified the software process to achieve a processing speed for KLogic (programmable logic controller [PLC] composed of software only) and the PC program (numerical operation program executed separately from robot operation) double that of existing models, and a signal input-output response speed four times faster than existing models.

4 Features

(1) Easier to use—user I/F, operability

The E controller comes equipped with two USB interfaces for users. This enables the teaching programs and the various setting parameters to be saved and loaded to USB memory in a short time at high speed. In addition, the teaching pendant screens can be saved (captured) to USB memory with a simple operation, greatly facilitating setting value checks or on-site creation of operation guides, etc. Users can also connect a USB keyboard for input via the keyboard, facilitating programming changes on-site.

We have also improved operability of the teaching pendant by moving the switches and lamps (motor power-on switch, error lamp, etc.) from the front of the controller to the top of the teaching pendant, eliminating the need to return to the controller to switch on the motor power, etc., during teaching operations. In addition, for the screen display we have enlarged the status display and other often-used monitor displays to make them easier to read, and made modifications to enable simultaneous checking of two items such as position information and signal information, to improve operability.

(2) Easier maintenance—maintainability

We added a self-diagnostic function that would be useful while the system is up or for daily maintenance. The display of safety circuit conditions, fan speed, and CPU temperature, etc. is useful for pinpointing breakdown locations. Examples of the safety circuit monitor are shown in Fig. 3. This improvement makes it easier to confirm the problem location when the motor power source fails to switch on.

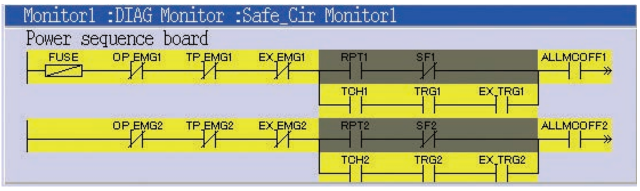
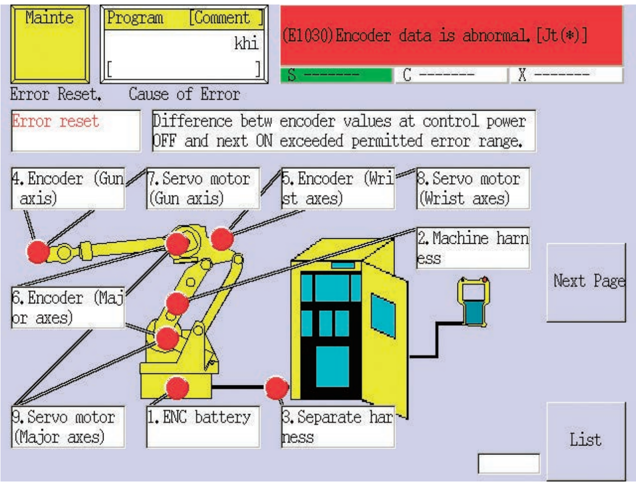


Fig. 3 Examples of safety circuit monitor


(E1030)Encoder data is abnormal.[Jt(*)]

Program [Comment]
khi
[ ]

Error Reset.

Error reset

Cause of Error

Difference betw encoder values at control power OFF and next ON exceeded permitted error range.

Fig. 4 Display example of maintenance support function

In addition, we have added a maintenance support function that displays on the teaching pendant information useful for resolving errors. A display example of the maintenance support function is shown in Fig. 4. When an error occurs, possible causes are displayed, together with their respective probabilities, investigation methods, procedures, time required, and necessary tools, etc., to help shorten the system recovery time.

(3) Easy information handling—network functionality

The E controller is equipped with two Ethernet connectors. Data that can be used to trace products inside the controller, robot error information useful for maintenance planning, etc. can be retrieved via the network. This can be done using such methods as a library function compiling functions for accessing the controller from the computer to retrieve information, and a web server function for displaying information in the controller on the browser software of a remote computer, etc.

Furthermore, Ethernet connection between controllers can enable connection to our vision device K-HIPE-R-PC, collaborative operation between multiple robots for handling heavy objects that cannot be handled by a single robot, and other high-performance system configurations.

We also support numerous fieldbuses that help to reduce wiring costs and increase system expandability (Table 1).

5 Expansion of safety functions

(1) Advanced safety functions

As an option for further expansion of safety functions, the E controller can be fitted with the robot motion monitoring safety function Cubic-S. Cubic-S takes its name from the three S's of "Supervise/Safety/Smart." It uses software to provide advanced safety functions that could not previously be achieved, enabling flexible, low-cost construction of production lines. Cubic-S offers eight safety functions: motion area monitoring, joint monitoring, speed monitoring, stop monitoring, tool orientation monitoring, protective stop, emergency stop, and safety state output.

These safety functions are given redundancy through the use of two CPUs, achieving the functional safety standard IEC61508 "SIL2" and ISO13849-1 "PLd/Category 3" safety performance, and obtaining certification from third-party certification authorities TÜV SÜD and UL.

(2) Application example

(i) Motion area monitoring function

In the past, a safety fence needed to be installed around the outside of the mechanically limited robot motion range. As shown in Fig. 5, application of Cubic-S enables installation of the safety fence around a smaller area, thus reducing the robot installation space.

(ii) Function for selecting motion range to limit space

An example of selectable limitation on operating range is

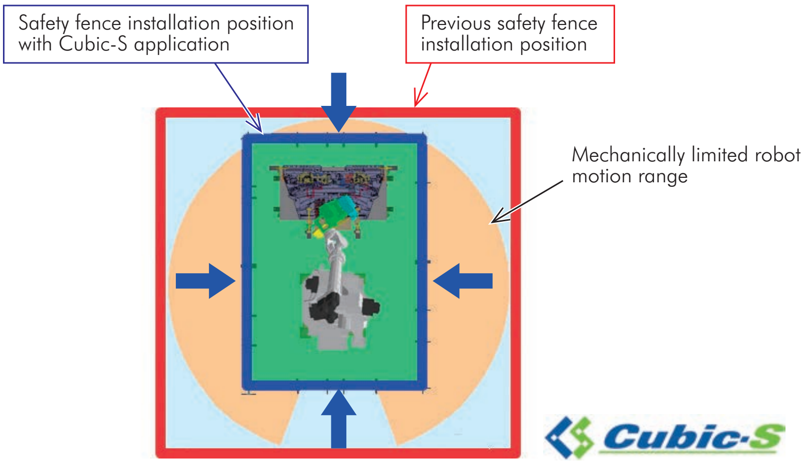


Fig. 5 Operating range limited by Cubic-S

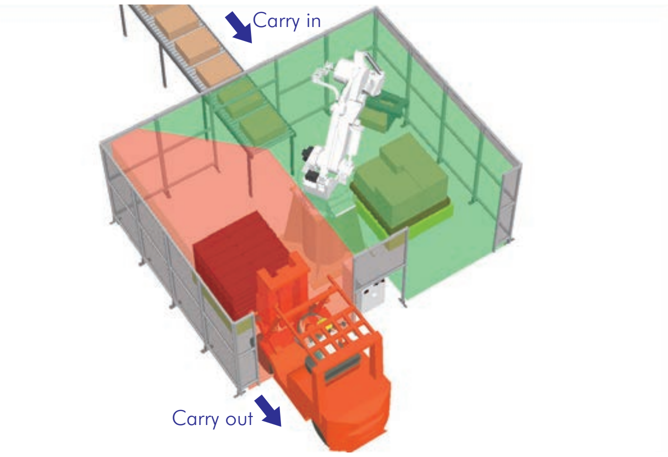


Fig. 6 Selectable limitation on operating range

shown in Fig. 6. In this example, two robot operating areas exist, with the robot piling up on one side of the operating area workpieces brought in on a conveyor, while a completed pile of workpieces is carried out by forklift in the other operating area. In this case, the robot's motion range needs to be limited when the forklift is carrying out the workpieces so that the robot does not intrude into the forklift area. Previously, multiple light curtains for detecting forklift and robot intrusion and a safety PLC for their control were required. With the application of Cubic-S, however, the motion range of the robot can be limited by detecting forklift intrusion, eliminating the need for light curtains and the safety PLC to limit the robot's motion range.

Closing remarks

The E controller is already adopted by many users and contributes to their daily production. We intend to strive for further functional expansion and performance improvement, in order to address user needs on a finer level and to expand the application range of robots.

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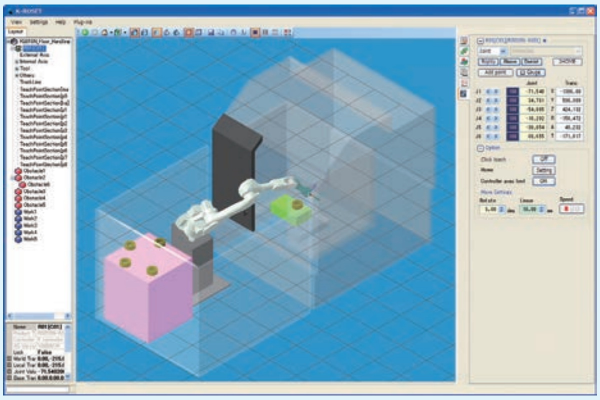
Technical Description

K-ROSET robot simulator for facilitating robot introduction into complex work environments



With the aims of improving the competitiveness of our robot systems and differentiating our robot products from those of our competitors, we are developing various applications based on robot simulators. This paper presents the new robot simulator K-ROSET and describes applications expanded on its system.

Preface

As the range of applications for robot systems has increased, various complicated issues have arisen, such as coordination between robots and their peripheral equipment and the installation of robots with multiple applications on the same line. Additionally, there is a demand for simple creation of advanced robot operation programs. In order to resolve these issues, the various companies that make robots are working to improve and add functionality to their own application examination simulators.

In 2011, we developed K-ROSET, a new robot application examination simulator. In addition to the basic functions that are demanded of a robot application examination simulator, K-ROSET provides an environment for developing and testing robot operation programs on a computer. K-ROSET's functions can also be expanded through the addition of the necessary applications. In this paper, we will provide an overview of K-ROSET and examples of how its functions can be expanded.

Table 1 Main functions of K-ROSET

- Interference checks
- Setup location analysis
- Cycle time verification
- I/O simulation
- External axis support
- Modeling of various types of tools
- Simultaneous verification of multiple robots
- Display of trajectories
- Distance measurement
- Timeline verification
- Simple shape modeling
- Virtual Teach Pendant
- Creation of animations
- CAD data importing

1 Overview of K-ROSET

In order to improve the efficiency of robot teaching, it is necessary to make use of offline tools such as robot simulators. We have developed the K-ROSET robot simulator and the KCONG automatic teaching data generator as offline tools to simplify the introduction of robots, and we provide our users with optimally-configured robot systems that make use of the tools in different ways according to the purpose and use.

K-ROSET is a tool that simulates the operations of

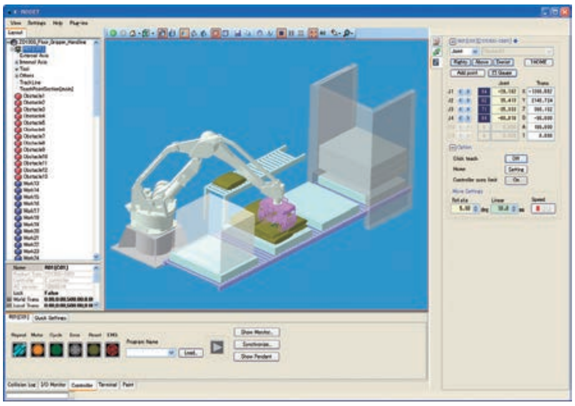
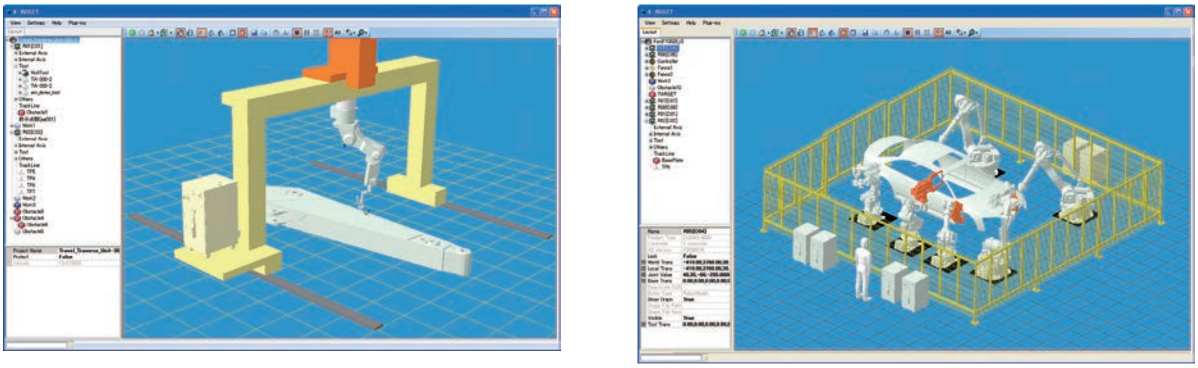


Fig. 1 Operation screen of K-ROSET



(a) Arc welding

(b) Spot welding

Fig. 2 Simulation examples of applicable targets

actual robots on a computer. It enables operating robots using the same methods, and executing operation plans using the same logic, as with the actual robots. Furthermore, by adding necessary applications, it is possible to automate the actual work of robot teaching, eliminating teaching work based on experiences and trial and error that used to be performed by humans.

The main functions of K-ROSET are shown in Table 1, while its operation screen is shown in Fig. 1.

(1) Structure

With K-ROSET, we have improved operability by adopting a software structure that integrates 3D rendering software with high processing speed and low memory requirements, complete with an operating interface that is conveniently laid out around it. By placing the robots, workpieces, teaching points, etc. on the screen, the operator can intuitively generate an operation program for the robot and simulate an actual system on the computer.

(2) Applications

Actual robot systems can be used for a wide variety of tasks that include handling, arc welding and painting, and on K-ROSET, simulations can be performed separately by application (Fig. 2). It is also possible to simulate robot systems in which robots with different applications (such as arc welding and handling, or handling and sealing) are installed simultaneously (Fig. 3).

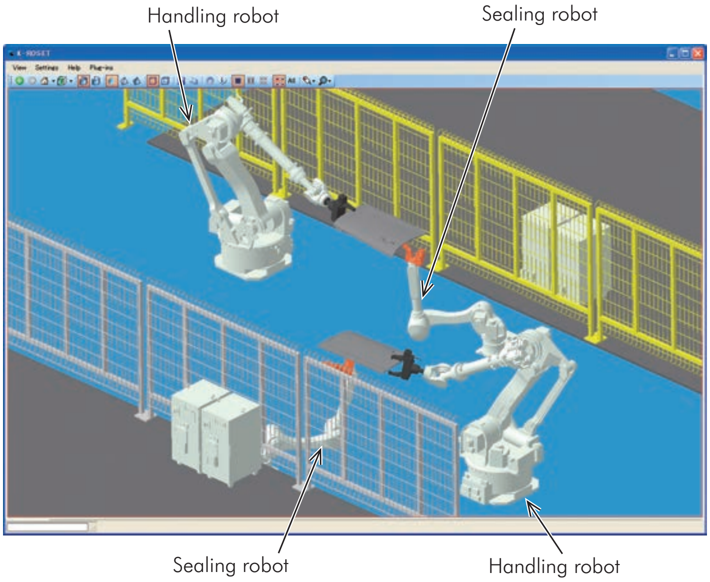


Fig. 3 Simulation example of multiple applications

2 Characteristics of K-ROSET

With complex robot systems that include multiple robots or things like external axes, conveyors and peripheral equipment, it is vital to be able to study the operation without using the actual robots and equipment. When doing so, making use of the following robot simulator functions can be expected to have the benefits shown in Table 2 during the various steps of introducing manufacturing equipment.

① Layout examination
② Creation and verification of robot operation programs
③ Cycle-time verification

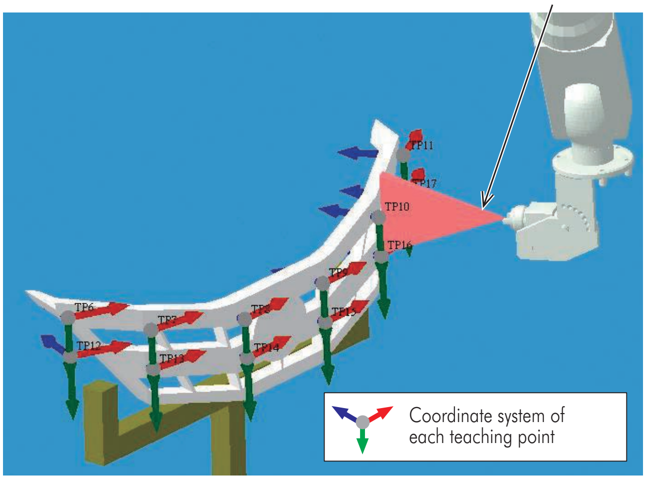
The parts of K-ROSET that compute robot operations make use of the same operation software that is used in robot controllers. Additionally, because its simulation speed is several times faster than the operation speed of actual robots, it can carry out high-precision and high-speed computation of cycle time.

Making use of K-ROSET's functions eliminates the trouble of guiding the robot into a proper position through manual operation, making it possible to reduce teaching time. For example, it is possible to click on a workpiece on the screen to create a teaching point in that location and drag and drop that teaching point into the program area (the edit screen area) to create an operation instruction.

Table 2 Merits of robot simulators

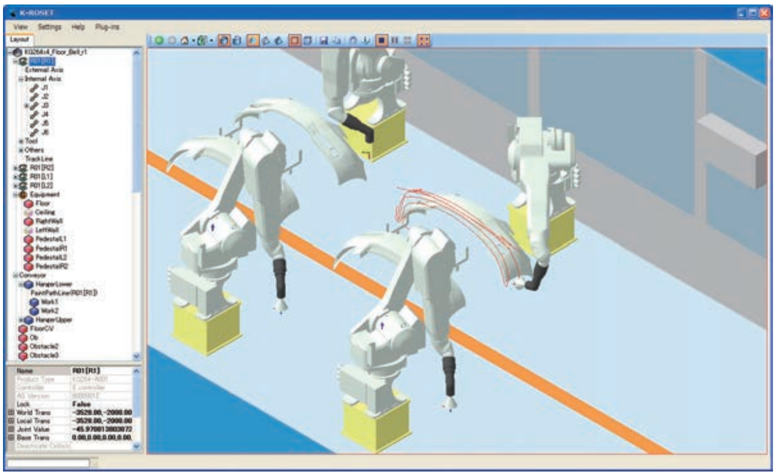
Before Introduction	At the Time of Introduction	After Introduction
System proposal	Examination of applications	Automatic teaching
Layout examination	Verification of operation	Verification of improved

Display of painting operations



Coordinate system of each teaching point

Fig. 4 Simulation example of teaching points creation



Name R01 [R1]
Lock False
World Trans -3529.00,-2000.00
Local Trans -3529.00,-2000.00
Joint Value -45.9700138003872
Base Trans 0.00,0.00,0.00,0.00,

Fig. 5 Simulation example of real application

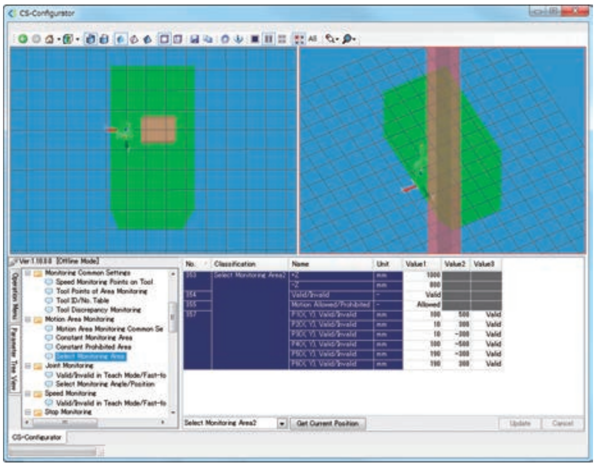
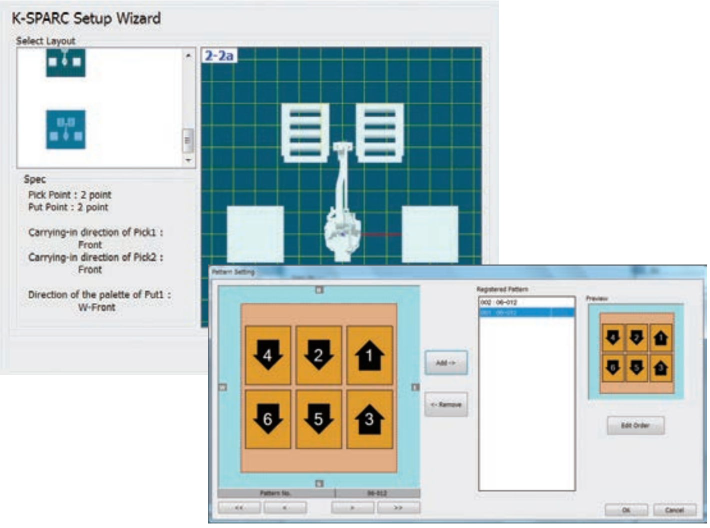


Fig. 6 Example of CS-Configurator setting screen



Spec
Pick Point : 2 point
Put Point : 2 point
Carrying-in direction of Pick1 : Front
Carrying-in direction of Pick2 : Front
Direction of the palette of Put1 : W-Front

Fig. 7 Example of K-SPARC setting screen

Fig. 4 shows an example in which teaching points have been created for a workpiece, while an example of operation based on the teaching points created is shown in Fig. 5. The operation trajectory of the robot tool tip is shown in Fig. 5.

3 Examples of customization

With K-ROSET, users can create their own operation interfaces, expand functionality and otherwise customize the program (using plugins). In addition to using K-ROSET's main simulation function, it is possible to use new functions and custom functions along with K-ROSET.

Actual examples of additional applications that have been developed using customization functions are given below.

(i) CS-Configurator (Fig. 6)

Parameters for the safety monitoring unit can be set easily based on visual representation. For example, a 3D display enables intuitive configuration of the monitoring space.

(ii) K-SPARC (Fig. 7)

Palletization patterns are automatically generated by K-SPARC, and K-ROSET is used to arrange robots and equipment. Additionally, the operation program can be run to confirm the loading operation.

(iii) Interference prediction function (Fig. 8)

When changing programs after robot installation, connecting to this function online makes it possible to predict interference between robots, workpieces and surrounding equipment during operation and to easily check the locations of predicted interference using a 3D display, preventing interference before it occurs.

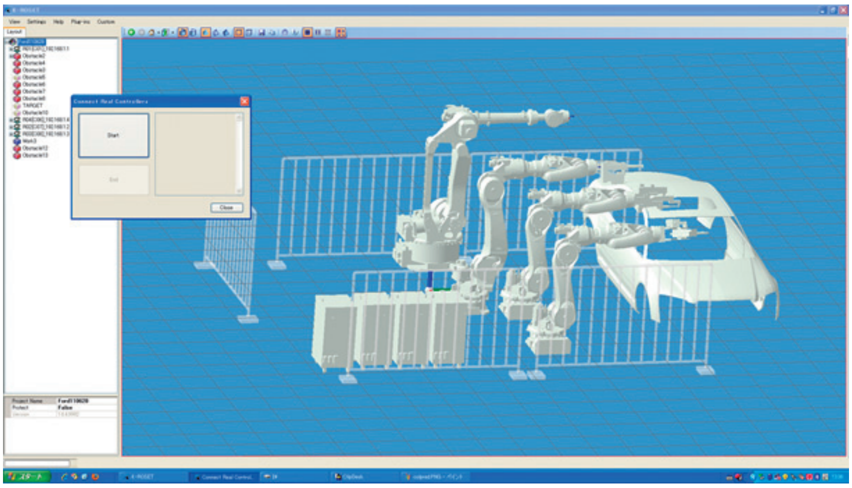
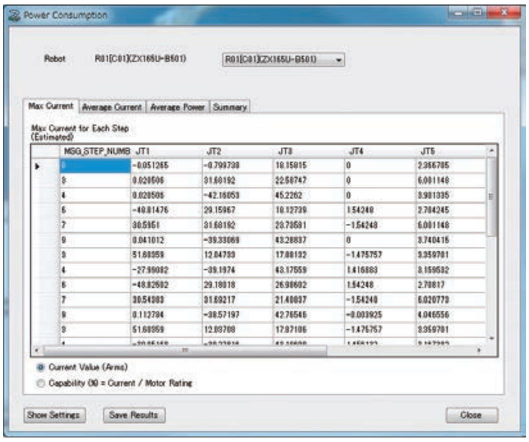


Fig. 8 Example of interference prediction function



Robot R01[C01](ZX165U-B501) R01[C01](ZX165U-B501)

Max Current for Each Step (Estimated)

MSG_STEP_NUMB	JT1	JT2	JT3	JT4	JT5
[illegible]	-0.051265	-0.799730	10.15015	0	2.356705
3	0.020506	31.60192	22.50747	0	6.001140
4	0.020506	-42.16053	45.2262	0	3.981335
6	-40.01476	29.15067	10.12739	1.54248	2.704245
7	30.5951	31.60192	23.73681	-1.54248	6.001148
9	0.041012	-39.33069	43.28837	0	3.740415
3	51.60359	12.04730	17.08132	-1.475757	3.359701
4	-27.99082	-39.1974	43.17559	1.416883	3.159532
6	-48.82502	29.18018	26.98602	1.54248	2.70817
7	30.54303	31.69217	21.40037	-1.54248	6.020773
9	0.112784	-38.57197	42.76546	-0.003925	4.046556
3	51.60359	12.03708	17.87106	-1.475757	3.359701

● Current Value (Arms)
○ Capability (%) = Current / Motor Rating

Fig. 9 Example of power consumption simulation

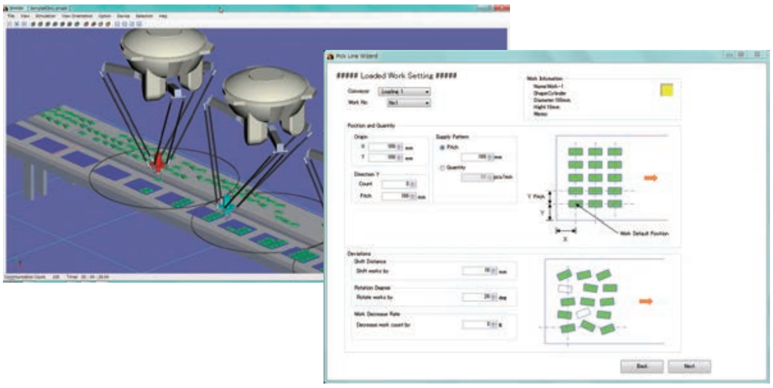


Fig. 10 Example of K-PET setting screen

(iv) Electrical consumption simulation function (Fig. 9)
This function can be used to run a robot operation program on K-ROSET, estimate the current and power used during operation, and display the results in tabular format.
(v) Picking robot simulation (K-PET)
In recent years, the use of robots in consumer products industries such as food, drugs and cosmetics has expanded rapidly, and it is particularly common to use them in combination with vision systems for the high-speed transfer of small-item workpieces. Quick verification of a robot's transfer ability is one of the keys to the expansion into these markets. Because of this, we are working to develop systems that are specialized for this kind of application and can carry out setup and simulation in a more simplified manner. K-PET, a specialized tool for the computer simulation of picKstar, a high-speed picking robot developed by Kawasaki, is shown in Fig. 10. K-PET features a menu that can be used to easily set up feed and discharge conveyors, feeding and discharge methods for the workpiece in question, etc. Additionally, it makes it easy to determine how multiple picKstar units will be arranged.

4 Linkage with other applications

(1) Linkage with vision systems

Linking K-ROSET with other applications makes it possible to carry out more advanced application verifications. Development is now underway for a simulation function that combines K-ROSET with K-VFinder, a 2D visual recognition system that is used with products such as picKstar. Doing so will make it possible to simultaneously carry out studies of vision system installation on a computer and operation verification of robots that are combined with vision systems.

An example of a linkage with a vision system is shown in Fig. 11. The workpiece information generated by K-ROSET on the left side of the screen is sent to K-VFinder on the right side, and a simulation is carried out as if the workpiece had been recognized with an actual camera.

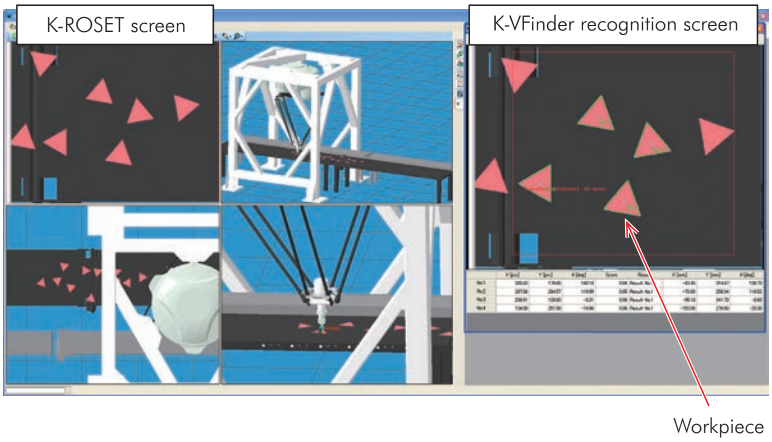


Fig. 11 Example of K-ROSET and K-VFinder

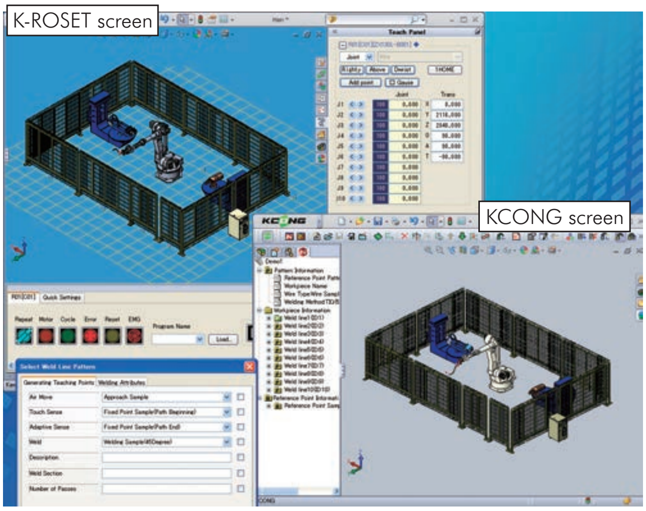


Fig. 12 Example of K-ROSET and KCONG

(2) Linkage with automatic teaching systems

The KCONG software for automatic teaching data generator comes with a built-in 3D CAD program, and K-ROSET uses the same 3D CAD program so that it can be linked with KCONG. We have thus enabled linking data between the two systems to merge the application study function (including peripheral equipment) of K-ROSET with KCONG's function for automatically generating teaching data based on 3D workpiece data.

Figure 12 shows this linkage. KCONG automatically generates teaching points based on the data for the system layout created using K-ROSET. Additionally, the data created is given to K-ROSET for operation verification.

Concluding remarks

We do not simply develop tools for robot application study and simulation. We are also working to make use of robot simulation technology as a tool to differentiate our robot systems.

We intend to continue to differentiate ourselves from other companies through the development of offline study systems and a range of other applications, in order to provide our customers with more desirable and effective robot systems.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Bin-picking robot system
—Application of 3D vision system

Operations for loading workpieces onto machine tools and handling workpieces between processes are important towards building a manufacturing line. In particular, the operations for picking workpieces in bulk need to be automated.

This paper describes a bin-picking robot system as a case of application of a 3D vision sensor developed by us.

Preface

At present, in machining processes for machine parts, loading of workpieces into the machine tools, transfer between processes, and other workpiece transfer operations between machining processes are often still dependent on manual labor. If this mechanical parts picking and transfer between machining processes were to be automated using robot systems, it could make the machining process layout and flow more flexible, and increase the rate of line automation as a whole.

In the materials processing production site, automation has been slow in coming for the workpiece bin-picking operations where workpieces are randomly placed in container boxes and other large part boxes. In particular, picking of forged parts, machine parts, and other heavy workpieces is a monotonous, repetitious operation that is a classic example of an unpleasant 3D (dirty, dangerous, and demanding) working environment. As a result, there is much demand for automation, and introduction of robot systems is eagerly awaited. In addition, if special equipment for arranging parts is used, such operations would not be able to handle multiple parts types, so a practical general-use industrial robot is needed. Furthermore, introduction of such a robot system necessitates development of vision technology to enable identification of complex workpieces in bulk.

At Kawasaki, we have various vision systems using stereo vision sensors and 3D laser sensors, etc., that are available as products for various robot applications in welding, assembly, inspections, and transport, etc.

For automation of workpiece bin-picking targeting forged parts, we have developed, based on our vision technology, a 3D vision sensor, a bulk workpiece recognition method, an online interference simulator, and a module controller for integrated control of various functions, and placed a robot system on the market that is capable of stable picking of random workpieces (Fig. 1).

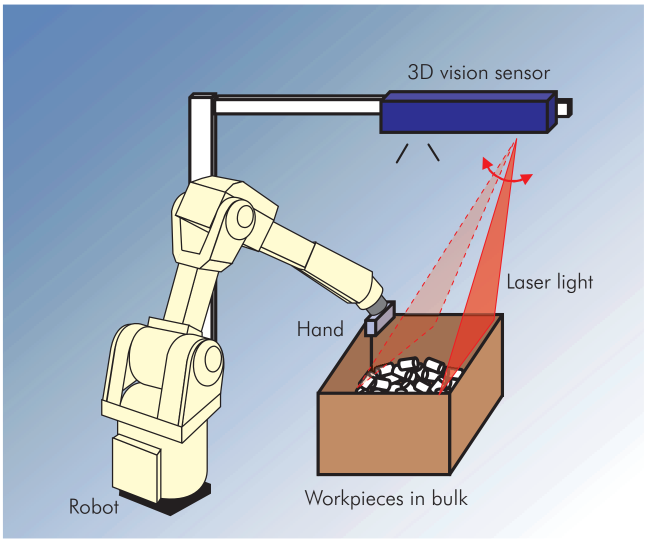


Fig. 1 Bin-picking robot system

1 Development issues and solutions

(1) Development issues

In ordinary picking operations, the method for recognizing workpiece positions and postures involves the use of cameras trained on workpieces laid out on a conveyor or other flat surfaces to perform 2D grayscale image processing. However, this method is limited in the range of picking automation applications, in that it requires workpieces to be arrayed in specified positions on the flat surface, or in a specified order, etc. For cases where bulk workpieces are randomly placed in container boxes, etc., bin-picking robot systems need to be able to recognize the 3D position and posture of each workpiece, and determine the workpiece to be picked. The main issues for automation of bin-picking operations are as follows.

① With diverse 3D positions and postures in randomly packed workpieces, individual workpieces are difficult to recognize against a background of piled-up workpieces.

② During workpiece picking operations, the robot or hand collides with surrounding workpieces or the container box.

③ Depending on the workpiece position or posture, some workpieces may be left behind within the container box.

(2) Solutions

As solutions to these issues, we have developed the following:

① A vision system capable of discerning changes in the surrounding lighting environment and the workpiece surface condition, and a stable bulk workpiece recognition method.

② Function for judging and avoiding potential collisions with surrounding workpieces.

③ Hand mechanism with diverse gripping patterns that keep residual workpieces to a minimum.

2 Development of bin-picking robot system

(1) Equipment configuration

The bin-picking robot system consists of a 3D vision sensor for recognizing bulk workpieces, an articulated robot for performing the picking operation, an electromagnetic hand for performing the grasping operation, and a module controller for performing integrated control of various equipment and operations sequences, etc. The equipment configuration is shown in Fig. 2.

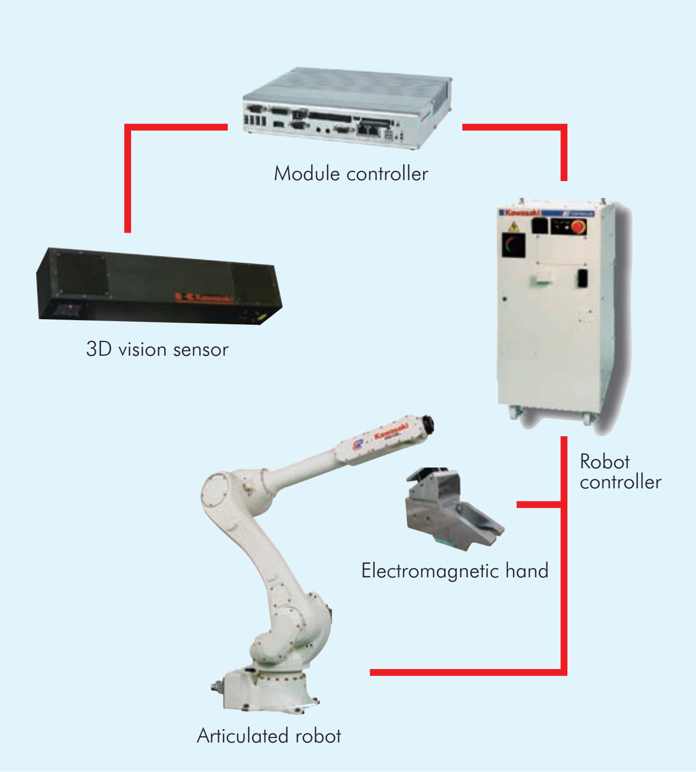


Fig. 2 System configuration of bin-picking system

Fig. 3 Laser Slit Scan Camera(LSC)

Table 1 Specifications of LSC

Item	Specifications:
Imaging distance (mm)	1,400 to 2,000
Measurement range (mm)	W800×D800×H600
Laser class	Class 3R
External dimensions (mm)	W610×D125×H125
Weight (kg)	Approx. 4.8

(2) 3D vision system

(i) Laser Slit Scan Camera (LSC)

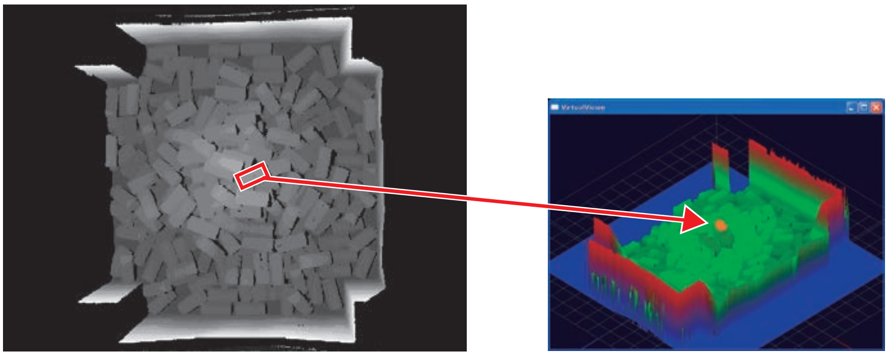
For the 3D sensing function for automation of bulk workpiece picking, we used a method for processing range images expressing height information in grayscale values. In this system, we used an active method projecting semiconductor laser slit light to obtain a range image that, unlike stereo cameras and other passive methods, enables height information to be obtained for edges and targets on patternless flat surfaces or curved surfaces. In addition, it can ensure stable imaging even with changes in the ambient light or reflection rates on the workpiece surface. For this product, we developed the 3D vision sensor Laser Slit Scan Camera (LSC) with a motor that drives a mirror to scan the laser slit light and obtain a range image. The LSC can measure the wide range of a large container box (W800×D800×H600 mm) with a single scan. An external view of the LSC is shown in Fig. 3, and specifications in Table 1.

(ii) Bulk workpiece recognition method

We have developed a bulk workpiece recognition method targeting cylindrical-shaped forged parts. In this recognition method, the workpiece targeted for gripping is picked

(a) Forged parts workpiece

(b) Image of region partitioning process



(c) Range image and result of grip target workpiece detection

Fig. 4 Images of bulk workpiece processing based on a range image captured with the 3D vision sensor, enabling calculation of the 3D positioning and posture. In addition, we eliminated the need for a template image model used in normal image recognition processes, enabling recognition of diverse workpiece postures.

The bulk workpiece recognition procedure is as shown below.

① Edge detection and partitioning process
The edges of each workpiece are detected from the range image, and region partitioning process is performed. An external view of forged material workpieces is shown in Fig. 4(a), and an image after region partitioning process is shown in Fig. 4(b).

② Feature quantity calculation
After the region partitioning process, labeling is performed for each sub-region, and feature quantities are calculated for the height, area center, surface curvature, and area, etc., of each extracted sub-region.

③ Detection of workpiece targeted for gripping
The workpiece targeted for gripping is determined from the sub-region extracted using the region partitioning process, and the 3D coordinates of the gripping position, and the workpiece tilt and rotation angles are calculated. The range image, and detection results for a workpiece targeted for gripping, are shown in Fig. 4(c).

(3) Online interference simulator

In previous bin-picking robot systems, when the robot approached the workpiece targeted for gripping, it would occasionally collide with workpieces surrounding the target workpiece or with the container box, causing the system to stop. To solve this problem and enable stable picking operations, we applied the interference check function of the Kawasaki robot simulator to develop an online interference simulator. The online interference simulator has the following features:

① Uses 3D measurement data obtained with the LSC to enable detection of robot collisions before performing the approach operation.

② Evaluates 3D positions and postures of workpieces, and the robot posture, to determine the most efficient priority sequence for workpieces targeted for gripping.

③ Determines the robot posture for the shortest robot operation time.

Operations screens for the online interference simulator are shown in Fig. 5.

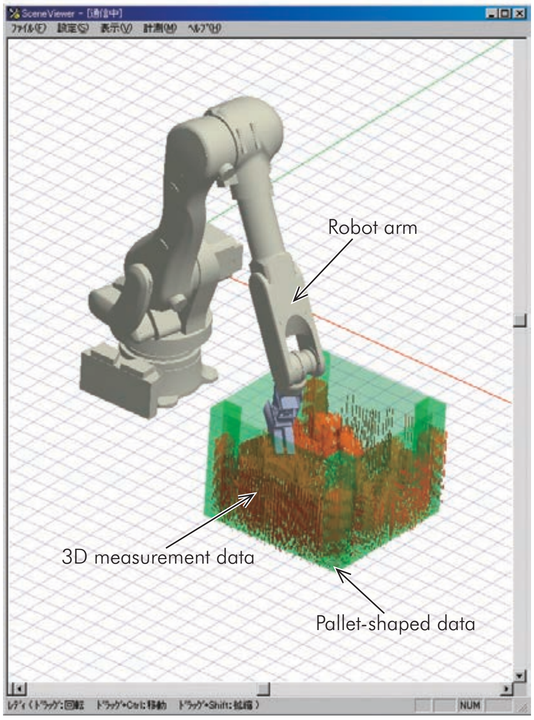


Fig. 5 Online interference simulator screen

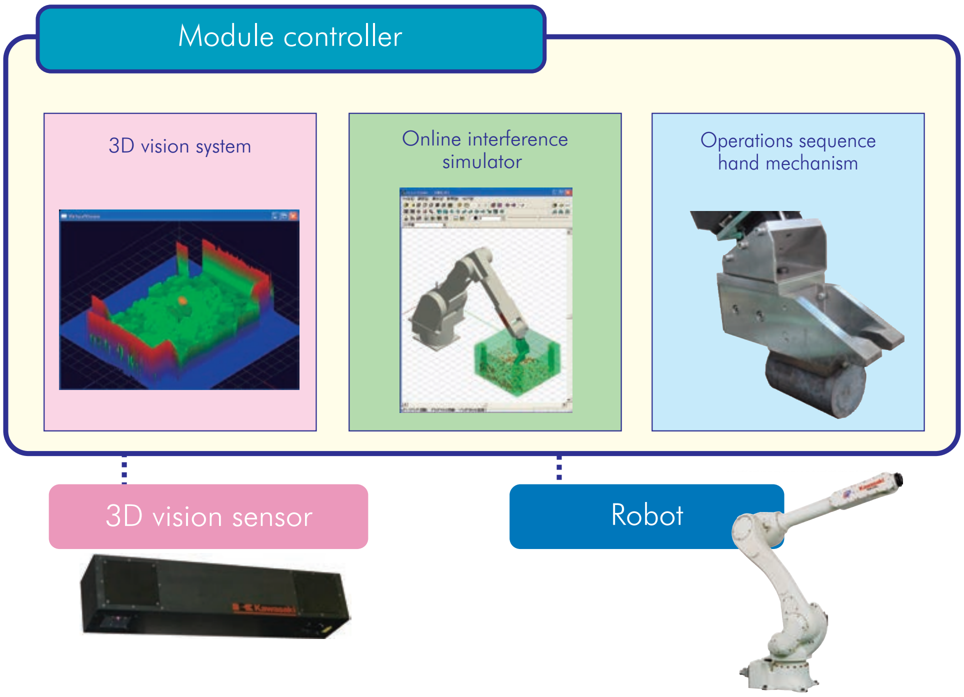
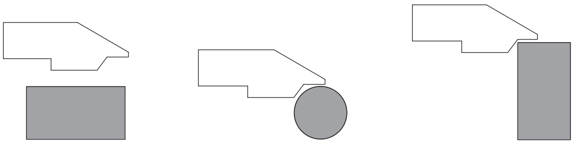


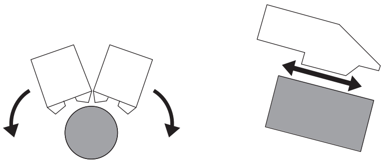
Fig. 6 System configuration of module controller

(a) Normal grip (b) Front edge grip (c) Bottom surface grip

Fig. 7 Views of electromagnet hand



(a) Normal grip (b) Front edge grip (c) Bottom surface grip



(d) Rotation shift (e) Forward and back shift

Fig. 8 Approach operation of electromagnet hand

(4) Module controller

We have developed a module controller for integrated control of the various functions in the bin-picking robot system. The module controller is the core of the robot system, and is standardized for construction of mass production-type robot systems for integrated control of the 3D vision system, online interference simulator, operations sequence, hand mechanism, and various sensors, etc. In addition, we provide a library based on a universal language (C# language) that enables easy customization for each customer, and reduces the robot system development time. The module controller system configuration is shown in Fig. 6.

(5) Electromagnetic hand

Normally, if cylindrical-shaped workpieces are loaded in bulk inside container boxes, workpieces near the walls of the container box are not picked until the very last, and sometimes get left behind without being picked. To resolve this problem, we developed an electromagnetic hand with multiple gripping patterns for the same workpiece targeted for gripping, minimizing the problem of residual workpieces. In addition, we used the online interference simulator to perform simulations of multiple gripping patterns, in order to automatically calculate approach operations that avoid hand collisions and enable picking of bulk workpieces. Views of the electromagnetic hand and its gripping patterns are shown in Fig. 7, and approach operation examples are shown in Fig. 8.

Fig. 9 Bin-picking system for forged part

3 Application example

We introduced a bin-picking robot system to a forged parts manufacturing line. This system can perform stable recognition of workpieces even with oxidized scaling or rusting of surfaces of forged part workpieces. In addition, the robot can continuously pick workpieces without colliding with surrounding workpieces or with the container box. The bin-picking system for forged parts is shown in Fig. 9.

Concluding remarks

Kawasaki has developed a 3D vision sensor, a bulk workpiece recognition method, and an online interference simulator based on our vision technology, to achieve a bin-picking robot system for practical application and placed it on the market. In the future, as a robot application using 3D vision sensors, we plan to engage in robot system development that moves beyond the handling sector to include the assembly and inspection, etc., of precision machine parts and electrical machine parts, which currently depend on manual labor because of the difficulty of automation.

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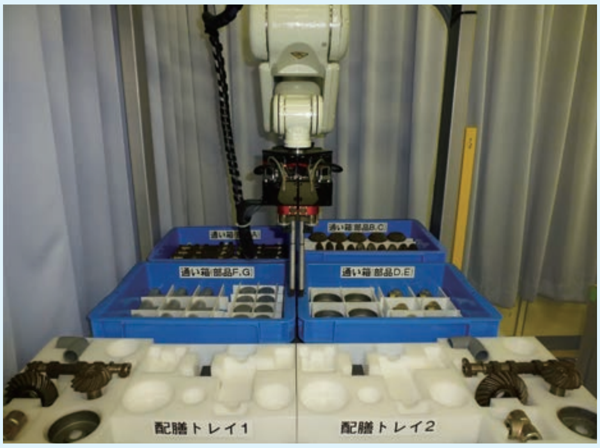
Catering hand system for a high variety of workpieces



We are promoting research and development into universal hand systems capable of handling a variety of workpieces as a core technology for expanding the scope of robot applications. In particular, we aim to realize robot-based automation of catering operations in assembly and outfitting processes, which has previously been considered difficult, through the use of universal hand technology and technology to integrate it as a system. This catering system is scheduled to be introduced and commissioned in our plants in FY2012.

Preface

In assembly plants for automobiles and other transportation machinery, or for machinery and devices mounted on such, catering is a process where robot application is lagging. Catering refers to an operation to collect the requisite number of part groups required for assembling a single device in a multi-item assembly line, arranging them on a tray, and supplying it to the assembly operator. This scene is shown in Fig. 1.

Compared with assembly operations that require touch, sight, and other advanced human intelligence, catering in many cases does not require so much proficiency. As a result, there has long been demand for the application of robots in this area of operation. In addition, with the recent mainstreaming of the multi-item line production method in manufacturing, demand for robots has grown still more to prevent catering mistakes due to careless human error. Even though human proficiency is not required, one factor behind the difficulty of using robots has been the failure to realize a robotic hand system suitable for catering.

To date, hands mounted on industrial robots have mainly been the air chucking type, air suction type, and electromagnetic type, etc. These types all require different claw shapes and air pressure adjustment for each part type, making them unsuitable for catering, which demands handling of a variety of type of parts.

The following solutions have been proposed for handling multiple types of parts.

① Enable exchange of hands.
② Attach multiple hands.
③ Install a universal function in the hand.

Fig. 1 View of catering operations

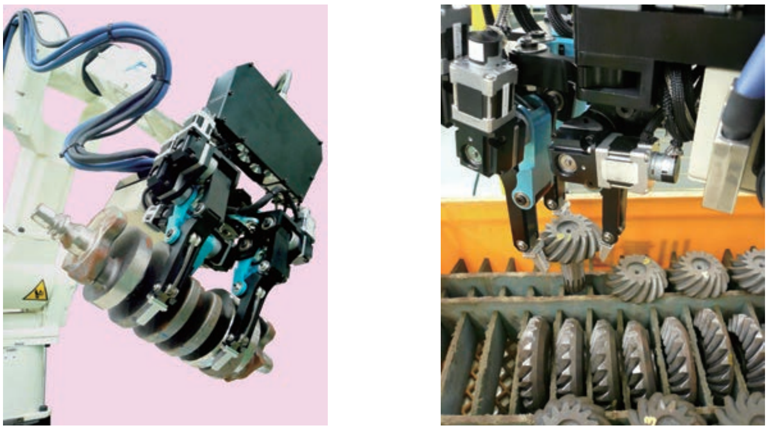


Fig. 2 Ealier version of the humanoid hand (2007)

Method ① is effective for cases where the number of part types is limited. At higher numbers, however, the increased system costs and cycle time delays can no longer be ignored. Method ② has the problem of the hands interfering with the surroundings when attempting to pick up parts stored in cramped environments. Method ③ has been the subject of active research and development efforts in both academia and industry. However, because of problems with cost and reliability and difficulties with teaching, etc., it has not come into widespread use. In recent years, however, examples of its practical use have gradually been increasing.

At Kawasaki, we commenced serious research and development into a universal hand for industrial use in the early 2000s, and displayed a prototype device for the first time outside the company at the International Robot Exhibition in 2007. At the time, we modeled the robot hand after the structure and function of a human hand, to give it universality. A partial view is shown in Fig. 2. Later, we restricted the application to catering use, performed functional analysis, and developed a universal hand system specialized for catering.

1 Issues toward realization of catering hand

An example showing parts to be catered for a motorcycle production line and their storage environment is shown in Fig. 3.

The characteristics are as summarized below.

① The part types (size, shape, material) are highly variable.

② Parts are collected and packed into storage boxes, and partitioned by frames, etc.

③ Within the partitioned spaces, the parts are loaded in random positions and orientations.

While the previous humanoid universal hand could

Fig. 3 Example of workpieces catered at a motorcycle plant

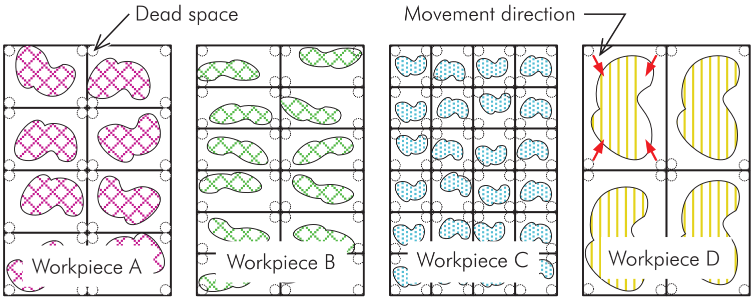


Fig. 4 Analysis of workpiece storage situation

respond well to ①, it was incapable of responding to ②. For the humanoid universal hand, with its freedom of fingertip bending, the finger joints became thicker so that the claws could not be inserted into the narrow gap between the partitions and the workpiece. In addition, one method for responding to ③ is to use a vision sensor to measure the variability in parts position and orientation, and then correct the position of the claw insertion. In this case, a camera must either be installed in each parts storage box or be mounted on the hand. The former would require a large number of cameras and, to ensure a field of view for the camera, the storage boxes would need to be placed in a larger environment. The latter, on the other hand, would necessitate a wait time in the robot operation to allow for measurement of the variability.

2 Development of 4-claw catering hand

(1) Policy studies toward issue resolution

While the type of catered parts and the storage environments vary, two common points as listed below can be found.

① The partitioned spaces are square.
② Beveling has been performed on parts corners.

In other words, parts of whatever shape, no matter how they are placed, will always result in a dead space in the four corners of the partitioned space (Fig. 4).

If we insert claws into the respective dead spaces, and move them horizontally toward the center, the parts will be moved toward the center and finally fixed in place. In other words, regardless of the parts shape or the random positions, we can complete handling with the same simple operations sequence. In addition, since handling is performed with four claws, a form closure (objects are fixed in place by point contact with surroundings with zero friction force) can easily be formed on the horizontal surface, so that parts can be securely fixed even with thin claws and weak gripping force.

From the above analysis, it appears that a configuration consisting of four claws is suitable as the basic form for a catering hand. Moreover, two degrees of freedom are needed for adjusting the vertical pitch and horizontal pitch of the four claws. For complex-shape parts, in bringing all four claws into contact it appears that four or more degrees of freedom for the hand are favorable.

(2) Hand characteristics

(i) Main functions and specifications

Based on this policy, the main specifications for the developed hand are shown in Table 1, and the configuration diagram is shown in Fig. 5.

Table 1 Main Specifications

Horizontal stroke (mm)	160
Vertical stroke (mm)	60
Fingertip strength (N)	100 or more
Open/close time (s)	0.3
External dimensions (mm)	W160×D190×H115
Weight (kg)	3.5

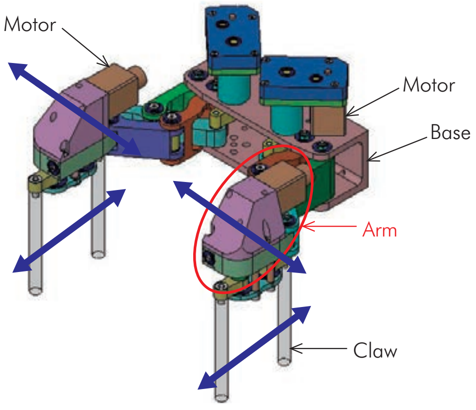


Fig. 5 Hand

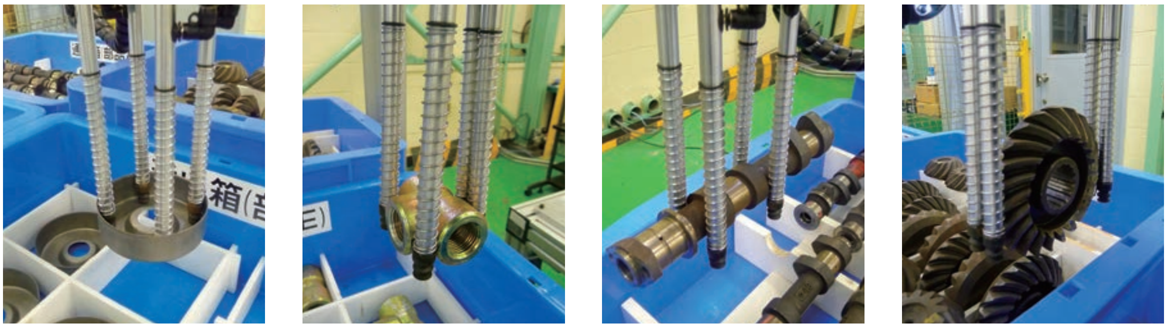


Fig. 6 Picking parts of different shapes

The hand employs a mechanism with four degrees of freedom mounting four servomotors, enabling independent control of the operations shown by arrows in the figure. Therefore, the claw's vertical pitch and horizontal pitch can be adjusted to match the size of the square partition space. In addition, if the claw's vertical pitch is closed all the way, we can change the hand to a 3-claw hand or 2-claw hand. A torque control function on the servomotors can be used to easily adjust the gripping force, enabling internal gripping and external gripping. As a result, parts of various shapes and hardness can easily be picked up from within narrow partitioned spaces (Fig. 6).

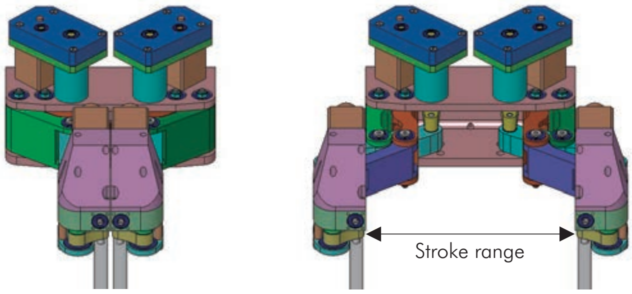
(ii) About the structure

The hand consists of a base, two arms, four claws, and four motors. The two arms are attached to the base, and the motors drive the arms in a horizontal direction. In addition, a motor and two claws are mounted on each arm. This motor drives the top claws in an arc in the opposite direction with each other.

The two arms use our unique Chebyshev linkage finger mechanism*. As a result, we can ensure a powerful gripping stroke with a compact base size, enabling gripping of parts of various sizes even in cramped environments. When a ball screw, etc., is used to design the hand, the stroke is normally restricted to half the base size or less. In our hand, however, the stroke is almost the same as the base size (Fig. 7).

In addition, the height of the structure is kept low to enable entry into shelves where the parts storage boxes are placed (Fig. 8).

* Chebyshev linkage finger mechanism: A linkage mechanism where a quasi-straight operation is obtained from a rotation operation.



(a) Fully closed position

(b) Fully open position

Fig. 7 Arm stroke

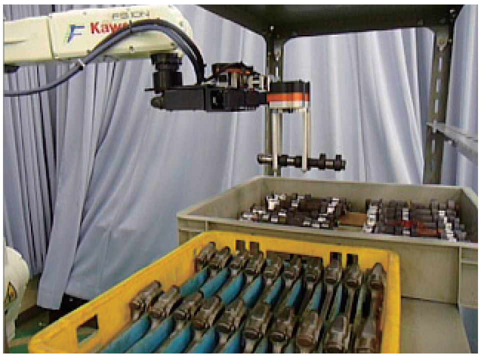


Fig. 8 Entry into shelves

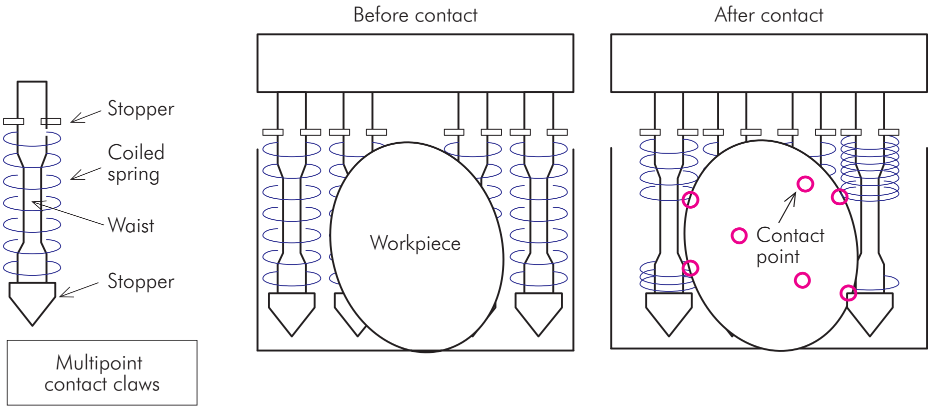


Fig. 9 Structure and function of multipoint contact claws

(iii) Stabilization of vertical direction

While incorporating four claws ensures stable gripping of workpieces in the horizontal direction, gripping in the vertical direction is obtained through friction with the claws alone.

To ensure a stable holding of the workpiece in the vertical direction without relying on friction, we developed a multipoint contact claw configured with a waisted shaft sheathed in a coiled spring. When this claw contacts the workpiece and further force is applied, the coil spring is distorted up or down, moving away from the workpiece and increasing the contact points. In other words, horizontal movement of the claws alone forms a 3D form closure and a stable state (Fig. 9).

Since the multipoint contact claw is configured with a simple structure using a general-purpose coil spring, we have avoided a larger claw diameter to enable insertion into narrow gaps.

(iv) Suction function

For handling plastic materials or other such parts where gripping could scratch the surface, we have enabled air suction holding in addition to the normal gripping. In other words, we created a hollow structure in the claws and attached air suction pads onto the tips. In addition, to avoid drooping or snagging in the air piping when the arm or claw moves, we have installed guide holes inside the arm to enable compact piping.

If the parts are light, two or four items may be picked up at the same time, enabling reduction in the cycle time for catering operations (Fig. 10).

(3) System configuration

The controller for governing the hand movement is encased separately from the robot controller, and they communicate directly with each other via an RS232C cable.

Fig. 10 Holding by suction

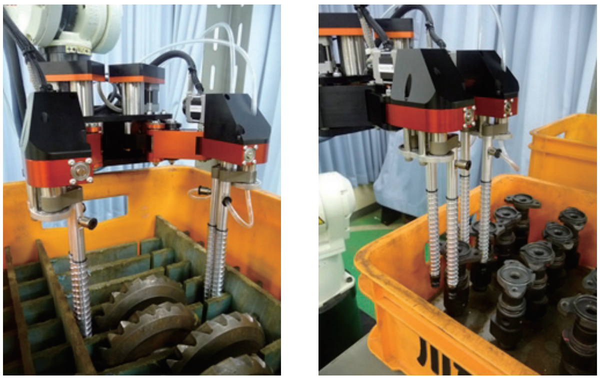


Fig. 11 Catering tests

The robot controller queries the hand controller at specified intervals regarding the motor position and torque and other statuses (normal/abnormal, servo on/off, etc.), and the hand controller responds. The robot controller uses this information to continuously monitor the hand, and sends various operations commands to the hand controller according to the robot operations program. Operations commands include a jog feed from the current position, jumping to the teaching position, gripping based on a set force, and origin point setting, etc.

In addition, as a useful tool for increasing efficiency during teaching operations, we enabled various hand operations as well as status monitoring on the robot teaching pendant screen. Furthermore, we have a direct teaching function where manual force can be used to directly adjust the pitch between claws or pressing force in relation to actual parts or storage boxes.

So while the hand system that we have developed is a multi-axis system, it does not require special training on the part of the user, and enables intuitive and easy operation.

3 Application study example

For the seven types of machine parts catered to our motorcycle plant, we performed an application study using actual storage boxes. We verified that the catering operation could be performed for all the parts without the need to exchange the claw shapes (Fig. 11).

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Concluding remarks

With the advances in recent years of robot-related equipment technologies, operations where robots can act in place of humans have steadily increased. However, as with the catering operation, even light operations that at first glance appear to be simple with no skill requirements can require advanced sensor systems or large-scale peripheral equipment when a manual labor operation is entirely converted to robot operation, and in many cases the cost benefit is lost.

To solve these issues, Kawasaki has adopted an approach of translating manual labor operations into the perspective of robot operations. For example, we translated catering operation as "an operation for picking undefined items from square partitions," which is an interpretation that can be easily applied to robot operations, and then we pursued a simple yet versatile device that can perform the operations.

There is increasing demand to apply robots for operations requiring human manual skills and environmental recognition functions based on the five senses. We intend to continue providing the best solutions for operations where robots are in need, based on a knowledge of what they are capable of.

Machine parts assembly robot system

To reduce labor and maintain product quality at production plants, complicated assembly operations need to be automated. This paper describes our approaches to the development of elemental technologies toward realization of assembly robot systems. In addition, we present examples of in-house applications using these technologies.

Preface

In the industrial sector, introduction of robots to production lines to improve productivity has progressed steadily. In the welding and painting lines in particular, where robot automation has been actively pursued, there is an extremely large number of robots in operation. In recent years, moreover, efforts have begun to introduce robots into new areas where automation has been lagging. One of these new areas is automation of assembly operations.

Behind this demand for automation of assembly operations is the need for a response to multiple-item variable-volume production. The manufacturing industries in advanced countries produce a wide variety of products, including customization of standard products, in order to respond to wide-ranging customer needs. This trend has raised the skill and knowledge levels demanded for assembly operations, increasing the burden on operators. Moreover, and particularly in Japan, a declining labor force population due to fewer children and more seniors has made it more difficult to ensure a stable supply of operators and transfer of skills to younger workers. Use of robots to automate assembly operations is expected to provide a possible solution to these issues.

In emerging countries, meanwhile, as represented by the BRICs, manufacturing has centered on mass production items, backed by a relatively low-cost labor force. In the future, however, as their local economies develop, they will be unable to avoid product diversification. When this happens, large costs will necessarily be incurred in manual operations and quality maintenance for each product. The introduction of robots will have major benefits since the automation of assembly processes will ease tooling changes and quality maintenance.

For these reasons, we can expect expansion of the market for automation of assembly operation using robots. But because assembly involves a combination of diverse operations, there are many difficulties to overcome in using robots. Therefore, robot manufacturers are engaged in research and development toward their practical application

We at Kawasaki also continue to be engaged in elemental technologies development centering on hand technologies for assembly that can enable diverse operations, with the goal of realizing an assembly robot

Fig. 1 Chebyshev linkage hand

system. In addition, as a result of these efforts, we have achieved automation of assembly operations at our own plants. In this paper, we present the elemental technologies related to our assembly robot system, and show some application examples in our production lines.

1 Issues of assembly automation using robots

If the basic operations are simple in nature, such as welding or painting, etc., robots often demonstrate abilities superior to those of humans. In many cases, however, the assembly process consists of multiple operations. In such cases, what would be easy for a human often is difficult for a robot, or involves excessive costs to realize.

A summary of the issues for assembly automation using robots can be divided broadly into the three areas listed below.

① Acquisition of dexterity
② Acquisition of flexibility
③ Acquisition of accuracy

We here introduce the elemental technologies that we have developed to address these issues and realize assembly robot systems.

2 Elemental technologies of assembly robot system

(1) Acquisition of dexterity—assembly hand technology

In the past, when robots handled multiple parts or performed multiple operations, the hand (gripper) needed to be replaced at each change of parts or operations. This means that as the number of targeted operations increases, the number of hands also increases, adversely affecting costs, footprint, and tact time.

To resolve this problem, we pursued development of universal servo hands that can be used for multiple parts and operations. We present a few of these here.

(i) Chebyshev linkage hand

Stroke size can be used as an index for evaluating hand dexterity. We developed the Chebyshev linkage hand, featuring a broad stroke (Fig. 1).

Use of the Chebyshev linkage for the hand mechanism* achieved a broad stroke compared to the compact hand body. This design enables parts of diverse sizes to be handled. Furthermore, the linkage joints are all composed of rotating joints that enable easy sealing and clean room applications. We also incorporated such general features of servo hands as strength adjustment of gripping force and measurement of open hand width.

* Chebyshev linkage mechanism: A linkage mechanism where a quasi-straight operation is obtained from a rotation operation.

(ii) Nail attachment

Even advanced-function servo hands cannot cover all kinds of diverse parts alone. Therefore, we developed a nail attachment to be mounted on the hand that enables handling a wider variety of parts (Fig. 2).

The nail attachment is automatically removed and attached by the robot on the existing finger part of the hand. We mount attachments with differing nail shapes in accordance with the size and shape of targeted parts, enabling handling of diverse parts.

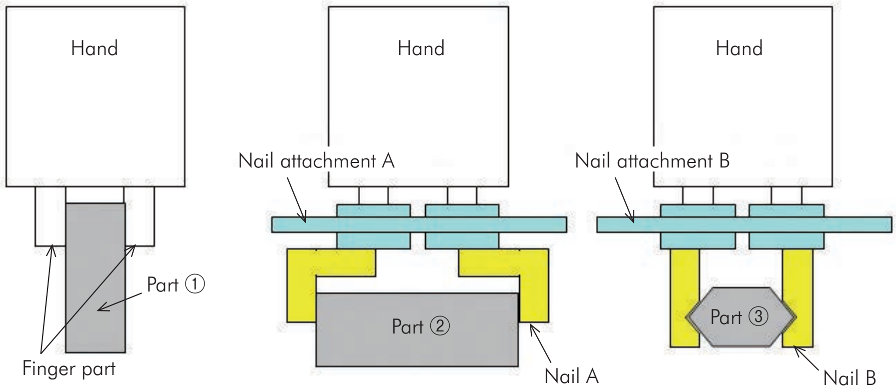


Fig. 2 Nail attachment

To fix the attachment in place, we use our own independently developed spring mechanism, and to drive the attachment, we use the existing hand actions. This eliminated the need for air or other additional drive sources, achieving lower costs and faster speeds than existing tool changers.

(2) Acquisition of flexibility—error absorption mechanism

In assembly operations, the robot often comes in contact with the products, or the hand presses against gripped parts. When this happens, even a slight error in assembly position can impose a heavy load on the robot. Therefore, in applying robots to assembly operations, various methods for controlling the pressing force have been adopted, such as use of a force sensor or a compliance device giving flexibility to the hand tips.

However, force sensors are expensive and have a risk of breaking down in assembly operation collisions. Also, compliance devices have the drawback of reduced positioning precision due to floating functions for tolerance of errors.

To address these issues, we independently developed our own compliance device, the error absorption mechanism.

(i) Error absorption mechanism

As shown in Fig. 3, the error absorption mechanism is mounted for use between the robot flange surface and the hand. When the error absorption mechanism is subjected to pressing, a floating effect activates in the hand and the error absorption function is exhibited. Furthermore, the force of a built-in spring enables operations for pressing parts gripped by the hand. This is effective for operations such as screw tightening that require contact between parts with suitable pressing force applied.

In addition, during normal times (when pressing is released), the floating effect remains inactive and the hand side is positioned in the center. This action enables high-accuracy operations for parts picking.

(ii) Pressed state detection technology

When using the error absorption mechanism to perform assembly, we can detect the occurrence of pressing by measuring the amount of displacement. We here offer two examples of configurations for achieving this detection.

① Marker imaging method

As shown in Fig. 4(a), we position markers above and below the error absorption mechanism and use a vision sensor to capture their image. Then, we compare the distance between the two markers before and after pressing to measure the displacement.

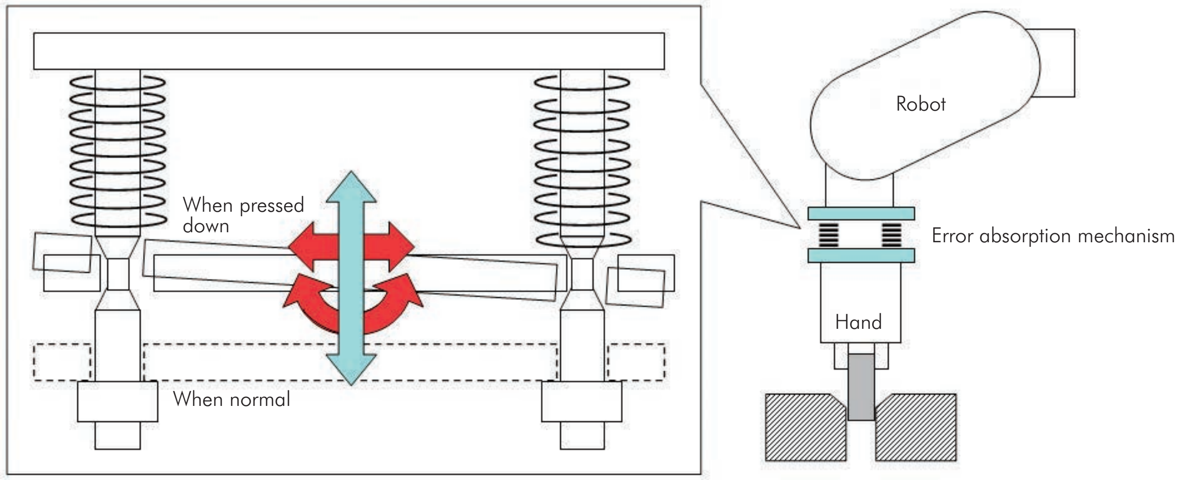


Fig. 3 Error absorption mechanism

② Touch (distance) sensor method

A touch sensor is built into the error absorption mechanism to detect the occurrence of displacement due to pressing.

Since the marker imaging method does not require a sensor on the robot side, we can build a more reliable system. The touch sensor method involves the placement of multiple sensors that enable the estimation of tilt.

This technology lets us determine whether parts have been successfully assembled or not. For example, as shown in Fig. 4(c), if a large displacement has been measured in the course of a parts insertion operation, we can conclude that parts have interfered with each other and the operation has failed. Using these detection results, we can respond with retries of the assembly, etc.

In addition, in assembly of gearwheels involving gear engagement, we can perform such advanced operations as searching for the gear engagement phase with the parts in a pressed state, and judging success by the release of error absorption mechanism pressing.

(3) Acquisition of accuracy—vision sensor technology

One effect expected of automation of assembly operations is implementation of uniform and accurate operations that humans have difficulty performing, to eliminate careless errors and maintain product quality. However, this issue cannot be resolved solely by the installation of robots; coordination with sensors is also essential.

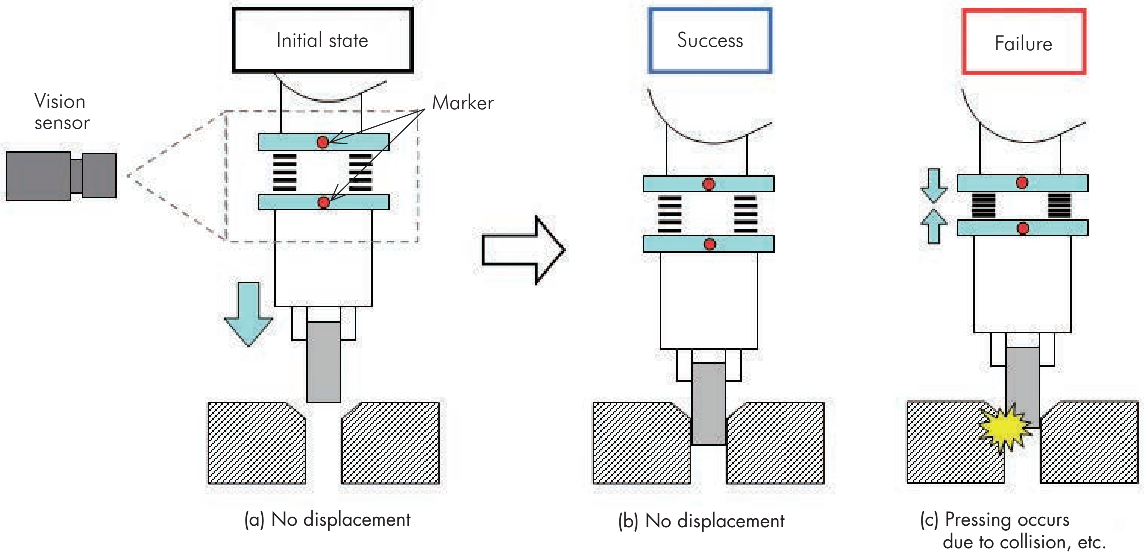
We have long been engaged in the development of vision sensors for robots and have applied them to many production sites. Here, we present an example of vision sensor technology applied to assembly robot systems.

(i) Position detection technology

To ensure performance of accurate assembly operations by robots, the position of the parts to be assembled must be determined to high precision. If the parts size or shape is fixed, then the simplest method is to install tools capable of mechanical positioning. However, with greater diversification of customer needs, the production site increasingly needs to produce diverse products. In such cases, provision of special tools for each part can lead to massive cost increases.

To address these issues, we applied a vision system to the assembly robot system for performing parts position recognition. These are installed on general-use pallets to perform visual recognition of the characteristics of supplied parts and measure their positions. Based on the measured position information, the robot can correct the parts assembly position.

This action achieves accurate assembly operations without the need for preparation of special tools for each product model, contributing to lower facilities costs.



(a) No displacement (b) No displacement (c) Pressing occurs due to collision, etc.

Fig. 4 Determination of assembly success or failure by error absorption mechanism

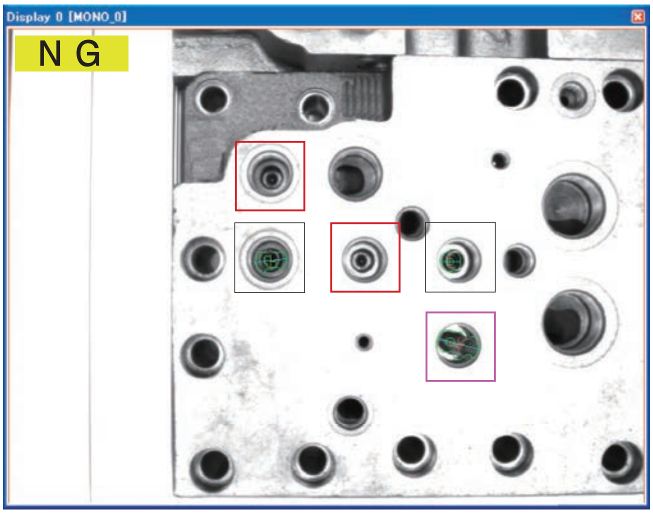


Fig. 5 Spring insertion condition check

(ii) Assembly error detection technology

In assembly operations, if a parts insertion omission or other error is overlooked, it can result in product defects that lead to major losses. For this reason, error detection technology is absolutely essential for automation of assembly operations.

To improve assembly reliability, we developed a system that uses visual recognition to detect the parts assembly condition. Fig. 5 shows a process of checking the condition of springs set into the product.

The position of an uninserted spring is framed in red in the figure. When such an error is detected, we can respond by either retrying the assembly or requesting the operator to make repairs.

In addition, a dropped part detection function can be mounted on the servo hand side as well, which together with visual recognition can improve reliability even more.

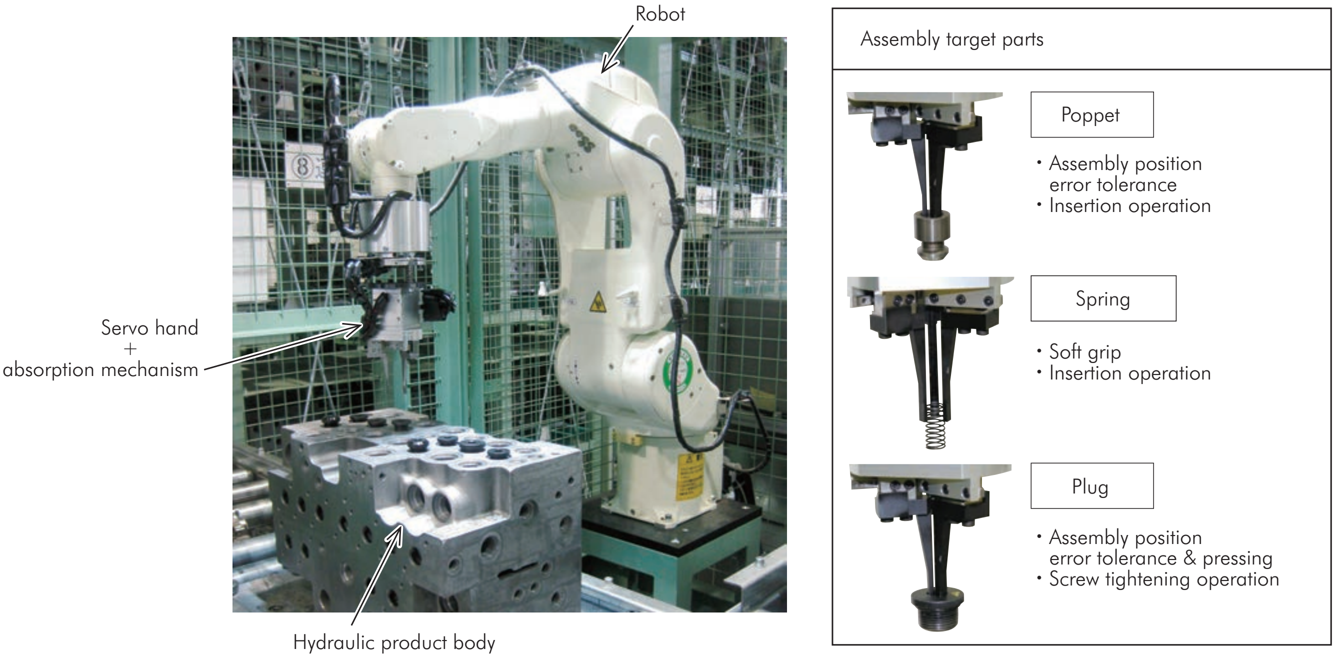


Fig. 6 Robotic assembly system for hydraulic product

3 In-house application example—hydraulic product assembly

Using the above-described elemental technologies for assembly robot systems, we are moving forward with the introduction of robots into various assembly operations inside and outside the company. Here, we introduce an assembly robot system that was installed on our own hydraulic product manufacturing line.

A system overview is shown in Fig. 6. In this system, the assembly targets are three parts—poppets, springs, and plugs (with screws)—with variation depending on the model. Operations include an insertion operation for poppets, with allowance for assembly position errors, a soft grip for springs that will not distort the workpiece, and bringing plugs into contact with the screw thread, with allowance for error, and performing a screw tightening operation. Use of the servo hand and error absorption mechanism achieves with a single tool what has previously required separate tools for each step.

In addition, we installed a vision sensor above the supplied product body to verify the product model and identify positioning deviations. The plugs need to be temporarily tightened by a certain amount to prevent thread seizing by the screw tightener used in the next process. Therefore, we use the vision system to manage the screw tightening amount, through measurement of the error absorption mechanism displacement.

Concluding remarks

With changing societal conditions in recent years, the range of robot applications is spreading from the relatively simple operations seen in the past to more complex operations that have previously been considered too difficult for automation. In this paper, we described the development of elemental technologies for assembly robot systems and presented in-house application examples.

We intend to continue research and development efforts into assembly robot systems, to respond to the increasing demands for automation of assembly operations.

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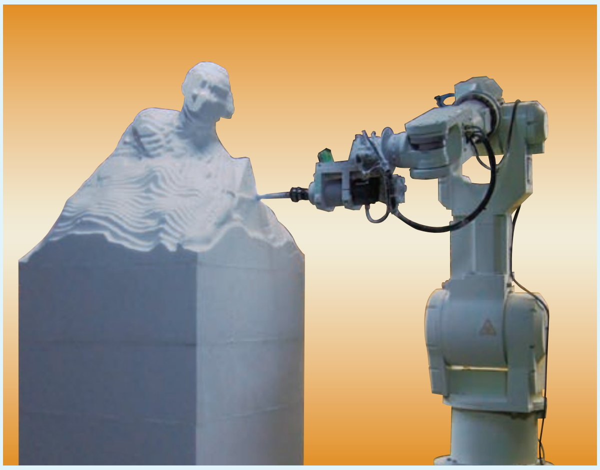
Precision-machining robot system



The enhanced precision of industrial robots and progress in their peripheral technologies have allowed robots to enter the field of machining. The wide operation range and affordability of the system offer the prospect of replacing NC machine tools in the prototype modeling field. This paper provides a commentary on milling robot systems for precision machine and presents examples of precision processing with robots.

Preface

Thanks to their versatile configurations, affordable price, and advanced ability for faithful repetition of operation instructions, industrial robots have evolved through application for automation of welding, painting, and other operations centering on the automobile industry. Furthermore, an increasing number of users have in recent years been making use of offline teaching with computers to shorten the time required for production planning proposals and line startup. To better meet these needs, industrial robots have acquired greater absolute accuracy for precise positioning into the specified spatial position as well as repeatability for faithfully repeating operations.

As robots have increased in precision through technological advances, demands for robots as substitutes for NC machine tools have also increased. But since robots generally have a cantilevered structure resulting in low rigidity, they are not suited for micron-order ultra-precision machining. Nevertheless, because robots offer a wide operations range and reasonable price levels, their application is expected in areas where micron-order precision is not necessary and the use of high-priced large machine tools would constitute a waste of resources. In addition, even in laser machining and other machining processes requiring sub-millimeter precision, where robot applications have previously been difficult due to insufficient precision, the possibility is increasing for application of low-priced industrial robots.

1 Application of robots to machining processes

In the process of developing new automobile models, as many as 40 to 80 seat prototypes processed out of urethane or Styrofoam rolls, etc., are produced for each model by the completion of the final design. While NC machine tools have been used in the past for this kind of prototype machining, the use of high-priced NC machine tools constitutes an overperformance in terms of precision. Moreover, sublimation patterns of prototype molds for industrial machinery, camera or printer models, and wood machining require the same level of precision as the seat molds or less.

If industrial robots are used in these fields, we can expect the following benefits.

① Cost reductions due to use of low-price robots.

② Achievement of wide-ranging 5-axis machining, including wraparound operations.

③ Combined use of traveling equipment and turntables for selecting flexible system configurations in accordance with workpiece size.

However, achieving substitution of NC machine tools will require an industrial robot with the necessary precision, and use of 3D CAD/CAM data to perform machining while using simulations to check for robot interference, etc.

In fact, there are areas where robot substitution is possible, and areas where only NC machine tools can be applied. These areas are shown together with their relationship to machining precision and market scale in Fig. 1. The machining precision required depends on the target workpiece. Therefore, we created a milling robot for practical application by increasing the robot precision and realizing a system demanded by the market.

2 Technology for achieving precision machining

To use industrial robots, whose development has mainly centered on the teaching playback function due to repetitive operations, as substitutes for NC machine tools, the following issues need to be addressed.

① Improvement of absolute accuracy through correction of machine difference and deflection

② Software for conversion of multipoint (hundreds of thousands of points) machining data into robot programs

③ Suppression of micro-vibrations in robots that occur in resonance with periodic variations (ripples) generated in reducers

④ Precision tool measurement with no machining position offset due to changes in the end mill posture

(1) Improvement of absolute accuracy

While industrial robots have a precision of 0.1 mm for repeatability (precision in the reproduction of teaching positions), their absolute accuracy (precision in moving to positions specified with coordinate values) is not as high. This is due to robot machining and assembly errors, zero-point errors of the joint angle sensors, or arm deflection. To ensure accurate positioning, we developed a technology that takes these error factors into consideration to correct the command position and hold the robot's average absolute accuracy to 0.5 mm or less. We also perform measurements before shipment to identify the robot part dimensions, the joint angle sensor zero point, and the rigidity of each part, and input the data to the robot controller, to achieve high-precision position correction.

(2) Conversion from G-code to robot program

In general, output from CAD/CAM to NC machine tools is performed in the industry standard format known as G-code. We have developed software for automatically generating robot programs from this G-code machining data. Since the user can continue using the G-code machining data generated for NC machine tools, the milling

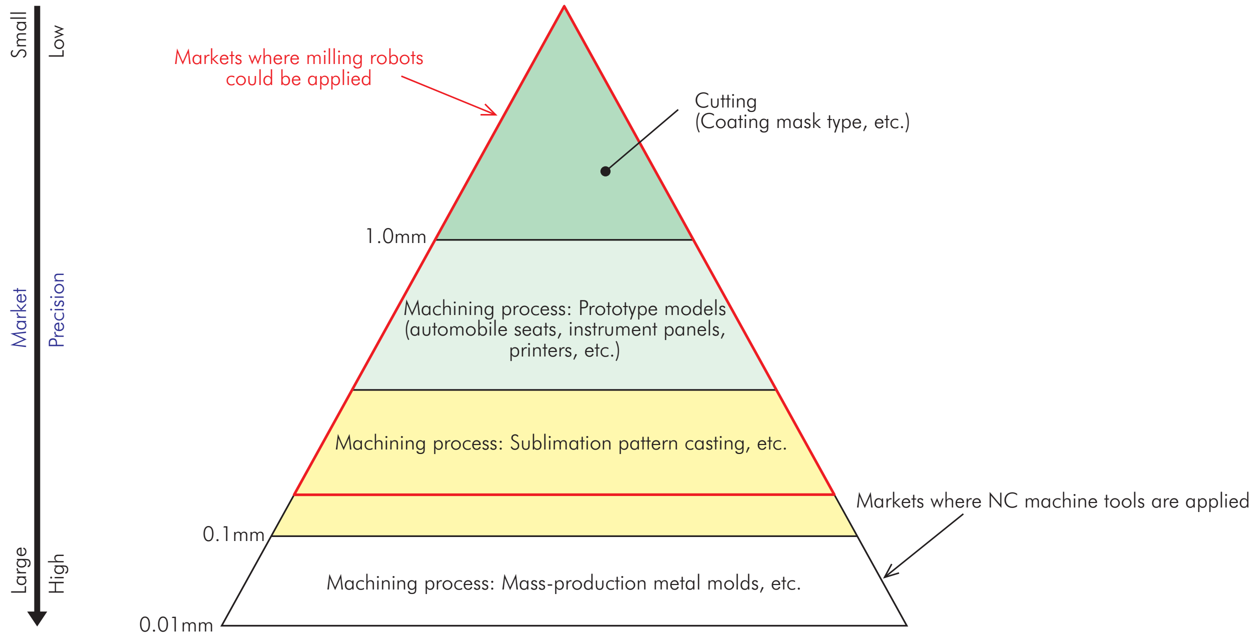


Fig. 1 Machining accuracy and market size

robot can be used without any special work on the part of the user. Furthermore, a simulation function of the KCONG for MILLING software, which automatically generates the robot program, lets the user check beforehand whether the operations range will be sufficient, or whether there will be interference. We use a DNC (Direct Numerical Control) server to send the robot program to the robot. Processing data flow for the milling robot is shown in Fig. 2.

(3) Suppression of micro-vibrations

Industrial robots use reducers with low backlash to improve positioning accuracy. Since these reducers achieve a compact size with high load in addition to the low backlash, they have a structural disadvantage of easily generating periodic torque variations or angular transmission errors. While this reducer ripple itself is small and normally does not cause a problem, when the ripple vibration matches the robot's own natural frequencies, it can generate micro-vibrations with amplitudes of around 0.2 mm, which can affect the machining process. When this micro-vibration is generated during a machining process, it can cause wavy microscopic irregularities in the workpiece being machined.

Depending on the posture, industrial robots change their inertia and alter their natural frequencies. In addition, even when tools are operated at a constant speed, the rotation speed of each articulated joint changes, making it difficult to avoid resonances caused by reducer ripples by manipulating the machining speed or natural frequencies.

Therefore, we use a method of adding signals to the motor torque command for extinguishing the ripples, which greatly reduces these micro-vibrations. With this method, we successfully reduced vibrations during workpiece machining to a level where scratches are no longer visibly discernible.

(4) High-precision tool measurement

In five-axis machining, the direction in which the end mill accesses the workpiece can change. As a result, if robot tool registration is not correctly performed, changes in the end mill posture can offset the machining point and create uneven surfaces in the workpiece after machining. While the industrial robot is equipped with the standard tool measurement method, it is not sufficient for performing five-axis precision machining.

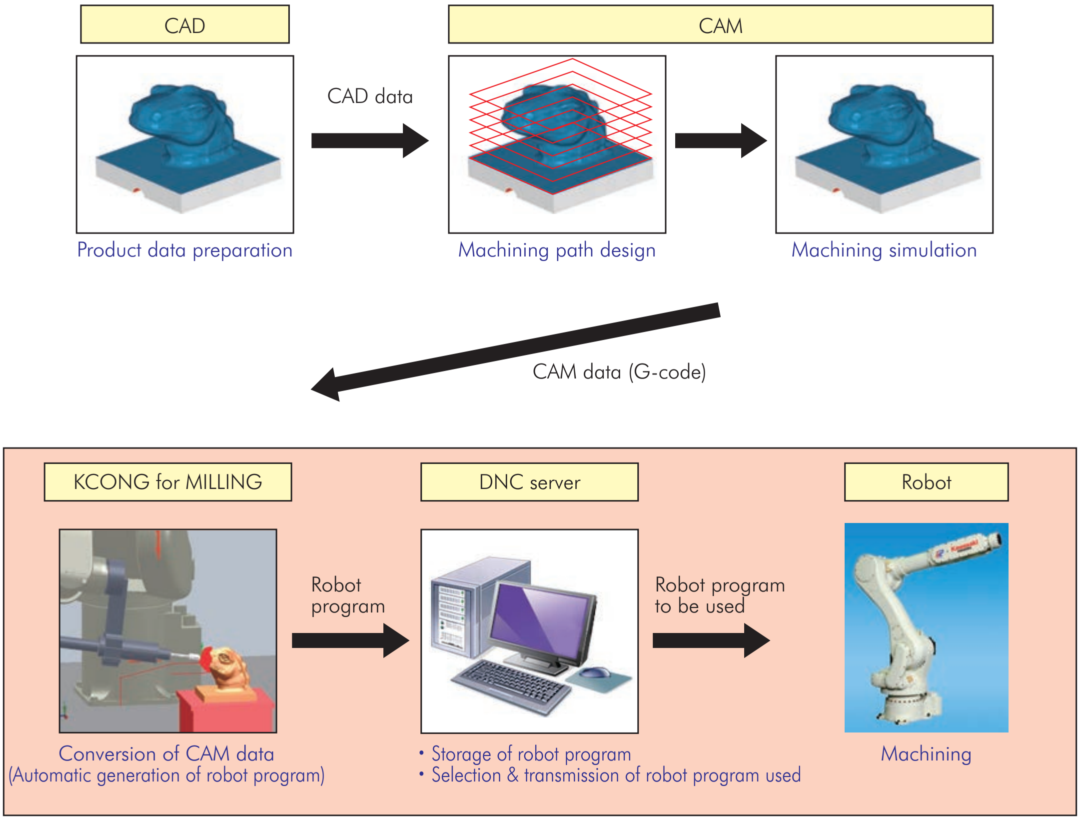


Fig. 2 Flow of machining data

Therefore, we developed a tool measurement method using a reference tool with a sphere attached to the end and a projection-type position sensor. An example of an actual tool measurement process is shown in Fig. 3. We operate the robot using sensor information so that the sphere's center position does not change, and then we read the robot's joint angle at that time to measure the tool position. Then, we switch to a reference tool with a different length and perform the same operation to measure the tool rotation axis.

Combining this tool measurement method with the robot's high-precision position correction technology, we achieved five-axis machining without generating uneven surfaces.

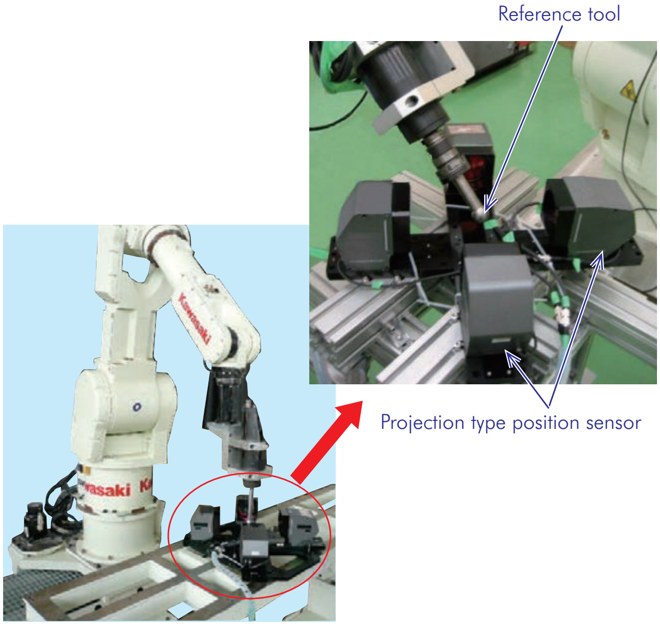


Fig. 3 Precision tool measurement

3 System configuration example

An example of a milling robot system configuration is shown in Fig. 4. The installation space is smaller than an ordinary NC machine tool, and layout changes are easier to make. Furthermore, by using a spindle replacement device to replace the spindle (machining axis) used for machining with a robot hand or other tools, the system can conduct such operations as loading or unloading of machined workpieces, or measurement before or after machining.

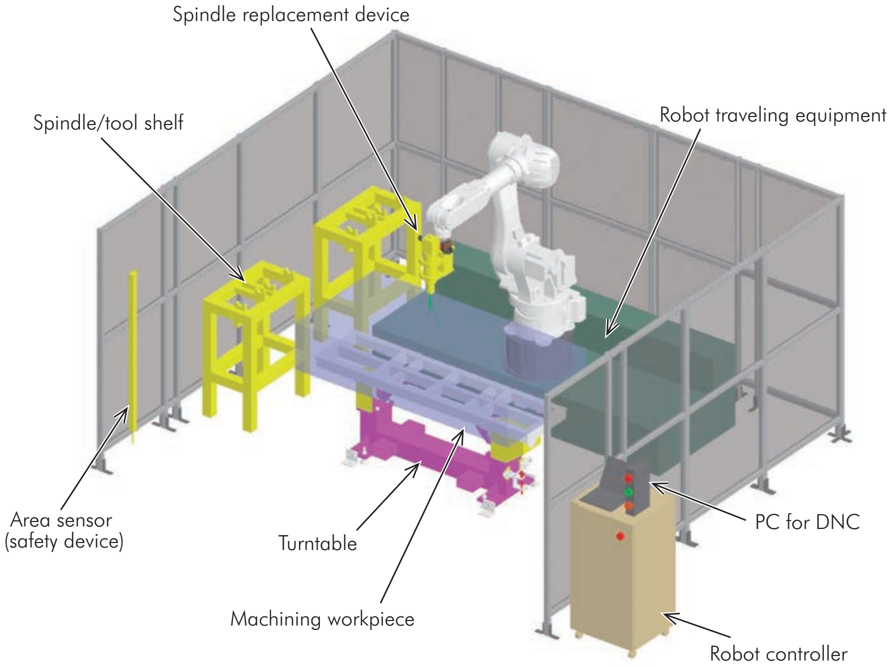


Fig. 4 Example of milling robot system

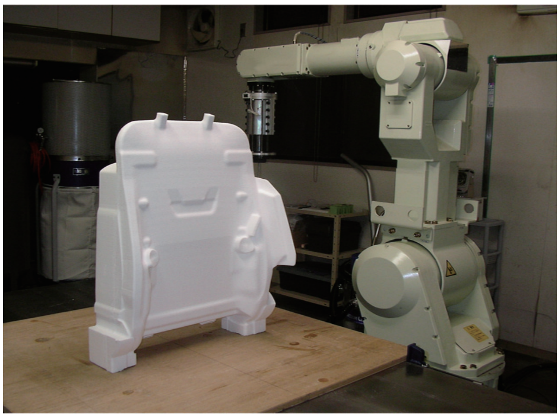
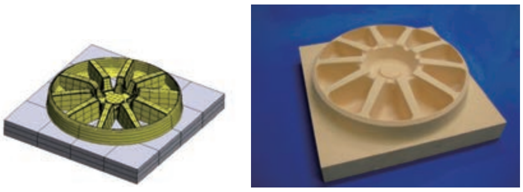


Fig. 5 Automobile seat prototyping

(a) Automobile modeling (Styrofoam)



(b) Wheel (chemical wood)

Fig. 6 Sample works

4 Application example

A machining example for an automobile prototype seat model is shown in Fig. 5. One robot can machine a workpiece the size of a seat for one person.

Other machining samples are shown in Fig. 6. While these sample parts previously required the use of NC machine tools, with milling robot machining we achieved space savings and lower costs.

This system was adopted for Nike Japan's 2010 FIFA World Cup campaign that was run in support of the athletes. As shown in Fig. 7, a robot carved messages collected from supporters into a life-size statue of an athlete, adding to the excitement of the World Cup.

5 Deployment to other processes

With high-precision machining now possible using industrial robots, deployment to various applications can now be expected. An example of impeller laser welding is shown in Fig. 8[1]. In addition, since free-form surface machining can be performed based on G-code, applications to curved surface finishing can also be expected.

Fig. 7 Nike Japan "2010 FIFA World Cup" campaign

Fig. 8 Application for laser welding

Concluding remarks

Machining processes, an area where industrial robots have not been used in the past, are now open to robot applications with the realization of advanced precision and G-code machining. Just as robots have come to be widely used in the automobile industry for welding and painting, we can now expect to see the use of affordable, versatile industrial robots spread widely in such fields as prototype model machining.

Reference

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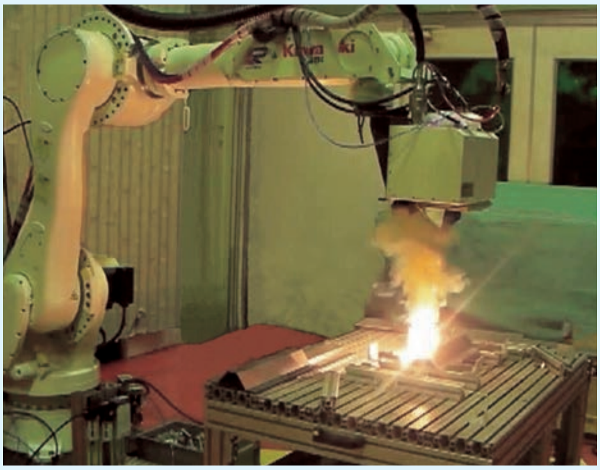
Advanced joining robot system



The environment surrounding the manufacturing industry is rapidly changing, and a reduction in energy consumption and a decrease in global warming gas emissions are being demanded of the industry. The demand goes beyond products to impact production processes, and a compatibility of a higher order between this demand and the quality of joints is needed. This paper describes the latest trends in Friction Spot Joining and Hybrid Laser-arc welding technology and how these technologies are applied.

Preface

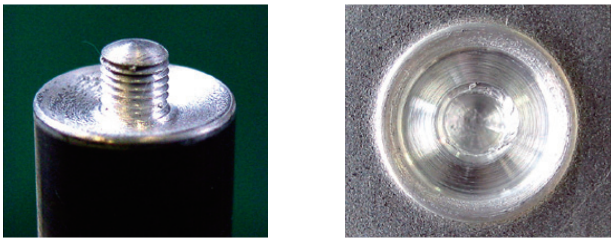
Robots arriving on the market from various manufacturers have shown remarkable improvements in robot unit performance, in operations speed and positioning precision, etc. However, this performance is evenly matched among the robots, and manufacturers are called upon to deliver higher cost performance by robot unit, or propose robot systems that come with auxiliary functions and additional functions. Auxiliary functions include handling, cutting, processing, joining, grinding and polishing, and various other production processes.

In particular, with regard to trends in joining technology, Friction Stir Welding (FSW), which was developed around 1990 by TWI (The Welding Institute) in Britain, is mainly applied to aluminum alloy railway cars, while Friction Spot Joining (FSJ), which was developed by Kawasaki as a further application of FSW, has been introduced to the production lines of automobile manufacturers, and the number of car models and vehicles using FSJ is steadily increasing. In addition, rapid advances in electronic devices over the past few years have led to improvements in controls and monitoring functions for conventional arc welding and resistance spot welding. As for laser oscillators, whose application is growing at a remarkable rate, efforts are underway to increase output capacity mainly in fiber lasers.

1 Friction Spot Joining (FSJ)

(1) Overview of FSJ

FSJ is performed using the joining tool shown in Fig. 1, featuring a threaded protrusion (probe) at the front tip. As a result, in the joining area an indentation is left behind where the probe was pressed in. The joining process is performed in three stages, as shown in Fig. 2. Two workpieces stacked on top of each other are first softened through friction heat generated between the rotating pressing tool and the workpieces, and then joined by having the upper and lower materials stirred by the probe threads. Then, the joining tool is extracted without moving in the direction of the workpiece surface to complete the joining process.



(a) FSJ joining tool　　(b) Joint

Fig. 1 FSJ joining tool and joint

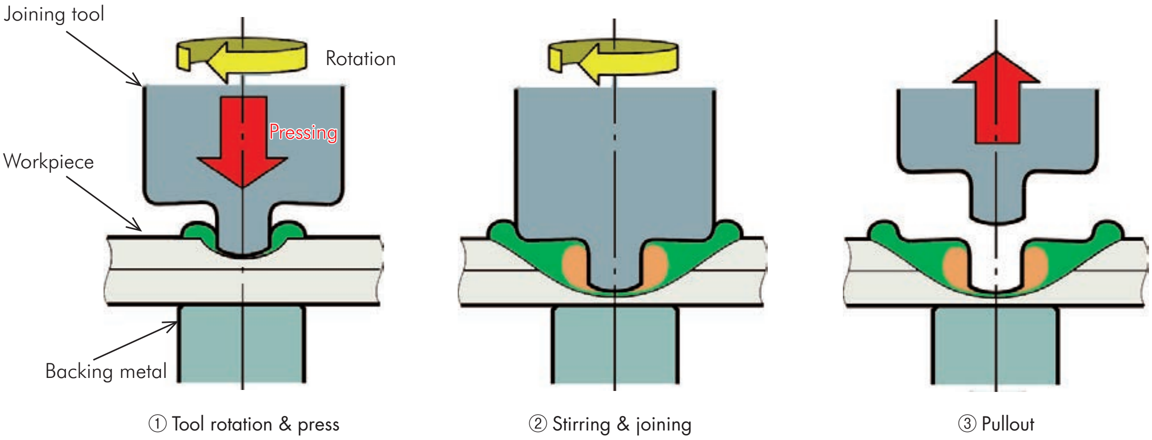


Fig. 2 Schematic diagram of FSJ joining process

(2) Conditions surrounding FSJ

In transport equipment sectors centering on the automobile industry, demand is rising for energy savings and reduction of global warming gas emissions.

Moreover, these needs are not limited to automobiles, aircraft, railway cars, marine vessels, and other products, but also extend to the manufacturing processes as well. As a result, energy savings in the manufacturing process have become an urgent issue in addition to creating lighter vehicle bodies.

(3) Applications in automotive industry

In the automobile industry, high tensile strength steel, light alloys such as aluminum alloys, and resin materials are finding increasing application mainly for the external plates of vehicle bodies to achieve lighter weight. With the application of materials other than the conventional steel, there is demand for introduction of new processes in cutting and joining processes, and within the joining process, FSJ is finding wider application for spot joining, a technique that is frequently used in external plate joining. Since a wide variety of workpieces flow through automobile production lines, an industrial articulated robot has been introduced to enable handling the various welding points of each workpiece. This robot can be used to perform high-precision repetitive joining operations by teaching not just the operation positions but also the tool pressing force, rotation speed, and other elements of the joining operation. An FSJ robot is configured by mounting an FSJ gun on a mid-size robot with a payload capacity of 165 kgf or 200 kgf, as shown in Fig. 3. Among automobile manufacturers in Japan, aluminum alloy is often used in the front hood, back door, or other so-called cover items, as shown in Fig. 4, and FSJ is used as the joining method. There are already more than 200 FSJ robots out in the market, which have been used on more than 1 million vehicles.

Fig. 3 FSJ robot

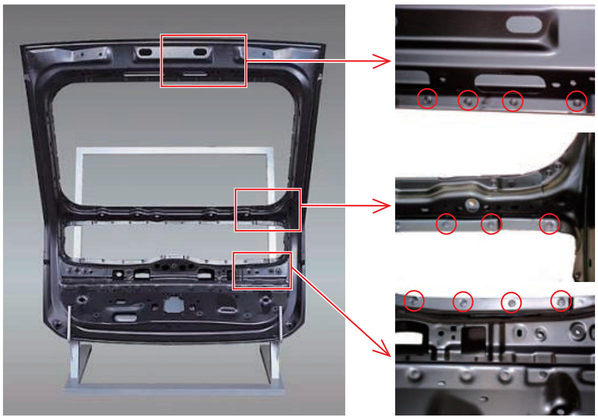
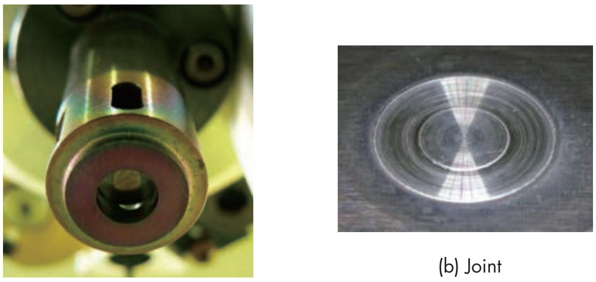


Fig. 4 Example of FSJ application

(4) Applications in aircraft industry

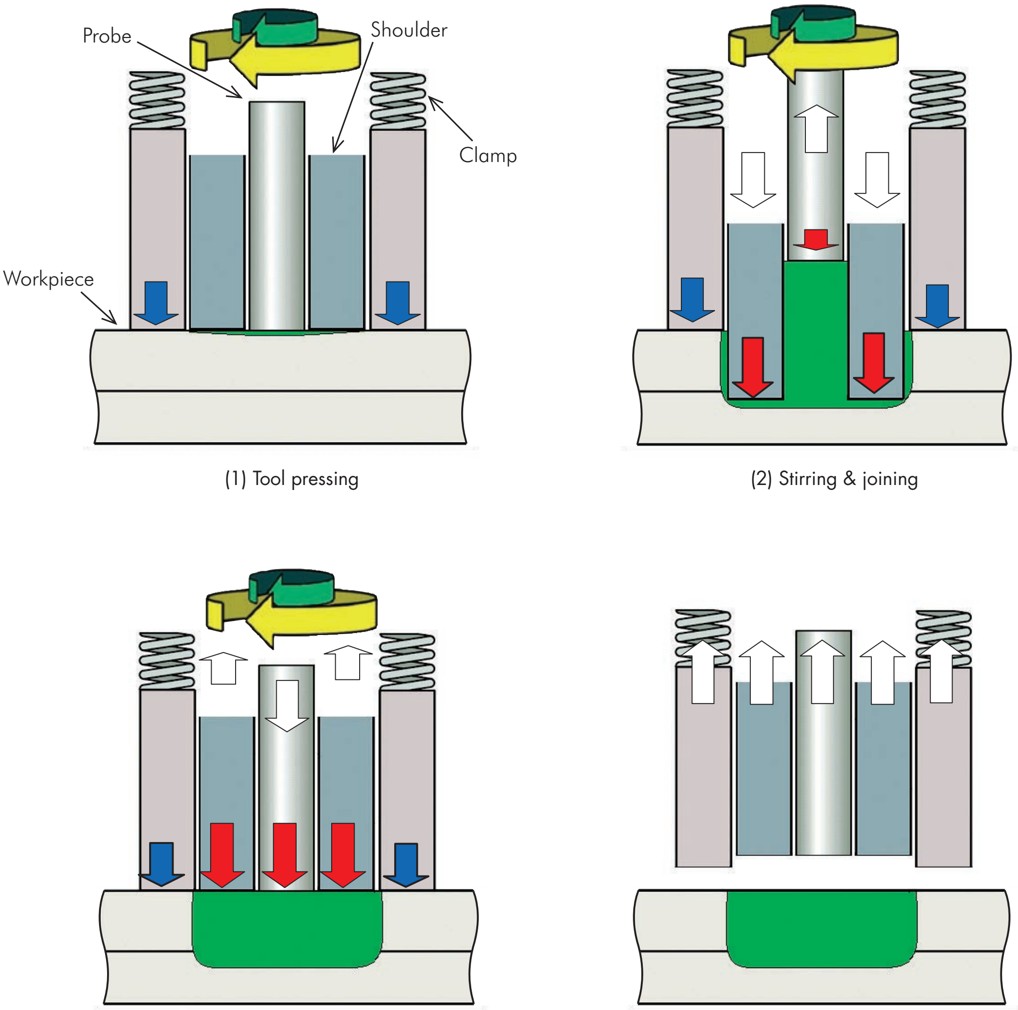
As with external plates of automobile bodies, aircraft fuselage joining involves frequent use of spot joining at lap joints. However, since bumps and indentations due to probe pressing, excess metal, and other factors are severely restricted, demand for application to fuselages is not for the conventional FSJ that leaves a hole, but rather for development of a hole-free FSJ[1)]. Kawasaki is not the only company researching application of hole-free FSJ to aircraft. Overseas, Boeing and Airbus are pursuing research in cooperation with research institutions, and we expect that research will accelerate in the future.

External views of the front end of a hole-free FSJ joining tool and the joint produced with it are shown in Fig. 5. The joining tool is concentrically divided into a probe and shoulder, and we developed a joining method that uses a clamp surrounding the tool for a smooth external appearance after joining. While the newly developed joining process is complex as shown in Fig. 6, the joining mechanism is the same as the conventional FSJ, which involves softening the material with friction and blending it through stirring. The workpiece materials move in response to tool pressure and pullout. The flow of materials in a hole-free FSJ joint is shown in Fig. 7.


(a) Front end

(b) Joint

Fig. 5 Front end of hole-free FSJ joining tool and joint



(1) Tool pressing

(2) Stirring & joining

(3) Backfilling

(4) Pullout

Fig. 6 Hole-free FSJ joint process

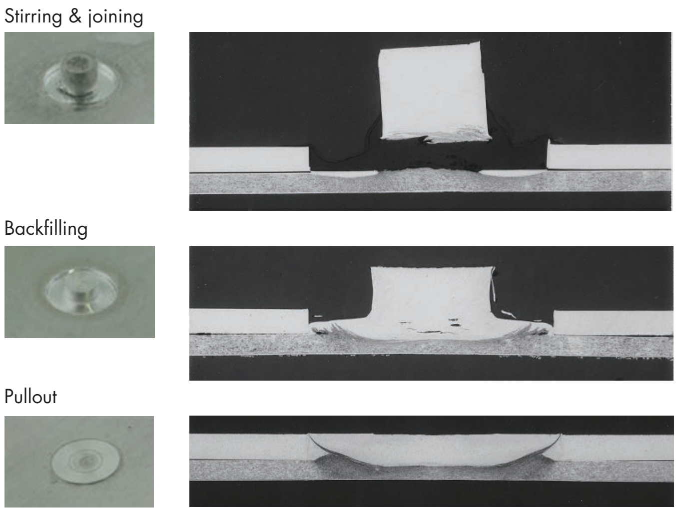


Fig. 7 Materials flow in hole-free FSJ joint

(5) Trends toward standardization

FSW, the joining method on which FSJ is based, had been the subject of efforts to make it an international standard since 2004, and the International Standards Organization (ISO) standardized it in FY 2011. Since its adoption by JIS will ensue in line with the ISO standard, FSW is expected to spread rapidly in Japan as well.

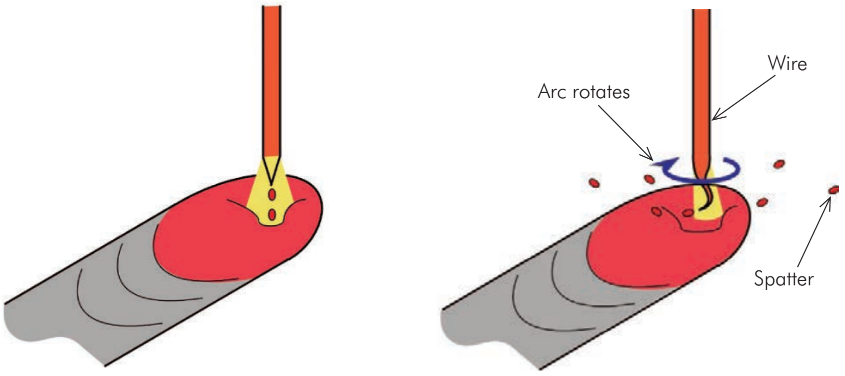
There have also been moves to standardize FSJ at ISO since 2006, and in 2009, Japanese device manufacturers, users, and neutral institutions have established a committee centering around the Japan Light Metal Welding & Construction Association, participating in international conferences toward the standardization of FSJ. Japan is the only country in the world where FSJ is put to practical use, and it plays a leading role in design policies and evaluation methods. Kawasaki in its role as a device manufacturer has been attending committees in Japan and overseas as a chief organizer.

2 Laser-arc welding

Companies that make use of arc welding, laser welding, and other fusion welding are demanding increased product competitiveness through improved productivity and quality. Issues related to fusion welding involve reduction of distortion in welding and control of materials quality degradation.

(1) High-current MAG (Metal Active Gas) welding

In arc welding, which is used for thick plates, we have achieved improved productivity by shrinking the size of the grooves where the weld metal is filled, and increasing the amount of weld metal filled in a single weld. However, if the groove becomes smaller, the arc sometimes cannot reach the bottom of the groove, resulting in fusion defects, etc. In addition, if the welding current is increased, once the current exceeds a certain level, the weld current and the magnetic field arising from the weld current interact, causing liquid droplets to form rotating arcs, which result in a spattered external appearance (Fig. 8). Therefore, we developed the high-current MAG welding method, which concentrates the arc to ensure adequate fusion even at the bottom of narrow grooves, thereby obtaining smooth external appearances even with large current. We have adequately grasped the characteristics of this welding method and implemented it in our robots to improve the efficiency of thick-plate welding.



(a) Normal current (b) Direct high current

Fig. 8 Rotating arc in high-current welding

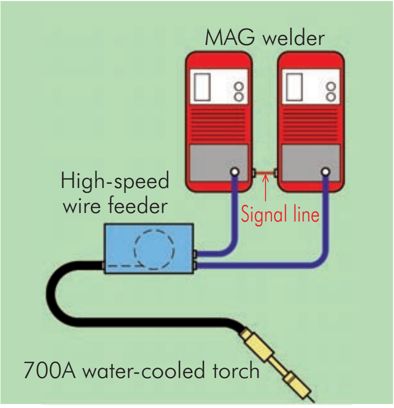


Fig. 9 Device configuration in high-current MAG welding

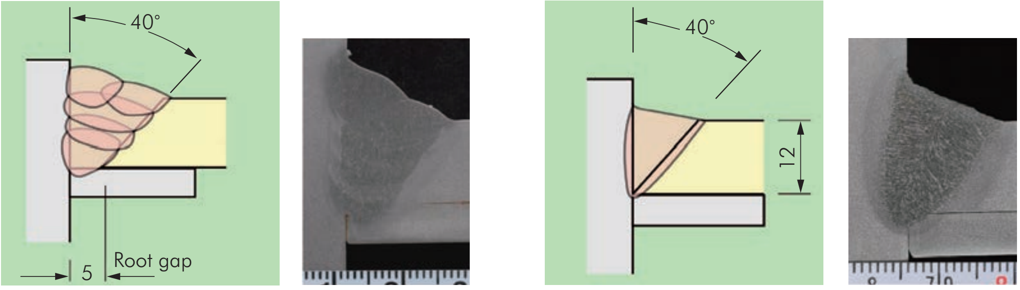
(i) Principles of high-current MAG welding

As shown in Fig. 9, high-current MAG welding uses two welding power sources and is used in combination with a welding torch capable of withstanding large welding current. With such large current flows, if we simply connect two welding power sources, it can result in a rotating arc and a decline in welding quality. Therefore, we carefully control the current from the welding power sources to achieve a suitable weld droplet transfer even with large current flows.

(ii) Benefits of introducing high-current MAG welding

This welding method has fewer execution paths and smaller grooves than joints formed within a conventional current range, reducing execution time and distortion. For example, the root gap as shown on the left side of Fig. 10 is closed to virtually 0 mm, reducing the amount of welding metal to be filled nearly by half. The right side of Fig. 10 shows a cross-sectional macro photograph of a joint executed within a conventional current range, and a joint executed with high-current MAG welding. With high-current MAG welding, we see that the welding reaches the bottom of narrow grooves, producing good joints with no defects.

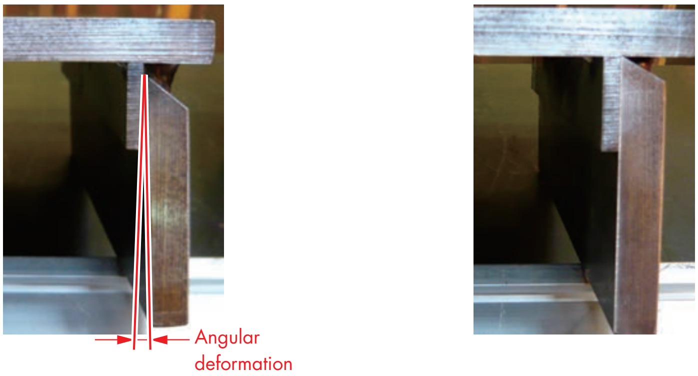
In addition, as can be seen from the shape of the joint in Fig. 10, shrinkage of the welding metal is known to result in deformation toward the narrow side of the groove after welding (angular deformation). Fig. 11 shows the external appearance of test samples of both welding methods. We see here that while angular deformation of about 5 degrees occurred with the conventional welding method, this was reduced to about 1 degree with the high-current MAG welding method.



(a) Conventional welding method

(b) High-current MAG welding method

Fig. 10 Joint geometry and cross-sectional photo for high-current MAG welding process and conventional welding process



(a) Conventional welding method

(b) High-current MAG welding method

Fig. 11 Comparison of deformation between high-current MAG process and conventional welding process

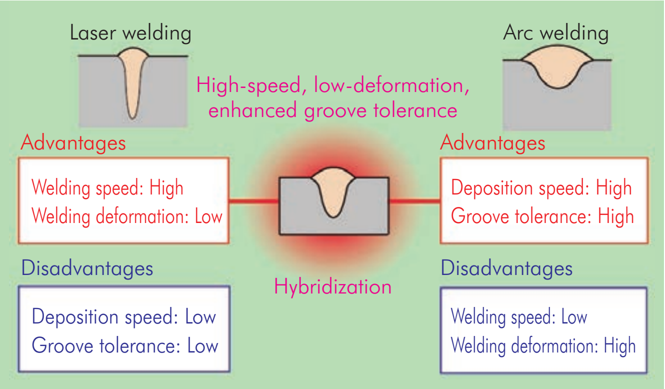


Fig. 12 Advantages of Hybrid Laser-arc welding process

(2) Laser welding

In heavy industries, high quality lasers such as fiber lasers using optical fiber for laser resonance media, and disk lasers using disks for the media constitute the mainstream of laser welding. We at Kawasaki apply laser welding for vehicle side grooves to achieve improved external appearance quality compared with conventional resistance spot welding. Vehicle models and the number of vehicles using laser welding are steadily increasing, with further expansion expected in the future. In addition, we are proceeding with research into a Hybrid Laser-arc welding that can be used together with arc welding. Hybrid Laser-arc welding is a welding method that combines the advantages of both laser welding and arc welding (Fig. 12). We are also advancing research and development into such new welding methods as the remote laser, which operates an optical mirror positioned at a distance from the workpiece at high speeds to perform welding.

Concluding remarks

While joining technology is often said to be a mature field, the appearance of new joining methods such as FSJ and the trend toward increased laser oscillator output show that the joining process in the production lines may actually be entering a period of transformation. Going forward, we will actively introduce these new joining methods to contribute to improved product quality and productivity both at Kawasaki and other companies.

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Reference

1) Fujimoto, M., Okada, H., Kamimuki, K.: "Application study of refill FSSW on Aerospace Industries," 9th International Friction Stir Welding Symposium (2012)

Kawasaki Heavy Industries Group

Main Products and Production Bases by Business Segment

Business Segment	Main Products	Main Production Bases
Shipbuilding	• LNG carriers, LPG carriers, crude oil carriers, bulk carriers, container ships, car carriers, high-speed vessels, submarines, ships for government and municipal offices, offshore structures	Kobe Works (Kobe) Sakaide Works (Sakaide, Kagawa Prefecture) Nantong COSCO KHI Ship Engineering Co., Ltd. (China)*
Rolling Stock	• Train cars, integrated transit systems, monorail cars, platform screen door systems • Gigacell (nickel metal-hydride battery)	Hyogo Works (Kobe) Harima Works (Harima-cho, Hyogo Prefecture) Kawasaki Rail Car, Inc. (U.S.A.) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.)
	• Rotary snowplows, dual mode vehicles • Rail cars, heavy lift cars	Nichijo Manufacturing Co., Ltd. Head Office (Main Plant) (Sapporo, Hokkaido) Nichijo Manufacturing Co., Ltd. Akebono Plant (Sapporo, Hokkaido)
Aerospace	• 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)
	• Aircraft components, rocket components, space equipment, target systems • Aircraft servicing, remodeling	NIPPI Corporation Aerospace Division (Yokohama) and Aircraft Maintenance Division (Yamato, Kanagawa Prefecture)
Gas Turbines & Machinery	• Aircraft jet engines, gas turbine engines for aircraft and ships, aircraft transmissions, peripheral equipment for engines • Gas turbine generators, Gas turbine cogeneration systems, mechanical drive gas turbines, mobile generator sets	Akashi Works (Akashi, Hyogo Prefecture) Seishin Works (Kobe)
	• Steam turbines for ground and maritime applications, diesel engines, gas engines, large decelerators • Controllable pitch propellers, side thrusters, steerable thrusters and other marine propulsion systems • Air blowers, air compressors, natural gas compression modules, wind tunnels, tunnel ventilation systems, electric dust collectors and other aerodynamic machinery	Kobe Works (Kobe) Harima Works (Harima-cho, Hyogo Prefecture) Wuhan Kawasaki Marine Machinery Co., Ltd. (China)
	• Air conditioning equipment, general-purpose boilers	Kawasaki Thermal Engineering Co., Ltd. Shiga Works (Kusatsu, Shiga Prefecture)
Plant & Infrastructure Engineering	• Cement, chemical, synthetic fiber, sugar and food processing plants; conveyers, transport systems, distribution systems, factory automation systems and other industrial plant systems • Flue gas desulphurization and denitrification plants • Automatic steel processing machines, vibration machines and other industrial machines • Steam turbines, gas turbines and other industrial machinery • Thermal power generation boilers and other industrial boilers for land and marine use • Ash handling systems • Nuclear power equipment • Tower/vessel heat exchangers • Municipal refuse incineration plants, sewage treatment plants, water production systems • Bulky waste crushing and screening plants, recycling plants, industrial waste processing plants • LNG and LPG tanks and other storage facilities, high-pressurer gas container, penstocks, airport facilities, rocket launch complexes, port cargo handling facilities, firefighting training systems, movable structures • Steel structures including steel pipe structures • Shield machines, tunnel boring machines	Harima Works (Harima-cho, Hyogo Prefecture) Anhui Conch Kawasaki Equipment Manufacturing Co., Ltd. (China)* Anhui Conch Kawasaki Energy Conservation Equipment Manufacturing Co., Ltd. (China)* Shanghai COSCO Kawasaki Heavy Industries Steel Structure Co., Ltd. (China)*
	• Crushers, grind mills, pulverizers, powder processing equipment, steel castings	EarthTechnica Co., Ltd. Yachiyo Works (Yachiyo, Chiba Prefecture)
Motorcycle & Engine	• Motorcycles, ATVs (all-terrain vehicles), utility vehicles, Jet Ski® watercraft • General-purpose gasoline engines	Akashi Works (Akashi, Hyogo Prefecture) Kakogawa Works (Kakogawa, Hyogo Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.) Kawasaki Motors Enterprise (Thailand) Co., Ltd. (Thailand) Kawasaki Motors (Phils.) Corporation (Philippines) P.T. Kawasaki Motor Indonesia (Indonesia) Changzhou Kawasaki and Kwang Yang Engine Co., Ltd. (China)*
Precision Machinery	• Hydraulic equipment for construction machines, hydraulic equipment and systems for industrial machines • Marine application machines, deck cranes and other marine deck equipment • Industrial robots	Akashi Works (Akashi, Hyogo Prefecture) Nishi-Kobe Works (Kobe) Kawasaki Precision Machinery (U.K.) Ltd. (U.K.) Kawasaki Precision Machinery (Suzhou) Ltd. Flutek, Ltd. (Korea)
Others	• Wheel loaders, snowdozers, load haul damps, concrete paving equipment, and other construction machinery	KCM Corporation(Main Plant) (Inami-cho, Hyogo Prefecture) KCMA Corporation (U.S.A.)

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