The Development and Application of an Industrial Collaborative Dual-Arm Robot for Tool Assembly Cells

Che-Chien Chen* and Jen-Chung Hsiao

***Abstract*—Industrial dual-arm robots have better performance than single-arm robots in terms of motion space, cooperative flexibility, and saving auxiliary tools. In the trend of closer collaboration between robots and human workers, dual-arm robots with safety features have the opportunity for rapid integration and flexible development in human-robot collaboration environments. Therefore, this study will introduce and explain the dual-arm robot system and key module technology developed by the Precision Machinery Research and Development Center, so that the robot can be applied to the industry more safely and quickly.**

Index Terms—Actuator, Dual arm robot, Industrial Collaborative Dual-Arm Robot , Safety zone, All in one, CoDAR.

I. INTRODUCTION

Since the development of the first industrial robot, Unimation, in 1961, industrial robots have been widely used in various automated production units. Industrial robots are mainly used to replace human labor in highly repetitive and high-risk automated operations, such as welding, handling, loading and unloading, and simple assembly work. However, with the advancement of research and production technology in the industry, new products are constantly being introduced while meeting various market demands to increase product market share. Therefore, high efficiency and small-scale diversified automation production have become an important trend in modern industry. To meet the requirements of small-scale diversified automation production, industrial arms with high application flexibility and high added value have become a focus of demand. Although the traditional single-arm mechanical arm can modify motion programming and replace end-effectors to perform various automated operations according to different requirements, it is still limited by the degree of freedom and flexibility of the arm. When facing multiple or highly complex assembly and processing operations, it is still unable to reduce the required assembly fixtures and requires multiple assembly stations to complete the entire automated operation, resulting in increased equipment cost and changeover cost in the production line.

In response to the above situation, it is foreseeable that dual-arm robots will soon become an important solution in the field of automation. Dual-arm robots have the characteristic of collaborative operation between two arms and can perform assembly operations with higher complexity, while reducing the need for multi-fixture assembly, effectively saving workspace and reducing the time and cost required for production line changeovers. This makes them suitable for flexible production lines with small quantities and high diversity. In recent years, arm manufacturers from various countries have launched industrial dual-arm robots, such as DLR-Rollin' Justin[1] shown in Figure 1, ABB Yumi [2]shown in Figure 2, NEXTAGE[3] shown in Figure 3, and so on. Therefore, looking at the future development of the robotics industry, dual-arm robots have become an important trend.

Fig. 1. DLR-Rollin' Justin

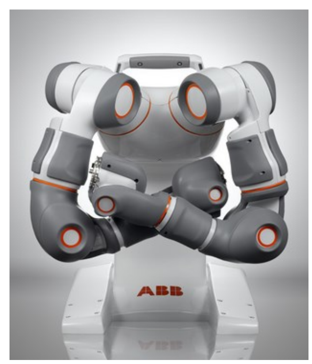

Fig. 2. ABB-Yumi

Fig. 3. NEXTAGE

Replacing human labor with robotic arms has always been the goal of industrial robotic arm development. However, due to the lower degrees of freedom and flexibility of traditional single-arm robotic arms, they have always been unable to match the complexity of tasks performed by humans. They often require peripheral equipment, resulting in a complex and costly system. One key reason why human labor can perform various

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complex and dexterous tasks is the coordination of dual-handed operations and the redundancy of the arms, as shown in Figure 4. Another important trend in future development is how to work collaboratively with humans in the same space to meet the needs of flexible production lines. Therefore, the Industrial Collaboration Dual-Arm Robot developed by the Precision Machinery Research and Development Center (hereinafter referred to as PMC) was born under such a conceptual framework for a new type of industrial robotic arm. It can achieve both speed and accuracy, provide several safety mechanisms, and offer more user-friendly operating methods to improve human-machine production efficiency.

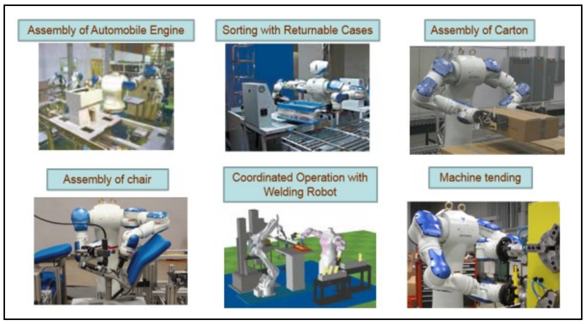

Fig. 4. The tasks that can be performed by a dual-arm robot.

II. Industrial Collaborative Dual-Arm Robot System

In response to future development trends and demands, the Precision Machinery Research & Development Center (hereafter referred to as the Precision Center) began to develop dual-arm robots in 2011, as shown in Figure 5. The industrial collaborative dual-arm robot system developed by PMC is designed with a high-performance all-software controller. The controller is equipped with advanced functions such as external signal dynamic tracking, multi-machine cooperative control, and CAD-based programming, as shown in Figure 6. In addition to the basic functions, the controller also supports more advanced features such as safety stop, hand-guiding, and program editing. The system provides users with a friendly and intuitive user interface, as shown in Figure 7, which allows operators to easily monitor and control the robot's movements and operations. The user interface includes a 3D simulation display of the robot's movements, as well as programming and control panels.

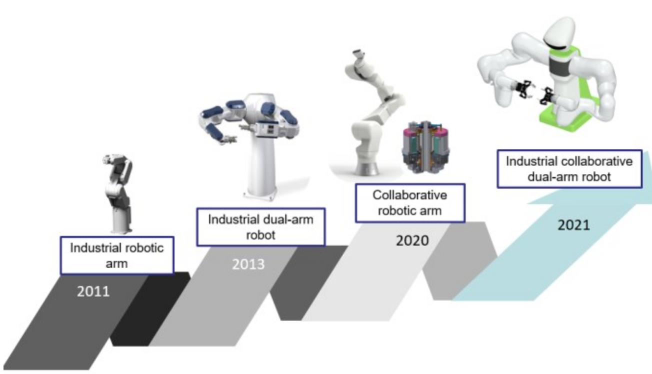

Fig. 5. Development timeline of dual-arm robot technology

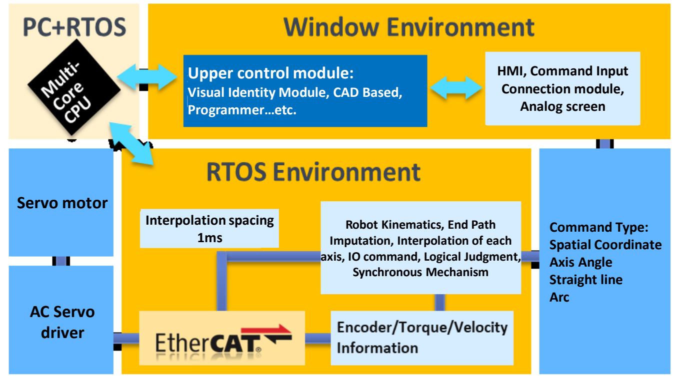

Fig. 6. Control Architecture

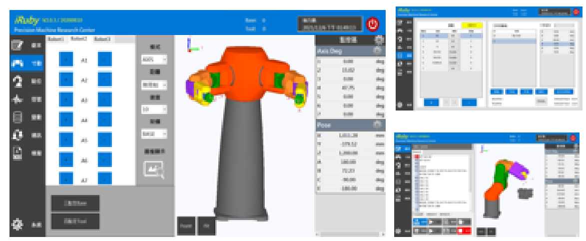

Fig. 7. User Interface

The center has continuously improved the basic functions of the system. In addition, the center began with a 7-axis configuration using a general-purpose servo motor system, high-rigidity structural design, and through the accessibility analysis technology shown in Figure 8, provided the best optimization of the working range. By 2020, the center had begun developing modular integrated joints, integrating domestically produced motors, high-precision reducers, position encoders, and domestic drivers, which can provide users with flexible assembly and replacement capabilities according to environmental requirements. Combined with self-developed controllers and advanced functions such as safety collision stop and manual teaching, the center provides a complete industrial collaborative robot solution for the industry. In 2021, the industrial collaborative robot was integrated into a dual-arm robot. In addition to basic safety mechanisms, it is equipped with a visual safety software module, which dynamically adjusts the working speed of the robot arm through safety zone detection technology to ensure the safety of the human-robot collaborative environment. The following section will provide a more detailed description of the industrial collaborative dual-arm robot system.

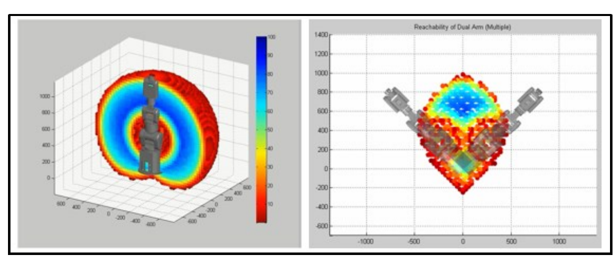

Fig. 8. Accessibility Analysis Module

A. ALL IN ONE Modular Design

The industrial collaborative robot arm developed by the Precision Machinery Research and Development Center consists of a single arm composed of two sets of 750W joint modules, two sets of 400W joint modules, and three sets of

100W joint modules. The 7-degree-of-freedom design enables the arm to perform lifting and assembly actions that humans can do. As shown in Figure 9, the joint module is integrated with a domestically-produced hollow motor, a harmonic reducer, an incremental and absolute encoder, a brake module, and a drive module. Figure 10 shows an actual 100W joint module.

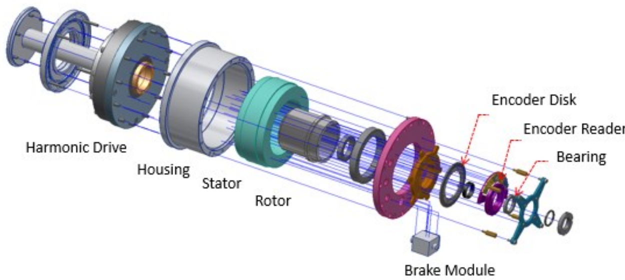

Fig. 9. Joint module composition diagram.

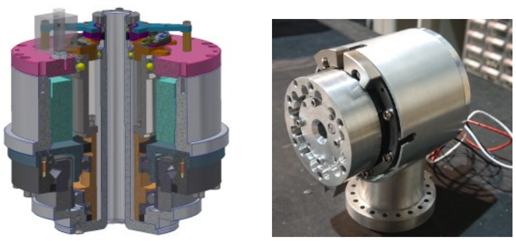

Fig. 10. Design and actual product of the 100W joint module.

In the design process, the required inertia of each axis was first calculated based on the specifications and travel distance, and then the torque was determined to decide the required motor capacity and reducer reduction ratio. The module specifications are shown in Table 1. The modules adopt the 48 VDC and Ether CAT communication protocol. Figure 10 shows the actual measured rated speed value and waveform of the 750W module, Figure 11 shows the actual measured rated speed value and waveform of the 400W module, and Figure 12 shows the actual measured rated speed value and waveform of the 100W module. All of them meet the design predicted values.

Table 1 Specification of actuator

Specifications	100W	400W	750W
Max. Speed	30 RPM	20 RPM	20 RPM
Max. Torque	42 Nm	210 Nm	600 Nm
Quality	2.1 kg	5 kg	10 kg
Max. Current	3.28 Arms	16.8 Arms	22.7 Arms
Communication Format	Ether CAT		
voltage	48 VDC		

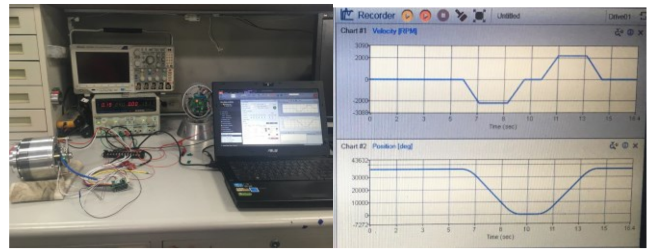

Fig. 11. Rated speed of the first axis (750W) is 2200 RPM.

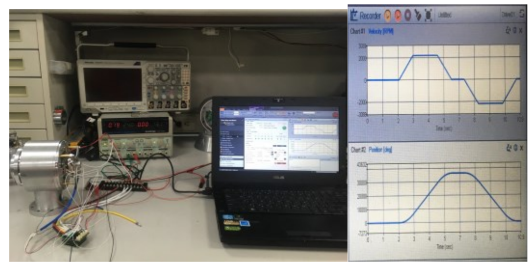

Fig. 12. Rated speed of the fourth axis (400W) is 2200 RPM.

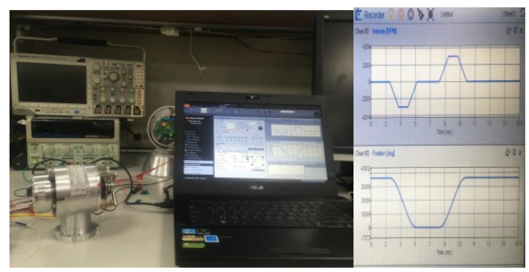

Fig. 13. Rated speed of the 7th axis (100W) is 3000 RPM.

B. Drive Module

Traditional drivers can only control multiple servo motors asynchronously, but in recent years, EtherCAT communication control drivers have appeared, simplifying many settings and wiring, and synchronously controlling multiple axis servo motors. This accelerates the development process and verification of results for users. Therefore, many international companies have invested in the core development of drivers that integrate EtherCAT communication functions. This can avoid the problem of noise interference when transmitting different core data and improve the limited data transmission speed. It also simplifies the driver circuit area.

In view of this, Figure 14 shows the self-developed drive controller of the precision machine center using the ASX58200 communication core chip, which integrates the PHY into the chip core, greatly reducing the circuit area. The MCU size is *10mm and is packaged in a BGA. The circuit board is a six-layer board. The overall maximum size of the driver is 73mm*73mm*40mm. The driving voltage is DC 48V, and the continuous current is 10A. The control switching frequency is 20KHz. It has position, speed, and current loop control, overvoltage detection, overcurrent protection, temperature detection, and instantaneous voltage protection functions, further realizing the safety protection technology of the sensorless precision machine center robot arm.

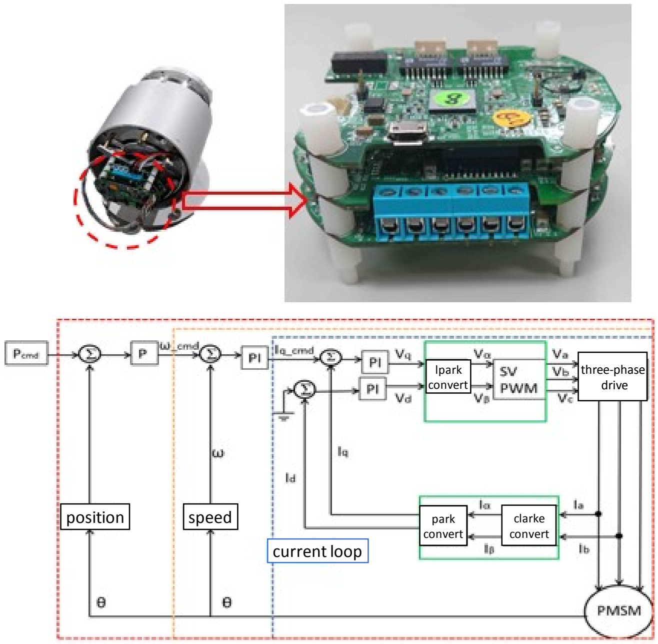

Fig. 14. The drive circuit board and three-loop control system.

The operating principle of the drive controller is to receive commands from the controller through EtherCAT communication, and use the PDO communication method to provide each actuator with a new command in each communication cycle, allowing the motion axes to run this command during that period. Through this, the function of single-axis motion or multi-axis differential motion is achieved. The drive circuit passes PWM to the GATE Driver through the MCU to control the MOSFET switch, enabling phase A, B, and C to generate 120-degree phase-shifted sine wave signals to control the motor's operating position. At the same time, the current sensor detects whether the current exceeds the momentary maximum current to prevent the motor from burning out.

In addition, the three-loop control system in Figure 14 is constructed on a microprocessor, consisting of position, velocity, and current loops. Figure 15 shows the current loop test waveform, Figure 16 shows the velocity loop test waveform, and Figure 17 shows the position loop test waveform. When the controller issues a position command, the motor maintains the rated speed under maximum load through velocity control, and maintains the rated torque through current control. Figure 18 shows the closed-loop control waveform test for each axis.

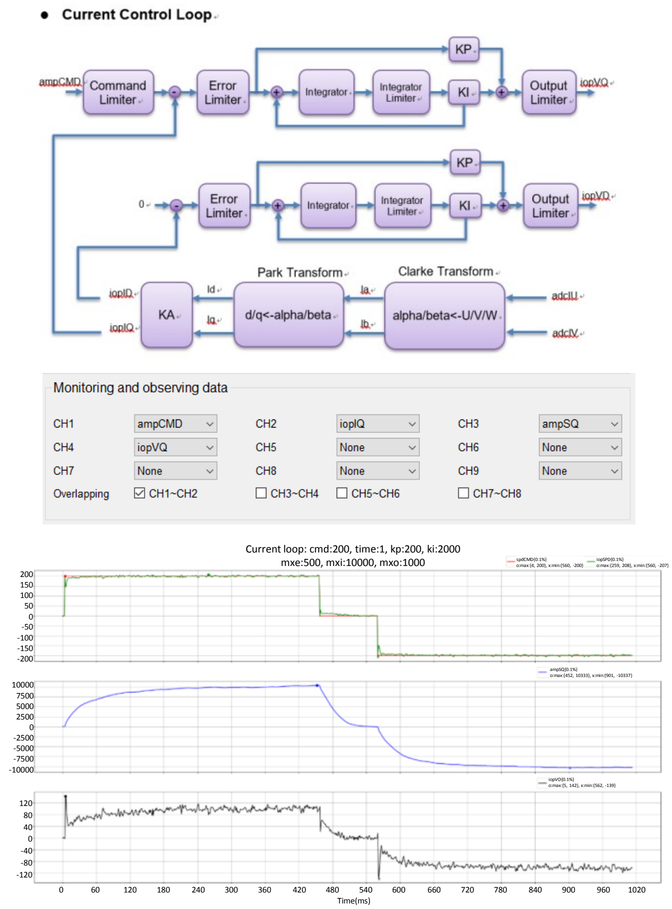

Fig. 15. Current loop test waveform.

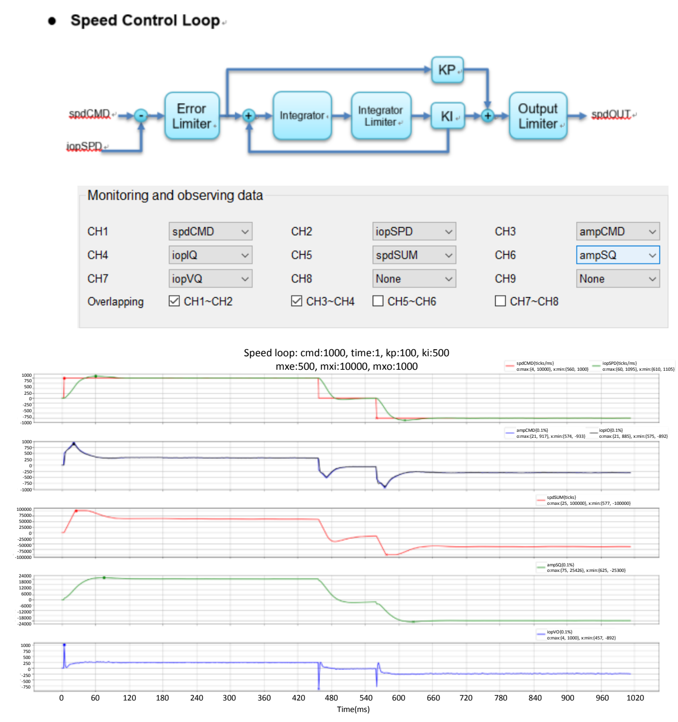

Fig. 16. Speed loop test waveform.

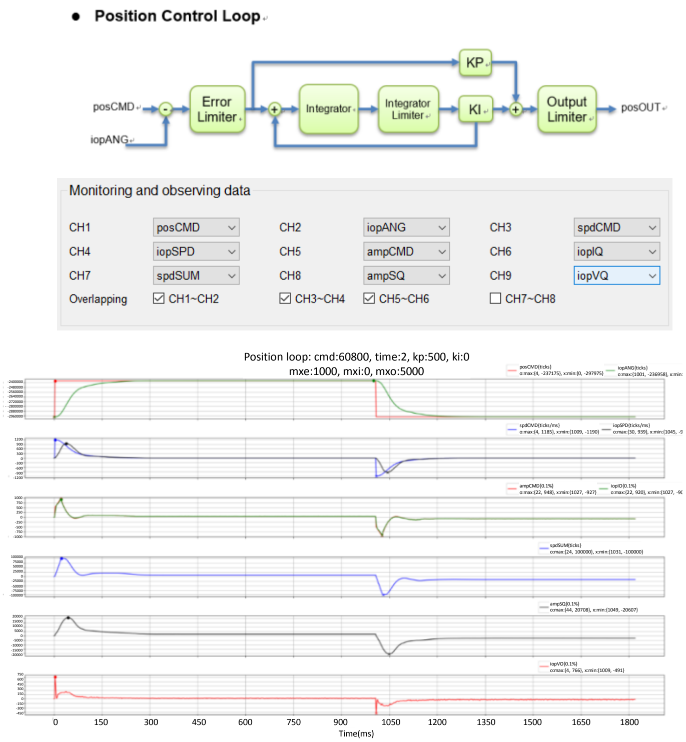

Fig. 17. Position loop test waveform.

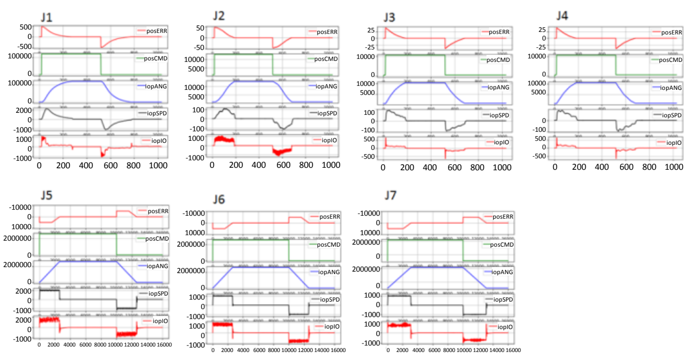

Fig. 18. Closed-loop control waveform test.

C. *Industrial Collaborative Dual-Arm Robot*

Figure 19 consists of two sets of industrial collaborative robotic arms, which we refer to as CoDAR. The first three axes support and control the main arm of the robot, determining the spatial position of the hand, tool, or end-effector, as well as the wrist. The latter three axes form the wrist without including the hand, and they primarily determine the placement or posture of the hand. The dual-arm robot is composed of four sets of 750W joint modules, four sets of 400W joint modules, and six sets of 100W joint modules. It has an aluminum extrusion structure as its body and a total of 14 degrees of freedom. The appearance is designed with streamlined and rounded features. Figure 20 depicts the working space and dimensions, and Table 2 provides the specifications and actual measurements of the dual-arm robot.

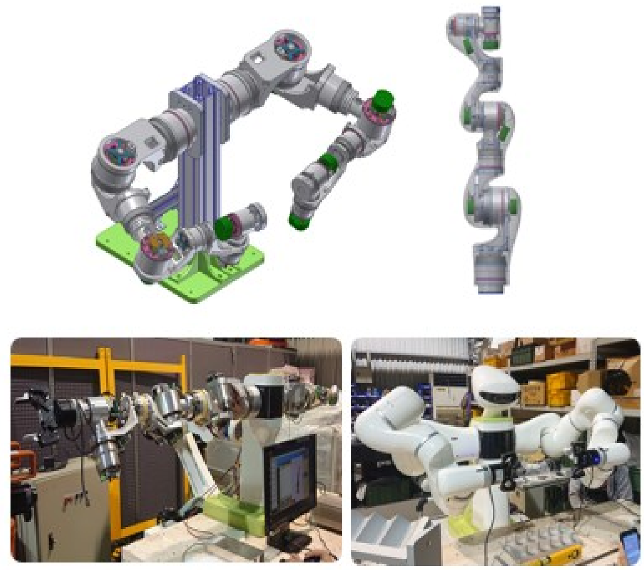

Fig. 19. Industrial collaborative robot arms.

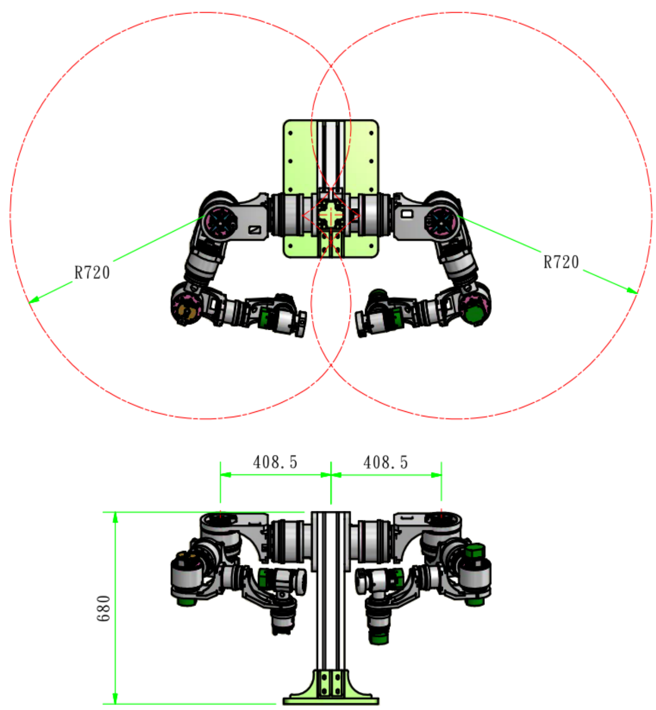

Fig. 20. Working range

Table 2 Specification of CoDAR

Specifications of Collaborative Dual-Arm Robot			
	Target Value		Actual measurement value
D.O.F	14		14
Max. Payload	10 kg		10 kg
Reach	720 mm		720 mm
Max. Speed	J1/J2	20 RPM	22 RPM
	J3/J4/J5 /J6/J7	20~35 RPM	22~35 RPM
Max. Angle	J1	+/- 180°	+/- 360°
	J2	+120°	+120°
	J3	+/- 180°	+/- 360°
	J4	+120°	+120°
	J5	+/- 180°	+/- 360°
	J6	+/- 110°	+/- 110°
	J7	+/- 360°	+/- 360°
Weight	36 kg		35.8 kg
Repeatability	+/- 0.05 mm		+/- 0.03 mm
Power	48 VDC		

III. Application Case

In the 2021 Taiwan Robotics and Intelligent Automation Exhibition, PMC showcased an automatic tool transportation system using an industrial collaborative dual-arm robot and an autonomous mobile robot (AMR). The ICAPS system was used as the upper-level dispatch system to coordinate the actions of the dual-arm robot and AMR according to the tool exchange instructions. The dual-arm robot was located in the tool disassembly area and, based on the tool demand list, grabbed the tool from the tool magazine, separated the tool, end cover, and tool box, and then placed them in their respective temporary storage areas. The AMR was located in the transport area, and based on the tool delivery demand list, sequentially picked up the tools from the temporary storage areas and placed them on the car to be transported to the machine tool. It then returned to the disassembly area to sequentially place the tools back into the temporary storage areas, waiting for the next tool delivery command, as shown in Figure 21.and Figure 22.

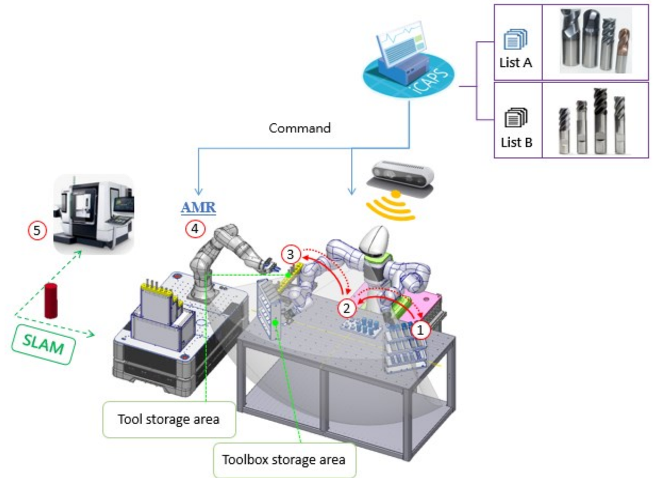

Fig. 21. Automatic tool transportation system

Fig. 22. Automatic tool transportation system in show

Additionally, with the use of safety zone detection technology, the machine arms can autonomously reduce speed and stop based on the speed and behavior intention prediction of personnel. This not only avoids collisions between personnel and machine arms in the collaborative space but also improves the energy loss situation caused by repeated emergency stops and restarts of the machine arms, which is in line with the future trend of decarbonization, as shown in Figure 23,

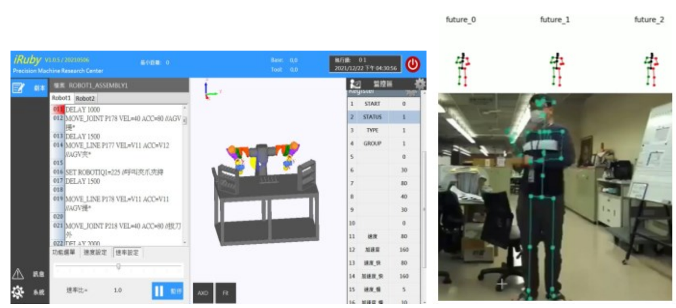

Fig. 23. Safety zone detection technology.

IV. Conclusion

Currently developed applications of dual-arm robots have demonstrated the flexibility and collaborative ability of the robots to independently complete highly complex and multi-process assembly tasks, such as engine or office chair assembly. With the booming development of intelligent technology, the demand for small-batch and diversified production is increasing. For the 3C industry, the introduction of dual-arm robots for automated production will be an important solution. However, facing the changing product design and the demanding conditions of high-precision assembly requirements, it is difficult for robots to completely replace human labor in production. Therefore, the future development of the automation industry will inevitably move towards a human-robot collaborative operation approach.

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