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ABSTRACT
The World Robot Summit (WRS) is a robotic 'challenge and exposition' organized by the Japanese government to accelerate social implementation, research and development of robots working in realistic daily life, society, and industrial fields. In this paper, we introduce a robot competition of the Industrial Robotics Category of the WRS, called 'Assembly Challenge', which is organized by the WRS Industrial Robotics Competition Committee in order to promote the development of the next-generation production systems that can respond to new production demands in agile and lean manners. After the pre-competition held in Tokyo in October 2018, the main competition, the WRS 2020, was originally scheduled to be held in Aichi (partly in Fukushima) in 2020, which was also the Olympic year. However, due to the pandemic of COVID-19, the event was postponed, and the competition was actually held in Aichi in September 2021. In this paper, we introduce the contents and results of the WRS 2020 and analyze the results. We would also like to summarize the 5-year project since 2017 and discuss the outcomes of the WRS.

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1. Introduction

The World Robot Summit (WRS) [3] is a robotic 'challenge and exposition' that aims to accelerate social implementation, research and development of robots working in realistic daily life, society, and industrial fields by bringing together the excellence in robotics from around the world, in order to promote a world where humans and robots successfully live and work together, based on the 'Japan's Robot Strategy' formulated in 2015.

The WRS consists of a robot competition called 'World Robot Challenge' and an exposition that displays the latest robot technology called 'World Robot Expo'. A pre-competition, the WRS 2018, was held in Tokyo in October 2018 and a main competition, the WRS 2020, was originally scheduled to be held in Aichi (partly Fukushima) in 2020, which was also the Olympic year. Due to the influence of COVID-19, however, the event was postponed and the WRS 2020 Aichi was held in September 2021 and the WRS 2020 Fukushima was held in October. Although the event was held in 2021 actually, we keep calling this event as the WRS 2020.

The competition has four categories such as 'manufacturing (or industrial robotics)', 'service', 'infrastructure and disaster response', and 'junior'. In the industrial robotics category, only one competition called 'Assembly Challenge' was held.

Since the development of the WRS and the competition contents of the WRS 2018 are detailed in the literature [4,5], this paper introduces the contents of the 'Assembly Challenge' for the WRS 2020, whose rules have been slightly revised from that for the WRS 2018, and the results of the competition held in September 2021 are shown. Besides, the results of the WRS project as a whole, which was carried out over the period of 5 years from 2017, are also described.

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2. Competition content

2.1. Basic problem setting for the competition of the industrial robotics category and changes from the WRS 2018

2.1.1. Basic concept and basic framework of the competition

In the high-mix low-volume production systems, 'agility' and 'leanness' are important [6–10]. In the WRS industrial robotics category, we chose 'product assembly' as the competition task among many tasks in the manufacturing domain and aimed to realize a robotic assembly system that can quickly and efficiently change the setup responding to a new product assembly request, even for a one-off product, without wasting resources (e.g. jigs) and time (e.g. for teaching); and we set 'Toward agile one-off manufacturing' as a catch phrase of the competition [4,5]. We have also drafted five levels for the next-generation production system as shown in Table 1 in order to clarify the direction that the WRS should aim for [4,5]. The Assembly Challenge of the WRS aims at Level 4 (production systems can be launched within two days when new product information is disclosed).

The basic problem setting process are detailed in the literature on the WRS 2018 [4,5], and this basic problem setting has been inherited in the WRS 2020 as it is[1].

In the WRS 2018, the kitting task was also introduced, in addition to the assembly task, aiming to realize a robot cell that picks up parts from the supplied parts bins and assembles the products like a human cell. In the WRS 2020, assuming a modular system that can handle high-mix low-volume production as shown in Figure 1, where parts are picked up from the parts bins and kitted at the parts storage area, the kitted parts are transported and supplied to one of the assembly stations by an automated guided vehicle (AGV), and the assembled product is carried out and transported to the inspection station by an AGV, the competition specifically focuses on realizing the product assembly station. Therefore, the kitting task has been abolished, and as described in detail in Section 2.2, the WRS 2020 Assembly Challenge has two tasks, the task-board task and the assembly task.

In order to verify the rule changes from the WRS 2018, a trial competition of the Assembly Challenge was held at the NEDO booth of the 2019 International Robot Exhibition (iREX2019) held at Tokyo Big Sight from December 18 to 21, 2019. Four teams, which were recruited from the WRS 2018 participating teams, participated in this trial competition. At the trial competition, AGVs, which are considered to be introduced at the WRS 2020, were introduced on a trial basis. Based on the results of this trial competition, the competition rules for the WRS 2020 were further reviewed.

2.1.2. Competition area and parts supplying method

In order to realize the above-mentioned basic concept as a form of competition, the competition area for a team (called 'team area') was designed for the WRS 2020 competition as shown in Figure 2. Similar to the WRS 2018, the team area has a system running area, where the robot system is running and team members cannot enter during the competition, and an operation area where the team members start/stop the robot system and monitor the operation. A storage area has also been added.

Parts are brought in and assembled products are carried out by an AGV[2] shown in Figure 3(a) and team

Table 1. Levels for the next-generation production system (draft version) [4,5].

	Aspects during setup changes		Aspects during operation	
	Agility	Leanness	Utilization rate improvement	Remarks
Level 5	0 day for new product (Changeover on the same day)	100% continual use (Introduction of universal hands that are able to perform jig-less assembly for multiple products, etc.)	Machine learning (temporal stoppage prevention/cycle time improvement), Fully automated recovery (even big stoppages)	Ultimate goal: Autonomous motion planning, etc.
Level 4	2 days for new product (Changeover on a weekend or an overnight business trip)	Available for new products only by recombining existing equipment. (Universal hands that can grasp multiple products, etc.)	Automatic recovery from temporal stoppage (learning through observing human intervention, etc.), Human intervention is required for big stoppages.	Target level at the WRS: Small number of universal hands
Level 3	1 week for new product (Changeover in a week, e.g. during large consecutive national holidays)	50% or more can be reused. (Utilization of specialized hand library, flexible jig, multi arms, etc.)	Operation rate improvements (prevention measures against temporal stoppages, etc.), Automated proposals of improvements	Off-line planning, Reduction of specialized tools with multiple arms, etc.
Level 2	1 month for new product	Reusing only robots	Reduction of temporal stoppage rate by absorbing part variations using sensors	The level possible with current technologies
Level 1	For specific products only (Changeover is not assumed.)	0% (No reuse is assumed.)	Controls parts variations to ensure an enough utilization rate. Human intervention is required for temporal stoppages	Many robot systems used today

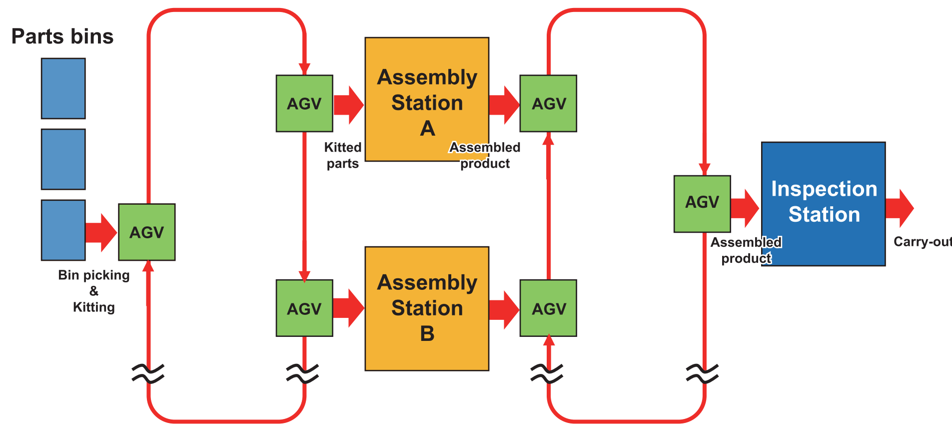


Figure 1. Basic concept of the WRS 2020 'Assembly Challenge'.

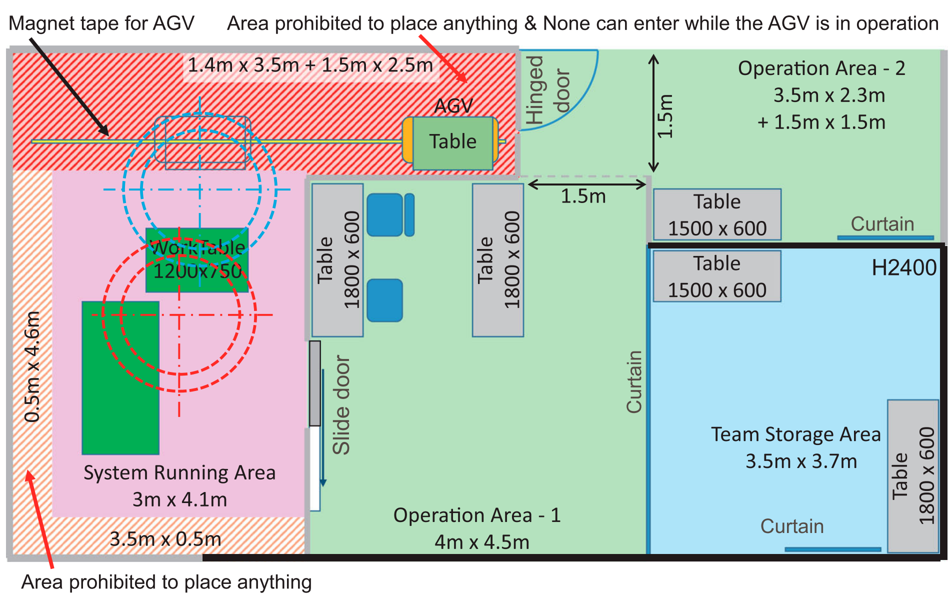


Figure 2. Team area.

members no longer need to enter the system running area during the competition unless the robot is completely stopped due to reset or other reasons. A lane for the AGV is arranged at the top of the system running area as shown in Figure 2. Team members can carry in and out parts trays through the door leading to the AGV lane.

In the task-board task, parts are supplied to the robot system during the 10-minute preparation phase before the start of the competition. In the assembly task, there are two products to be assembled, and the scoring is only given to the products that have been carried out from the system running area; therefore, the AGV must be operated not only in the 10-minute preparation phase before the start of the competition, but also during the competition time. Figure 3(b) shows an example where the AGV receives the assembled product and supplies the parts of the next product to be assembled in the system running area.

How the parts are placed in the parts tray is not known to the participating teams in advance, and their robot system must recognize the parts in the tray. On the other hand, small parts such as screws and washers can be supplied by the team with their own method in consideration of the actual supplying methods for those parts in the production fields.

2.1.3. Point allocation

Some points are allocated to each subtask for both the task-board task and the assembly task, and the total of these points becomes the competition point for that task.

Originally, any imperfect assembly cannot be regarded as a 'product.' In the WRS 2018, however, partial points were given even when each subtask was incomplete, e.g. when screw tightening was incomplete, in order to make a difference in the score as a competition. In the WRS 2020, we require 'completeness' at least at each subtask

(a) (b)

Figure 3. Bringing in the parts and carrying out the assembled product by the AGV. (a) AGV overview; (b) Bring-in/out of the parts tray.

Table 2. Competition schedule.

Sept. 9th	Sept. 10th	Sept. 11th	Sept. 12th
Day 1	Day 2	Day 3	Day 4
Assembly Challenge			Exhibition and Award Ceremony
Task-board Task	Assembly Task		
	Without surprise products	With surprise products	
AM: Try 1	AM: Rehearsal	AM: Try 1	
PM: Try 2	PM: Try 1	PM: Try 2	

Table 3. On-site participating teams of the WRS 2020 Assembly Challenge.

Team name	Country	Affiliation(s) of team members
ROBO-SUPPO plus	Japan	YANAGIHARA MECHAX
FA.COM @ Team Cross FA	Japan	Office FA.com Co.,Ltd.
PneuBot	Italy	Istituto Italiano di Tecnologia
Garage Robotics	Japan	Private
O2AC	Japan	OMRON SINIC X Corporation OMRON Corporation National Institute of Advanced Industrial Science and Technology Osaka Univ. & Chukyo Univ.
JAKS	Japan	Kanazawa Univ. & Shinshu Univ.
RPDC Robotics	Saudi Arabia	RPD Innovations

level and partial points for each subtask has been abolished. As a result, in practice, the referee does not have to make a delicate judgment on the partial points. Refer to Tables A1 and A4 in Appendix for the specific point allocation for each task.

A 'time bonus' is set like the WRS 2018, and bonus points will be given according to the remaining time only when the condition of 'perfectness' defined in each task is met. A 'completion bonus' is also set for the assembly task. This is to encourage the teams to complete assembling the product, rather than ending up with an incomplete assemble in order to earn points as a competition.

As shown in Table 4, the final total points will include the competition points for the two tasks, as well as the judging points for the technical data submitted in advance.

2.1.4. Reset and skip

A 'reset' is allowed in case something goes wrong during the competition. In the task-board task, all parts must be returned to their initial state when reset. In the assembly task, it is necessary to return at least one of the subtasks currently in progress to the initial state. To ensure safe work during the reset, the competition cannot be resumed for at least 2 minutes for each reset. Even though teams are allowed to declare resets as many as they want, this 2-minute suspension can also be expected to have the effect of suppressing frequent reset declarations by the teams.

While the task-board task is evaluated by the degree of perfection of the task board installed in the system running area, the assembly task is evaluated by the degree of perfection of the products that have been carried out from the system running area by the AGV. This means that no points are given to the products remaining in the system running area even if the product is completely assembled. For this reason, a remedy called 'skip' was introduced in addition to the 'reset'.

While the 'reset' basically requires returning to the initial state, the 'skip' declaration allows the team to skip the unloading operation by their robot system only if some error occurs during the unloading operation and they can manually unload the assembled product or the parts tray from their robot system, on which the assembled product is placed, and return it to the AGV.

Products unloaded by the 'skip' will lose the right to obtain the completion bonus and time bonus even if they are fully assembled products. If products are partially assembled, a penalty of halving the points will be imposed. In this way, although the 'skip' is subject to a

Table 4. Competition results.

	Task-board Task		Assembly Task							
	Day 1		Day 2		Day 3					
Team	AM	PM	AM	PM	AM	PM	Technical document	Total	Ranking	Award and Prize
ROBO-SUPPO plus	86	**120**	[10]	8	**74**	3	23	225	1st place	SICE Award Safety Award
Garage Robotics	**86***	72	[14]	23	19	**30**	25	164	2nd place	JSME Special Award *Best Assembly Skill Prize
O2AC	62	**119**	[0]	3	**6**	4	34	162	3rd place	JSAI Award
JAKS	52	**58**	[4]	6	**3**	0	27	94		RSJ Special Award
FA.COM @ Team Cross FA	0	0	[1]	1	0	0	30	31		
RPDC Robotics	0	0	[0]	0	0	0	21	21		
PneuBot	0	0	[0]	0	0	0	20	20		
Point Allocation	100		200		300		50	650		

certain penalty, it can avoid a situation in which the robot fails in unloading and no points are obtained.

In the next section, the details of each task of the WRS 2020 Assembly Challenge are explained.

2.2. Tasks of the WRS 2020 assembly challenge

The WRS 2020 Assembly Challenge is a four-day competition, including the exhibition, as shown in Table 2. The first three days are the actual competition days, and the final day is for the exhibition and awards ceremony. The competition has two tasks: the 'task-board task,' in which the elemental technologies for product assembly are competed, and the 'assembly task,' in which a model product, i.e. a belt drive unit, is assembled from parts prepared on a parts tray. The assembly task is further divided into the case of assembling two normal products (Day 2) and the case of assembling a normal product and a surprise product (Day 3). The competition basically consists of two tries in the morning and afternoon, and each try consists of slots in which two teams compete at the same time. The content of the competition is briefly introduced below. Please refer to the published competition rules [11] for the details of the rules.

2.2.1. Task-board task (Day 1)

The 'task-board task' competes for whether the robot system of each team can quickly and reliably perform the elemental works required for product assembly, and each part placed on the parts tray must be assembled to the designated position on the task board. As shown in Table A1 in Appendix, the parts are basically the same as those used in the 'assembly task', but the assembly of each part is independent and the order of assembly is free unlike the assembly task. The competition time is 20 minutes.

In the WRS 2020, the task-board task has been revised such that the task elements are more similar to those in the assembly task, by redesigning the task board

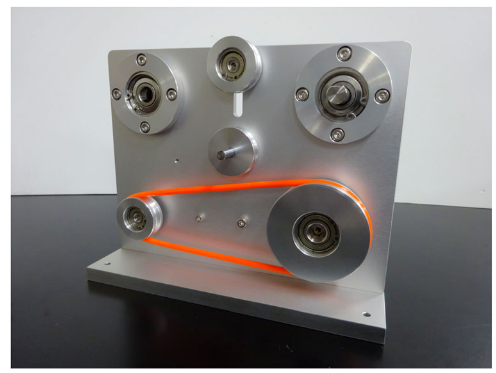
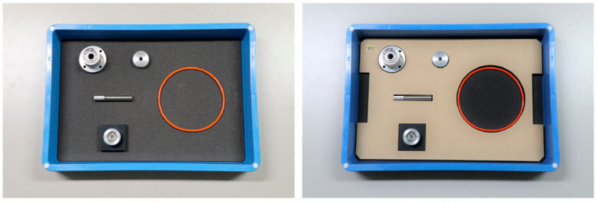


Figure 4. Task board (The board size is 200 [mm] wide and 150 [mm] high.)

significantly from that for the WRS 2018, such as the board material, parts to be assembled, assembly directions, the parts supply method, etc. Figure 4 shows the task board (completed state) for the WRS 2020. As shown in Figure 5(a), the parts are supplied by placing them in the parts tray in the same way as the assembly task described later, and the parts placement, which varies in each try, is not disclosed to the team in advance. The parts are arranged by the referee before the competition, and a template shown in Figure 5(b) is used to ensure the reproducibility of placement including the case of reset. A total of eight different templates were prepared, and each used in each slot of each try (4 slots/try × 2 tries). As mentioned in Section 2.1.2, parts trays will be carried in by the AGV in the WRS 2020.

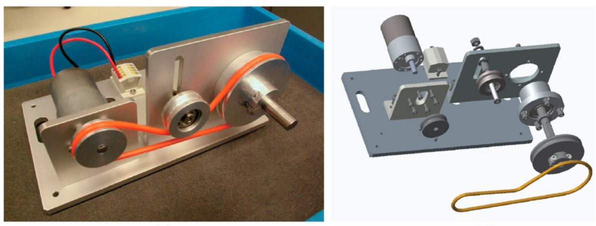
Similar to the WRS 2018, the task board used for the actual competition was slightly different from the task board sample that had been distributed to the team in advance; namely the assembly positions for each part were changed by about 1 mm from those of the sample. Although 1 mm offset is small for humans, this could be a big change for (teaching-based) position control robots.

Since the Assembly Challenge of the WRS aims at Level 4 (Table 1), the new dimensions of the task board



(a) (b)

Figure 5. Parts supplying method of the task-board task. (a) An example of parts placement on the parts tray; (b) Template.



(a) (b)

Figure 6. Belt drive unit. (a) Assembled; (b) Exploded diagram.

for the actual competition were disclosed to the team two days before Day 1, the date for the task-board task. By doing so, we asked the teams for their ability to respond quickly to such dimensional changes.

Table A1 in Appendix shows the point allocation of the task-board task. As for the time bonus, 1 point will be added every 20 seconds of the remaining time up to 50 points, if all subtasks are completed. To get the maximum time bonus of 50 points, teams need to complete the task within 3 minutes and 20 seconds from the start of the competition. For details on the task-board task, refer to the literature [12,13].

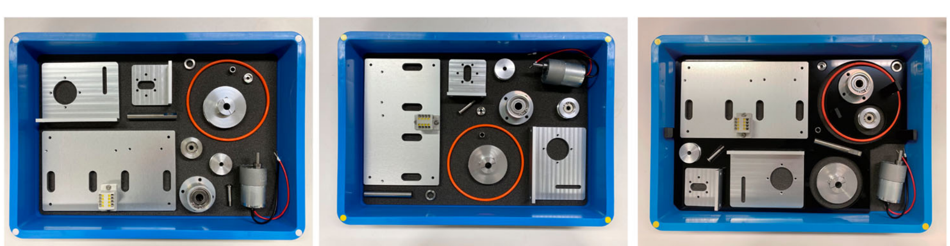
2.2.2. Assembly task (Day 2 and Day 3)

In the 'assembly task', the belt drive unit as shown in Figure 6(a) is assembled from the state where the parts are arranged in the parts tray as shown in Figure 7. This model product, which was designed for this competition, has been introduced since the WRS 2018 and consists of 33 parts with 19 types as shown in Figure 6(b), including various parts such as small parts like a M3 set screw, relatively large parts such as bearing holder and base plate, and flexible parts such as a belt. In the WRS 2020, some design changes have been made from the WRS 2018, such as the installation of a terminal block on the base plate, and new subtasks for inserting the terminals of the motor cables into this terminal block have been added. An assembly drawing of the is shown in Figure A1 in Appendix. The parts list of the belt drive unit (normal product) is shown in Table A2 and corresponding part numbers except #21–23 are shown in Figure A2 in Appendix. In the assembly task, the parts trays are carried in and the assembled products are carried out both by the AGV.

The placement of the parts is done by the referee, and the reproducibility is guaranteed by using a template as in the task-board task. Figure 7 shows three examples of parts placement patterns (one together with the template). A total of four different patterns were prepared for the template, and two different templates were selected from $\binom{4}{2}$ combinations so that the two parts trays provided in each try would be arranged differently. The placement pattern selected for each try was common to all teams during the try, and the placement pattern was changed for each try (one rehearsal and three tries in total). The placement pattern of parts on the parts tray was not disclosed to the team in advance.

On Day 2, teams must assemble two normal products, which information has been disclosed in advance. The competition time is 30 minutes. On Day 3, one surprise product, where the arrangement of parts has been changed from the normal one, must be assembled in addition to one normal product. Teams can also choose a surprise plus product, which is even more difficult than the surprise product. The competition time is 40 minutes for Try 1 but shortened to 30 minutes for Try 2.

With the surprise element introduced in Day 3, each team competes for how quickly and efficiently they can respond to new production demands, and such a surprise element was also introduced in the WRS 2018. However, at the WRS 2018, it was required to assemble a product including 'surprise parts,' parts that have not been disclosed in advance; however, it was a somewhat unrealistic competition setting because teams could not



(a) (b) (c)

Figure 7. Examples of parts placement on the parts tray for the assembly task. (a) Pattern A; (b) Pattern B; (c) Pattern C with template.

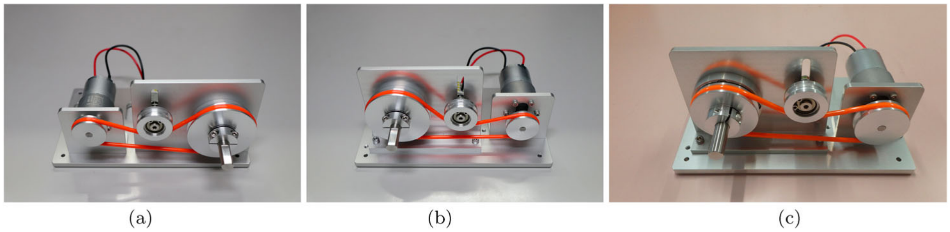


Figure 8. Comparison of the normal belt drive unit products and the surprise products. (a) Normal product; (b) Surprise product; (c) Surprise plus product (a combination of $\phi 45$ motor pulley diameter and $\phi 48$ output pulley diameter).

prepare a hand to grasp those parts if they do not know the information of the parts to be grasped in advance. Therefore, in the WRS 2020, the surprise product in which only the arrangement of the parts to be assembled is changed without changing the parts themselves was introduced. Besides, the surprise plus product, where not only the arrangement but also some of the component parts may be changed within a pre-determined range, was also introduced. The list of the parts that may potentially be used for the surprise plus product was announced to the teams in advance as shown in Table A3 in Appendix, so that teams have enough time to prepare appropriate hands for those parts.

Figure 8 shows a comparison between the normal product and surprise/surprise plus products. The surprise product shown in Figure 8(b) has the motor plate and output shaft plate positioned reversely left to right and the eccentric motor shaft positioned reversely up and down, compared to the normal product shown in Figure 8(a). Threaded holes have been added to the base plate to reverse the position of the motor plate and output shaft plate. Figure 8(c) is an example of the surprise plus products, in which the diameter of the motor pulley is slightly larger, and conversely the diameter of the output pulley is slightly smaller.

The timeline for the surprise product is as follows.

1 month before the competition Announcement of the possible parts for the surprise plus products is given to the teams as shown in Table A3. At this point, the team decides whether to choose a surprise plus product and begins preparing to assemble the surprise plus product, dealing with a given variation of parts.

2 days before Day 3 Information on the surprise product shown in Figure 8(b) will be disclosed to all teams. This gives the teams the same amount of time between the disclosure of new dimensions of the task board and the actual competition. At the same time, the committee will survey the teams on their choice for which surprise or surprise plus product they will assemble on Day 3.

Figure 9. Product evaluation station.

1 day before Day 3 For the team that selected the surprise plus product, the parts that the team should actually assemble are disclosed from the combination of the parts shown in Table A3. The parts used in the surprise plus product can change for each team that selects the surprise plus product.

Day 3 Each team assembles one normal product and one surprise or surprise plus product of their choice in each try in the morning and afternoon.

Table A4 in Appendix shows the points allocated to each subtask of the assembly task. Each subtask is shown in Figure A3 in Appendix. Teams may optionally ask the referee to evaluate the assembled product in terms of appearance and function to get additional points. Figure 9 is the evaluation station for evaluating the function of the assembled belt drive unit. There is a weight of about 2 [kg] behind the WRS character.

When taking the product evaluation test, scoring is performed after the test; therefore, there is a risk that the scoring points will drop due to loosening or disengagement of parts because the load is applied to the product in the functional evaluation test. The completion bonus is given when all subtasks except Subtasks I1 and I2 are completed. Furthermore, if a completed product also passes the product evaluation test, it is considered as a 'perfect product' and the time bonus is given according to the remaining time, if all of two products are perfect.

The time bonus is up to 100 points on Day 2, with 1 point awarded for every 10 seconds of time remaining. In order to get the maximum time bonus of 100 points, it is necessary to complete and carry out two normal products within 13 minutes and 20 seconds from the start of the competition. In Try 1 on Day 3, the time bonus is up to 130 points with 1 point for every 10 seconds remaining. In order to get the maximum time bonus of 130 points, one normal product and one surprise (plus) product must be completed and carried out within 18 minutes and 20 seconds from the start of the competition. In Try 2 on Day 3, the competition time is shortened by 10 minutes, but in the calculation of the time bonus, 10 minutes is added to the actual remaining time.

Regarding Day 3, the points of each subtask of the normal product are weighted according to the degree of completion of the surprise (plus) product in order to encourage the teams to challenge the surprise (plus) product. For example, if all the subtasks of the normal product are completed, the total points of the subtasks will be 40 points on Day 2. However, on Day 3, if the total points of the subtasks of the surprise product, which must be assembled at the same time, are 50% of the full score, the points of the normal product will go down to 24 points (the total of the full points of each subtask multiplied by 0.5 and rounded up to the nearest whole number). For details, refer to the rule book.

2.2.3. Exhibition (Day 4)

On the last day of the competition schedule, the actual competition was not held, but the exhibition by teams with excellent results or noticeable technologies was held, where the performance of their robot systems was reproduced and the technical contents were explained to the general audience in easy-to-understand manners.

3. Competition results and analysis

3.1. Participating teams

We started recruiting teams in June 2019 and closed the application at the end of August. Sixteen teams passed the document screening and were scheduled to undergo the final screening by March 2020. However, due to the COVID-19 pandemic, the activities of many teams in Japan and overseas were restricted. In addition, in response to that the organizers officially decided to postpone the holding of the WRS 2020 in April 2020, the deadline for the final examination was treated flexibly in consideration of the activity status of each team. During this time, the Industrial Robotics Competition Committee had been preparing for the competition and had been closely watching the situation of the teams that had not passed the final examination; but unfortunately, some domestic and foreign teams had announced that they had declined to participate.

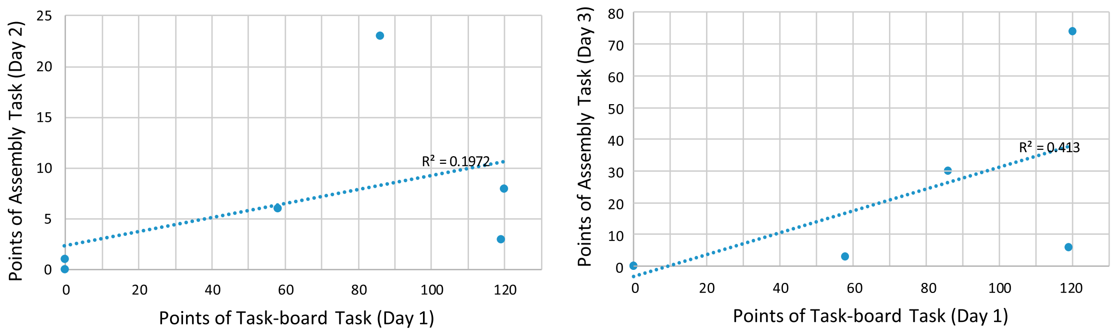
The new dates for the WRS 2020 were announced in July 2021, and seven teams shown in Table 3 finally participated in the competition on site. The seven teams consisted of five domestic teams and two overseas teams. The domestic teams included a variety of faces, such as a team consisting mainly of university laboratories, a joint team consisting of university laboratories, national laboratories, and companies, and teams of system integrators. Overseas teams came from the Middle East and Europe.

For teams that were unable to participate on-site due to the COVID-19, a new remote participation category was established in which teams were asked to perform part of the competition at their respective activity sites and submit a video that will be judged and scored by the referees. Two teams from Japan and abroad participated in this remote participation category.

3.2. Competition results

The competition results of the WRS 2020 are shown in Table 4. The table also shows the points allocated for each task and technical document. The 1st place was ROBOSUPPO plus, the 2nd place was Garage Robotics, and the 3rd place was O2AC. Day 1 and Day 3 have two tries in the morning and afternoon, and the higher points are added to the total points. The morning of Day 2 is a competition rehearsal, and the points there are shown just for reference. Table 4 also shows the society awards and special awards received by each team. It was regrettable that some teams, including overseas teams, were not able to fully demonstrate their abilities due to the COVID-19 pandemic, since some teams were not fully prepared and some teams could not participate as full members.

In Try 2 on Day 1, the two teams completed the task board and got a time bonus, resulting in higher points than the full score for the task-board task. This is a big improvement from the WRS 2018, where there was no team that could complete the task board. In addition, only one team, which ranked first overall, completed a normal belt drive unit in Try 1 on Day 3. Unfortunately, no



(a) (b)

Figure 10. Correlation of the task-board task and assembly task performances. (a) Correlation with the performance of the assembly task on Day 2; (b) Correlation with the performance of the assembly task on Day 3.

major progress was made here as only one team completed the belt drive unit at the WRS 2018. The readers may view videos of the competition from the WRS official YouTube channel [14]. Some highlights of the videos can also be seen from the supplemental material of this paper.

In the remote participation category, a Chinese team, YH-CASIA, received a special award in recognition of their performance.

3.3. Competition result analysis

3.3.1. Task-board task

The task-board task contains the necessary elements for the assembly task; and it played as a task for the team to hone the skills for the assembly task during the preparatory and development phase, since the task board sample had already been distributed to each team for the final examination. Therefore, it is expected that the team with a high score for the task-board task on Day 1 will tend to get a high score for the subsequent assembly task on Days 2 and 3.

Figure 10 shows the correlation between the score of the task-board task and the score of each assembly task of Day 2 and Day 3 in a scatter diagram. In calculating the correlation, the team who abstained from the task was excluded, and the score of the assembly task was only the points obtained from the competition, excluding the points of the technical document evaluation.

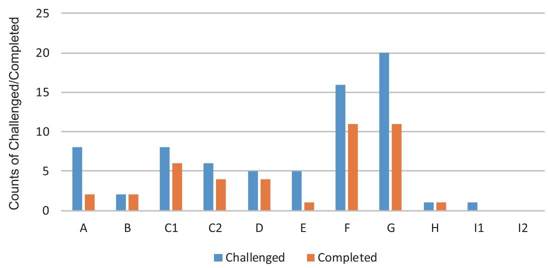
The correlation coefficients are 0.44 with the results of Day 2 (normal products only), and 0.64 with the results of Day 3 (normal and surprise (plus) products, whereas the correlation coefficients of the WRS 2018 evaluated in the same way were 0.29 and 0.20, respectively [15]. Since the correlation coefficients have increased from those of the WRS 2018, it can be said that the task board of the WRS 2020 well reflected the elements of the assembly task, although the number of teams is small and the accuracy is not high. However, note that the correlation with the score of Day 3, which included more difficult content than Day 2, was higher, suggesting that the participating teams needed a certain amount of time to change and adjust their setup from the task-board task to the assembly task.

3.3.2. Assembly task

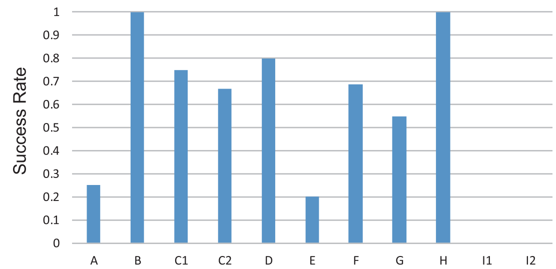
In the assembly task, the difficulty level of each subtask is analyzed by the number of challenges and the success rate. The number of challenges is the total number of challenges (or attempts) for each subtask by all participating teams, and a challenge after reset is counted as a new challenge. For the normal product, the number of all challenges for each subtask of two normal products in Try 1 on Day 2 and each one normal product in Tries 1 and 2 on Day 3 (three units in total for a team) was counted. For surprise products, the number of all challenges for each subtask of each one surprise product assembled in Tries 1 and 2 on Day 3 (two units in total for a team) was counted. Since the degree of perfection of each of the surprise products and the surprise plus products was low, number of challenges for these two products was counted together without distinction.

The number of successes is the total number of completions of each subtask. Accumulation is performed by checking the recorded video and the score sheet by the referee; and even if it seems to be completed from the video, those that were not recognized as completed according to the rules (such as when the screws are not fastened sufficiently) are not counted. However, products that were not evaluated by the referee because they were not carried out from the system running area are included for candidates for counting and the completeness of each subtask was carefully checked with the recorded video.

Once the number of challenges and the number of successes are counted, the success rate of each subtask is



(a)



(b)

Figure 11. Difficulty analysis of the assembly task on Day 2. (a) Number of challenges and completions for each subtask; (b) Success rate of each subtask.

calculated as:

$$\text{Success Rate} = \frac{\text{Number of Successes}}{\text{Number of Challenges}}.$$

Figure 11 shows the result of analyzing the difficulty of each subtask for the normal product. Subtasks F and G that attach the motor plate and output plate to the base plate are the first subtasks to be performed; and of course the number of challenges is large. However, the success rate is not very high due to some failures such as misalignment and screw tightening failure. Teams that could not be prepared well tended to reset repeatedly in these first subtasks, which also resulted in decreasing the success rate.

Subtask A, which attaches the motor to the motor plate, is another subtask in the early phase of the assembly; and although the number of challenges is high, the success rate is extremely low. This is because (i) the motor is relatively large, heavy, and cylindrical, resulting in failure in grasping, (ii) the motor shaft position is eccentric, resulting in failure in alignment, and finally, (iii) the alignment with the holes in the motor plate is inaccurate, resulting in failure in screw tightening. Since the success rate of Subtask A is low, the number of challenges for Subtask B, which is premised on the success of Subtask A, is extremely low.

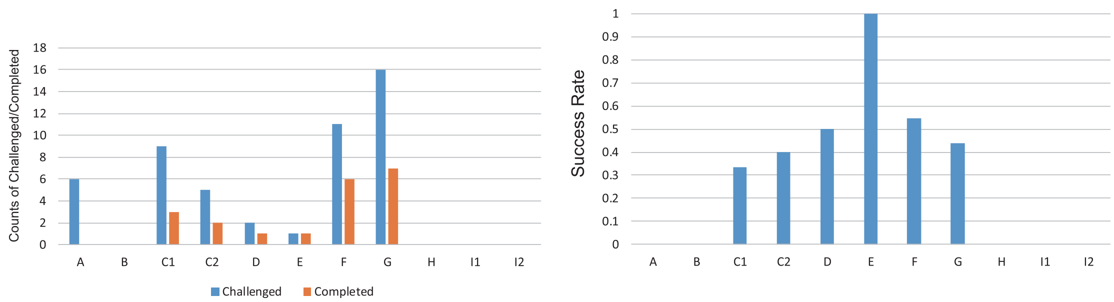
On the other hand, Subtasks C1 and C2, the next subtasks on the output plate side, have a higher success rate while having the same (or similar) number of challenges as Subtask A. From this, it can be said that Subtasks C1 and C2 were less difficult than Subtask A.

Subtask D, which follows Subtasks C1 and C2, naturally has fewer challenges than Subtasks C1 and C2, but has a higher success rate. Presumably, this subtask was a relatively easy one for the teams that were able to reach this point. On the other hand, Subtask E, which is to assemble the tension pulley, has an extremely low success rate and seems to be a difficult subtask even for the teams that could reach this subtask. This is due to the fact that this subtask should be performed by two robots, where one of them must grasp the tension pulley passing its shaft through the slit of the output plate while the other one must fasten the nut, as well as the fact that small parts to be handled, such as the spacer, washer, and nut, were prone to fail in grasping.

Subtask H, which loops the belt over the pulleys, is difficult to discuss statistically since only one team attempted it once; but it seems that teams that could reach this point can manage to increase the success rate of this subtask, taking a benefit from the experience of the task-board task in which the similar subtask is imposed.

Subtasks I1 and I2, the final subtasks of inserting the cable terminals into the terminal block, were tried by only one team without success. According to the hearing from the team done afterwards, a reasonable success rate was achieved during the adjustment phase at the team development site; but the characteristics (e.g. flexibility) of the cables of the motor supplied for the actual competition seemed to be slightly different, and their robot system had not been adjusted so well that it can deal with the variations in cable characteristics.

Figure 12 shows the result of the difficulty analysis of each subtask of the surprise product. As for the surprise products, each team challenged accordingly because the scoring policy induced them to challenge the surprise product. As a result, the number of challenges tends to be similar to the normal product, but the success rate does not follow the same trend. In particular, Subtask A has a success rate of 0, even though it has been challenged 6 times in total. In addition, Subtasks C1 and C2, which had a relatively high success rate for the normal products, also have a slightly lower success rate for the surprise products. In the team hearing done afterwards, one team reported that while they were able to perform those subtasks on the normal product, they were more difficult on the surprise product, where the placement of the two plates was reversed, because their two robots ware not placed symmetrically with respect to the belt drive



(a) (b)

Figure 12. Difficulty analysis of the assembly task on Day 3. (a) Number of challenges and completions for each subtask; (b) Success rate of each subtask.

(a) (b) (c)

Figure 13. Robot systems of the top three teams. (a) ROBO-SUPPO plus; (b) Garage Robotics; (c) O2AC.

unit to be assembled. This asymmetry in robot placement may have contributed to the lower success rate of Subtask A and Subtasks C1 and C2.

In addition, only one team challenged Subtask E in Try 2 on day 3; and they succeeded in this subtask, despite that it was considered a difficult subtask in the normal product. As discussed below, this team took an approach of using low-cost tools and jigs, taking the advantage of 3D printers.

Although the difficulty level of each subtask of the assembly task has been analyzed, we think that the number of samples is still insufficient to accurately analyze the difficulty level. In the WRS 2020, only one team completed a normal product, and it was on Day 3, when a surprise product should have been assembled as well. No team completed the surprise product. If this competition is to continue, it will be necessary to increase the number of trials by more teams and analyze the difficulty of each subtask in more detail, without making major changes to the model product. It will then be necessary to identify the missing elements in the current model product and revise the model product so that it becomes more appropriate for the competition.

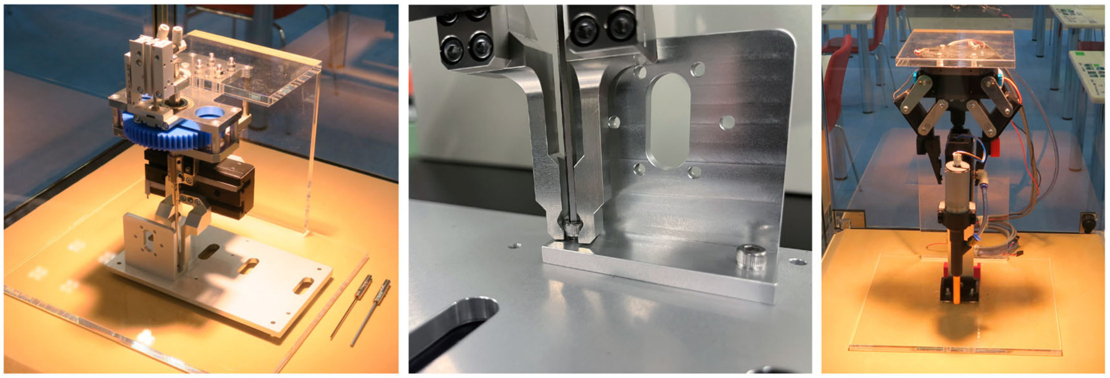
3.4. Comparison of the top three teams' approaches

From the analysis of the competition results using video recordings and the hearings from the top three teams conducted after the competition, it was found that each team took a distinctive approach. The following sections show some of the aspects of their approaches. Figure 13 shows overviews of the robot systems of the top three teams.

3.4.1. Hands and various tools

ROBO-SUPPO plus, which won the first place overall, introduced a hand with a built-in driver as shown in Figures 14(a,b). This hand is a chuck type two-finger hand with a built-in rotating shaft that drives a bit for fastening the screws, and it can smoothly grasp and fasten the screws. The bit is interchangeable according to the size of the screw, and the hand can be used as a normal two-finger chuck hand if the bit is not attached. The basic concept of this hand with built-in driver was invented by FA.COM, who participated in the WRS 2018/2020, and the ROBO-SUPPO plus hand is a further improvement on this concept.

Garage Robotics, which placed second overall, introduced a two-finger gripper and a set of cable-less tools shown in Figure 14(c). The two-finger gripper can grasp parts by itself, but can also grasp various tools such as screw drivers as needed. Although the idea of grasping tools by the hand has been used by other teams, this team took a very unique approach of supplying power for driving the built-in motor of the tool and air for suctioning the parts directly from the hand while grasping the tool. This enables to eliminate the power cable and vacuum tube from the tools, which has fundamentally solved the



(a) (b) (c)

Figure 14. Examples of hands and tools used in the WRS 2020 (Photos in Figures (a) and (c) were taken at the WRS exhibition booth of the 2022 International Robot Exhibition (iREX2022).). (a) Hand of ROBO-SUPPO plus; (b) Close-up view of the ROBO-SUPPO plus hand; (c) Hand and tool of Garage Robotics.

problem of cable handling, and contributed significantly to making the system slimmer compared to the conventional approach replacing large tools attached to the wrist of the robot.

O2AC, who finished third overall, took the same approach of grasping a driver tool with a two-finger hand as their predecessor team, O2AS, did at the WRS 2018. A major feature of the O2AC approach is that the driver tool can be grasped from various directions, unlike the Garage Robotics method, where the tool grasping direction was fixed. This allows the robot to approach the tool, even in situations where the robot is likely to interfere with the environment or the target product, by changing the grasping direction of the tool.

3.4.2. System configuration

The top three teams also took their own unique approach to configure their robot system. ROBO-SUPPO plus, which won the first place overall, basically used the controller of the industrial robot as it is, and connected the controllers of the two robots via PLC. The system was designed to have a moderate degree of autonomy by making good use of commercially available systems and functions provided by robot manufacturers, such as vision sensors and image recognition software for parts recognition and compliance control for shaft insertion; it was a solid configuration unique to a system integrator.

Although the robot is basically operated based on teaching data, the operation program is divided for each part and the main program is structured in such a way that even if the order of the picked parts from the parts tray changes slightly due to recognition errors or other reasons, the parts can be correctly assembled by placing them on the temporary table. At the competition, the high-speed movements of their industrial robots were impressive.

In contrast, O2AC, which ranked third overall, does not use teaching data basically, but generates robot trajectories using the MoveIt, a motion planning package on the ROS environment, where they originally extended the functions in order to realize the coordination/synchronization of the two robots and the interference avoidance between them using a digital twin. Force control was used for probing motions during screw tightening and compliant motion during shaft insertion so that positioning errors of the parts are absorbed. For image recognition of parts, a two-step approach was taken, first roughly recognizing parts using a deep neural network (DNN) based on RGB images taken by an RGBD camera attached to the hand, and then estimating the exact pose using contour lines or range data. This team was also outstanding in its ability to autonomously recover from errors without easily resetting the task.

Finally, it is worth mentioning that Garage Robotics, which came in second overall, was able to reliably perform object recognition by using an open-source DNN, regardless of lighting conditions, in addition to the hardware (hands, tools, and jigs) innovations described in Section 3.4.1.

Their system configuration was centered on a computer (Jetson) that performs image recognition, in which a visual programming tool (Node-RED) was used to centrally manage the movements of peripheral devices including the robot controllers with a no-code manner for easy maintenance, while utilizing the functions of existing industrial robots. This approach, namely, placing a controller with high software maintainability on top of the existing industrial robot controllers, would be more suitable for system integrators who are accustomed to handling such existing robot controllers than building a ROS-based system with an external PC like what O2AC did. Therefore, this was a remarkable effort in terms of the practical way of robot system configuration.

3.4.3. Efforts and potentials leading to agile changeover

Finally, based on the above comparisons in terms of hardware and system configuration, we discuss the efforts and potentials of each team that lead to rapid setup and agile changeover.

Although the ROBO-SUPPO plus tends to be attracted only to their high-speed robot operation, they also showed ingenuity in the alignment operation of parts by pushing them against the environment or grasping them by hand so that the use of special jigs would be minimized. Since they used the controller of the industrial robot as it is, however, it was necessary to change almost all of the operation programs to accommodate the surprise product, highlighting the issue of agile changeover when using industrial robot controllers.

O2AC, on the other hand, can generate robot trajectories with MoveIt, which means that it has the ability to quickly respond to new production demands as long as CAD data is available. O2AC was also the most active in its efforts to jig-less assembly leading to agile changeover. Although the team used a simple two-finger hand, they were able to achieve jig-less assembly by aligning the part by closing and opening the hand or by pushing the part against the environment during grasping phase, so that some of the relative position error of the part with respect to the hand are absorbed, and by utilizing force-controlled probing movements during assembling phase. Although such a jig-less approach is difficult to operate at high speeds, it would be advantageous in very-low-volume production, where quick start-up is more important than efficiency during operation, combining with the ability to automatically generate robot trajectories from CAD data (digital twin).

Playing against the jig-less approach by O2AC is the approach of Garage Robotics, which is second overall. This team took an approach to actively use jigs that can be fabricated quickly at low cost. Specifically, they prepared various jigs fabricated at low cost using a 3D printer to realize reliable assembly, by taking advantage of the high precision positioning repeatability of industrial robots. New jigs for the surprise product were also quickly fabricated on site after the information was disclosed. In addition, other low-cost special jigs, which were achieved through their creative ideas, were prepared for the necessary alignment of each part. In a sense, they have demonstrated the possibility of 'agile setup and changeover by low-cost jigs utilizing 3D printers and creative ideas'.

In the WRS 2020 Assembly Challenge, product information was disclosed two days before the competition based on the definition of the targeted Level 4 (Table 1). This means that even teams using industrial robot controllers as is had sufficient time for re-teaching. If the information had been disclosed for the first time on the day of the competition, these teams would have had difficulties to respond to it.

On the other hand, if a robot trajectory can be automatically generated from CAD data (digital twin) like what O2AC did, it should be possible to respond to the information disclosure even on the day of the competition (Level 5). It is also interesting to see if Garage Robotics' approach of 'rapid setup and agile changeover using low-cost jigs' is also effective for building Level 5 systems.

The product information disclosed in the Assembly Challenge was not 3D-CAD data that is readable for computers, but simply drawing data for team members, that is, it needs to be manually input to the system. For teams who take a CAD-based approach like O2AC, providing product information in the form of 3D-CAD data would enable faster response.

4. Outcomes of the assembly challenge

The WRS competition design and organization, which began as a NEDO project in 2017, ended up with a five-year R&D work due to the postponement of the WRS 2020 main competition by the impact of the COVID-19. Having reached a milestone after the WRS 2020 Aichi, this section summarizes the outcomes of the Assembly Challenge.

4.1. Competition rules and benchmark

The most significant achievement was the formulation of rules for such a robotics competition of the manufacturing domain, while there had been no robotics competitions on the subject of full-scale product assembly. The establishing rules that enable us to reproduce the competition could serve as a benchmark, just like a similar competition, the Robotic Grasping and Manipulation Competition, Manufacturing Track [16]. The parts used in the competition are basically available from MISUMI-VONA, which has purchasing sites around the world, allowing anyone to reproduce the competition, and the results of the WRS 2018/2020 competitions will continue to be the benchmarks for product assembly by robots in the future.

The Assembly Challenge was designed for realistic product assembly situations, and the difficulty level was set relatively high. For this reason, even the winning team in the WRS 2018 scored less than 30%, and in the WRS 2020, the winning team scored just over 30%, even with the time bonus. Therefore, it would be quite possible to hold the competition again without major changes to the competition rules[3]

4.2. Raising awareness of the importance of 'agility & leanness' and growth of participating teams

Various teams from universities, national laboratories, corporate R&D departments, and system integrators from Japan and abroad participated in the Assembly Challenge. Although it was regrettable that all the teams originally planned to participate in WRS 2020 were unable to do so due to the COVID-19, we believe that the large number of applications received was a result of the recognition and support of the importance of 'agility and leanness', that the Industrial Robotics Competition Committee considered as a feature of the next-generation robot systems in the future manufacturing field, by relevant parties.

In addition, many teams recognized the importance of 'agility & leanness' more deeply by studying the competition rules, and improved their technical skills by actually participating in the competition. Among the teams that participated in both the WRS 2018/2020, some teams showed remarkable growth. We know that several research results have been reported by the participating teams of the WRS 2018 [17–23] and hope that more will be reported by the participating teams of the WRS 2020. Therefore, our initial goal of 'accelerating social implementation and research and development of robots through competitions' has been fully achieved.

4.3. Hands and other technologies born from the competition

Along with the growth of the participating teams, some technologies can be said to have emerged from this competition. A typical example is the hand with a built-in driver introduced in Section 3.4.1, which was invented by a team at the WRS 2018 and further improved by another team at the WRS 2020, showing a great effect at each competition.

This may be one of the best solutions as a hand for grasping and fastening screws when assembling small lots of products, as aimed at in Assembly Challenge. Although it was the individual teams that devised and improved their own hands, we can say that it was the competition that provided the groundwork that led to the invention of such a hand.

In addition to this, the low-cost jigs using a 3D printer, etc. introduced in Section 3.4.3 and the system configuration method utilizing the functions of existing robot controllers introduced in Section 3.4.2 should also be noted as new approaches to agile &lean manufacturing.

4.4. Safety and health management of the competition

Ensuring safety and health is of utmost importance in robotics competitions. Especially, the Assembly Challenge that uses industrial robots can pose a significant risk if appropriate safety measures are not taken. Therefore, in the Industrial Robotics Category, various measures were taken based on the basic principle of 'safety and health first,' and the participating teams were also required to comply with health and safety[4]

At the WRS 2020, the Industrial Robotics Competition Committee established its own 'Safety Award' to recognize the best team which is chosen by the safety and health management committee, evaluating their safety and health activities from the system startup to during the competition.

Thus, we believe that through the three competitions, the WRS 2018 (pre-competition), the trial competition in 2019, and the WRS 2020 Aichi (main competition), we were able to promote the awareness of safety and health among the participating teams. For a summary of health and safety initiatives at the WRS, please refer to the report by Noda et al. [25].

4.5. Staging the competition

Apart from the competition rules design, we would also like to emphasize the outcomes of the staging aspect of the competition. The Assembly Challenge is a competition in the field of manufacturing that is unfamiliar to the general public; therefore, it has been fated that it is difficult for them to understand what are challenging and highlights of the competition.

The Industrial Robotics Competition Committee had been working to provide easy-to-understand explanations of the competition by assigning competition commentators and local reporters since the WRS 2018. We have also introduced an indicator to show the progress of the task from the trial competition in 2019, as shown in Figure 15. With those efforts, the competition of the WRS 2020 was very well received by the audience.

5. Conclusion

This paper briefly introduced the 'Assembly Challenge,' a robotics competition of the WRS 2020 Industrial Robotics Category, and presented the results of

Figure 15. Task progress indicator.

the competition held in September 2021. This NEDO project, which started in 2017 to design and implement a robotics competition, was postponed for one year due to the COVID-19, but have reached a milestone by successfully holding the WRS 2020 Aichi. Therefore, the outcomes of the research project as a whole were also summarized. We believe that the goal of accelerating social implementation and research and development of robots in the manufacturing field through competitions has been achieved.

We set the goal of the Assembly Challenge to Level 4 of the next-generation production systems, but we have not yet achieved this level. Therefore, we also believe that it is very important to continue such competitions to maintain the continuous research and development to achieve Level 4 and even Level 5 (production systems can be launched without hardware changes on the same day when new product information is disclosed) [4,5,11].

We hope to see further acceleration of the research and development of next-generation production systems toward Level 5 by continuing the 'Assembly Challenge' in some ways in the future so that university laboratories and system integrators will continue to work on this challenge, or both will complement and cooperate with each other.

Notes

1. Regarding introducing collaborative robots, which has been attracting attention these days, we consider it as a 'practical solution,' at least in the manufacturing fields, for introducing robots without drastically changing the manufacturing site where people are working. Based on the idea that everything should be done by robots in the future manufacturing fields, the WRS Assembly Challenge does not incorporate the elements of human-robot collaboration into the competition.
2. Ideally speaking, the start command of the AGV operation should be automatically issued from the robot system. In this competition, however, the start command was manually issued from the remote control box, since the AGV was provided to the team for the first time at the competition venue and preparing such a coordination with their system is considered to be difficult for them.
3. One of the points that need to be improved from the WRS 2020 competition rules is the parts tray. In the WRS 2018, we prepared dedicated parts tray with partitions. In the WRS 2020, however, parts tray without partitions were used in consideration of the versatility of the tray and to prevent the robot hand from interfering with the partitions during picking. However, in the actual competitions, cylindrical parts such as shaft and motor rolled and moved during transportation by the AGV, making picking those parts very difficult. If the parts are kitted in the previous stage, as assumed in Section 2.1, then putting the kitted parts back into the parts tray without partitions means that the position information of the parts at the time of kitting will be lost unnecessarily since the parts may move in the tray. With a parts tray without partitions, it is also difficult to check for missing parts. Therefore, we should have used general purpose parts trays with shallow partitions. Thanks to this 'unpartitioned' tray, however, the WRS 2020 Assembly Challenge became a challenging task in terms of image recognition and parts picking.
4. In recognition of these efforts, the WRS Industrial Robotics Competition Committee received the 6th 'Mukaidono Safety Award' Incentive Award in 2020 from the Institute of Global Safety Promotion (IGSAP). This is the first time a robotics competition has received this award.

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Appendix 1. Parts Information, Subtask Definition, and Point Allocations

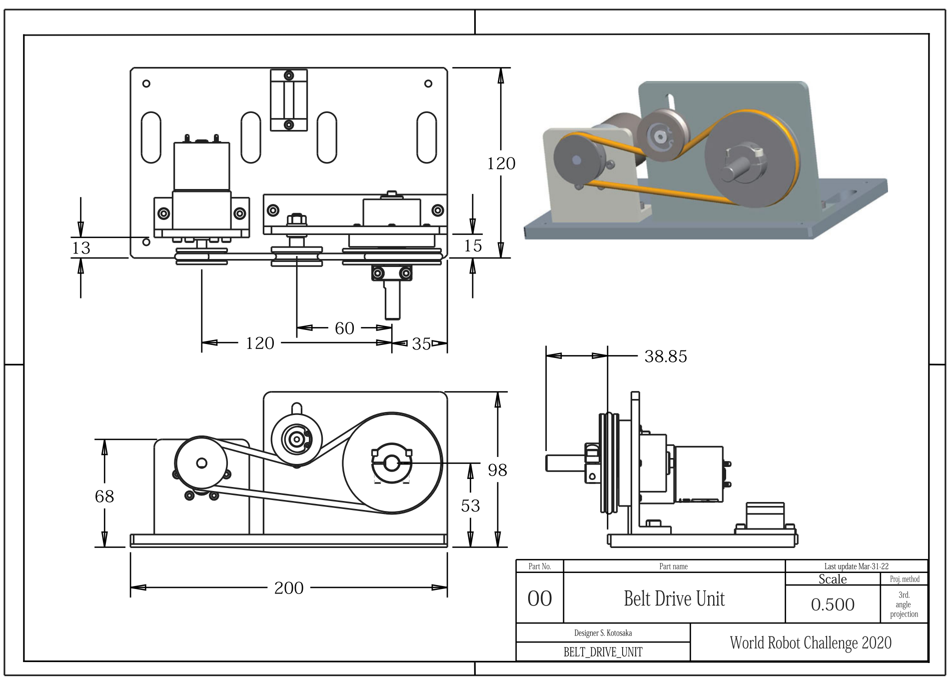

Figure A1. Assembly drawing of the belt drive unit.

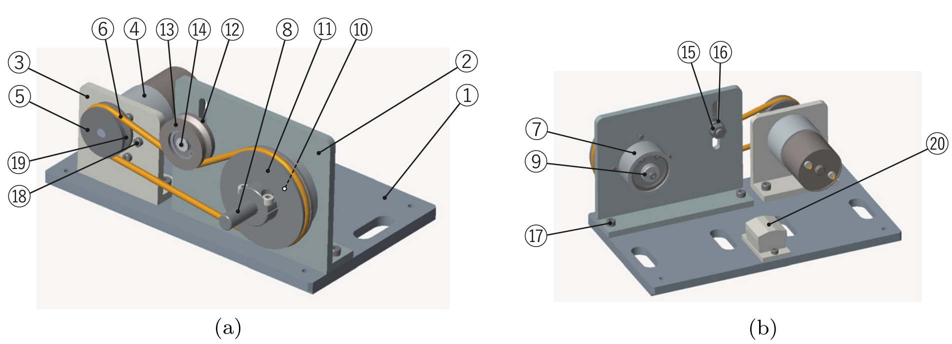

Figure A2. Part numbers of the belt drive unit. (a) Front; (b) Rear.

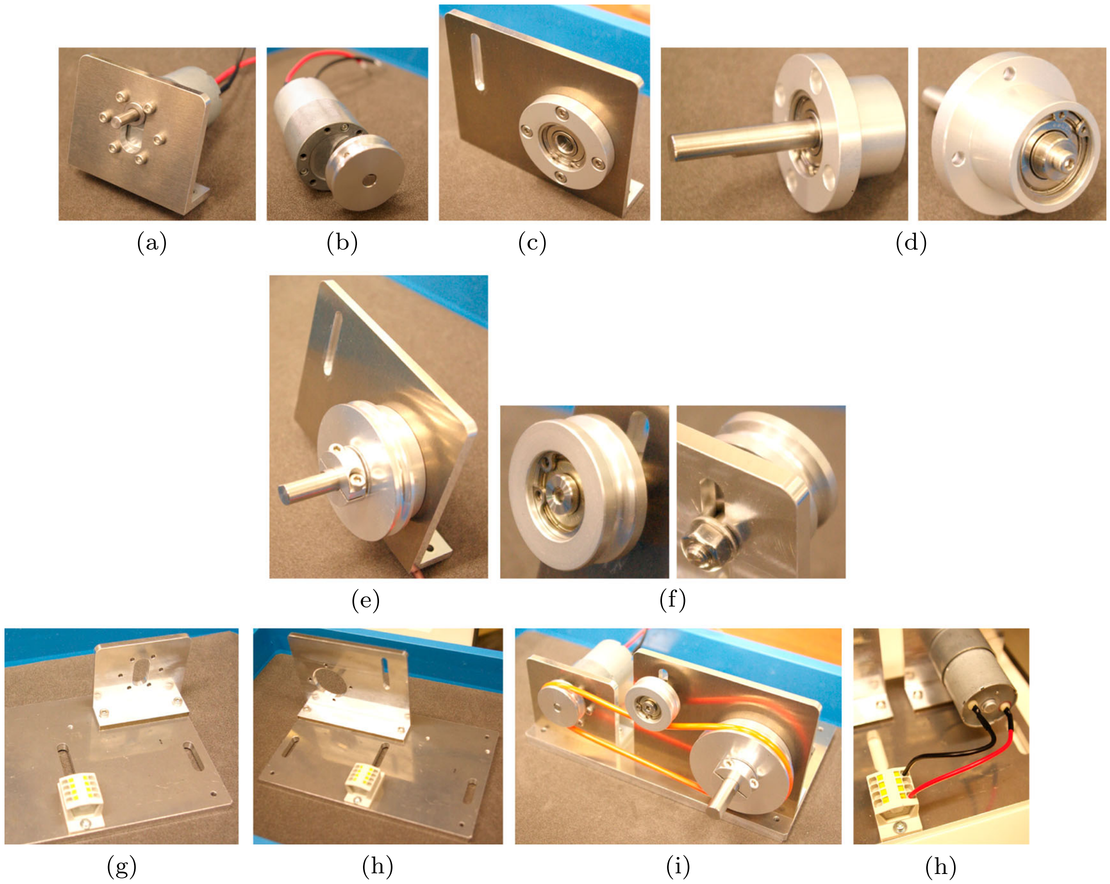

Figure A3. Subtasks of the assembly task. (a) Subtask A; (b) Subtask B; (c) Subtask C1; (d) Subtask C2; (e) Subtask D (only the difference from Figure A3(c) and (d)); (f) Subtask E; (g) Subtask F; (h) Subtask G; (i) Subtask H (only the difference from Figures A3(a) through (g)); (h) Subtasks I1 and I2.

Table A1. Subtasks of the task-board task, allocated points, and part compatibility with the assembly task.

Subtask	Part Name	MISUMI Model No.	Part Compatibility	Description	Points
1	Bearings with Housing	SBARB6200ZZ-30	YES	Insertion into a hole &	14
	M4 Bolts	4 × SCB4-10	YES	Screwing into a tapped hole	
2	Idler pulley	MBGNA30-2	(YES)	Insertion into a slot &	14
	M6 Nut	SLBNR6	YES	Fastening a nut and a bolt	
3	Drive Shaft	SSFHRT10-75-M4-FC55-G20	YES	Insertion into a hole	14
4	M3 Set Screw	MSSFS3-3	(YES)	Screwing into a tapped hole	14
5	4 mm Round belt	MBT4-400	(YES)	Looping over pulleys	14
6	Pulley	MBRFA30-2-P6	YES	Placing onto a shaft	10
7	M3 Bolt	SCB3-10	YES	Screwing into a tapped hole	10
8	M4 Bolt	SCB4-10	YES	Screwing into a tapped hole	10
Total					100

[NOTE 1] Threaded pin is already attached on the idler pulley while the idler pulley and bearing shaft screw are separated for the belt drive unit.
[NOTE 2] Length of M3 set screw is shorter than that for the belt drive unit.
[NOTE 3] Length of round belt is slightly shorter than that for the belt drive unit.

Table A2. Parts list of the belt drive unit.

Part No.	Part Name	MISUMI Model No.	QTY
1	Base Plate	N/A	1
2	Output Shaft Fixing Plate	N/A	1
3	Motor Fixing Plate	N/A	1
4	Geared Motor (Gear ratio 1:70)	N/A	1
5	Pulley for Round Belt (4 mm) - Setscrew, P.D. 30 mm	MBRFA30-2-P6	1
6	Polyurethane Round Belt (Welded Joint Product) P.D. 4 mm L=380 mm	MBT4-380	1
7	Bearing with Housings (Double Bearings)	SBARB6200ZZ-30	1
8	Drive Shaft (Straight) D10h7	SSFHRT10-75-M4-FC55-G20	1
9	End Cap for Shaft	EDCS10	1
10	Bearings Spacers for Inner Ring (Output Pulley)	CLBPS10-17-4	1
11	Pulley for Round Belts - Clamping Type, P.D. 60 mm	MBRAC60-2-10	1
12	Bearing Spacers for Inner Ring (Tension Pulley)	CLBUS6-9-9.5	1
13	Idler for Round Belt - Wide	MBGA30-2	1
14	Bearing Shaft Screw	BGPSL6-9-L30-F7	1
15	M6 Hex Nut (Fixing for Idler Shaft)	SLBNR6	1
16	M6 Flat Washer (Fixing for Idler Shaft)	SPWF6	2
17	10 mm M4 Socket Head Cap Screw (Metric Coarse Thread)	SCB4-10	9
18	10 mm M3 Socket Head Cap Screw (Metric Coarse Thread)	SCB3-10	6
19	6 mm M3 Hex Socket Set Screw (Metric Coarse Thread)	MSSFS3-6	1
20	Clutch lock terminal block (compact)	TW1004	1
21	Weidmuller Wire-end ferrule	H0.5/14D	2
22	NAUL1015 UL compliant wire (black)	NAUL1015-22-BK-10	1
23	NAUL1015 UL compliant wire (red)	NAUL1015-22-R-10	1

[NOTE 1] Parts #1-3 are custom-made parts ordered to MISUMI.
[NOTE 2] Part #4 is not a part of MISUMI. It is available from https://www.pololu.com/product/4744.
[NOTE 3] Part #20 is supplied with Part #1 attached with screw.
[NOTE 4] Part #21 is crimped on the ends of the wires of Parts #22 and 23.
[NOTE 5] Parts #22 and #23 are supplied with Part #4 soldered to each terminal.

Table A3. List of parts that may be used in the surprise plus product.

Part No.	Part Name	MISUMI Model No.
5	Pulley for Round Belt (4 mm) - Setscrew, P.D. 40 mm	MBRFA40-2-P6
5	Pulley for Round Belt (4 mm) - Setscrew, P.D. 45 mm	MBRFA45-2-P6
5	Pulley for Round Belt (4 mm) - Setscrew, P.D. 48 mm	MBRFA48-2-P6
11	Pulley for Round Belts - Clamping Type, P.D. 45 mm	MBRAC45-2-10
11	Pulley for Round Belts - Clamping Type, P.D. 48 mm	MBRAC48-2-10
11	Pulley for Round Belts - Clamping Type, P.D. 80 mm	MBRAC80-2-10

Table A4. Subtasks of the assembly task and allocated points.

		Product Level		
Subtask and Additional item	Description	Normal	Surprise	Surprise plus
A	Motor to plate with screws	4	5	5
B	Motor shaft & pulley	3	4	8
C1	Bearing holder & plate	3	4	4
C2	Output shaft, washers, end cap & screw	3	4	4
D	Output shaft & pulley	3	4	8
E	Tension pulley & plate with washers & screw & nut	5	6	6
F	Motor plate & base plate with screws	2	3	3
G	Output plate & base plate with screws	2	3	3
H	Belt with tension	5	7	14
I1	Terminal connection	5	5	5
I2	Terminal connection	5	5	5
Completion Bonus	All subtasks (excluding subtask I1 and I2) are completed	30	120	175
Product Evaluation	Visual and function	30		
Total		100	200	270