The 2010 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 18-22, 2010, Taipei, Taiwan

PaDY : Human-Friendly/Cooperative Working Support Robot for Production Site

Jun Kinugawa, Yuta Kawaai, Yusuke Sugahara and Kazuhiro Kosuge

Abstract— **In this paper, we propose a novel human-friendly/cooperative working support robot named PaDY (in-time Parts/tools Delivery to You robot). This system reduces the worker's load and improves work efficiency by recognizing the worker's behavior at a production site, and supporting the worker. We propose a method estimating the pace of work of a worker so as to adjust the motion of the robot to the pace of work, and confirm its effectiveness by performing experiments. We describe the concept of PaDY, the measurement of a worker's motion for motion planning of the robot arm, and the method of estimating the pace of work based on statistical data.**

I. INTRODUCTION

The industrial robot plays a key role in achieving steady quality in a manufacturing industry. Indeed, industrial robots are critical to manufacturing. In particular, the use of industrial robots promotes efficient production through the automation of work and has reduced unnecessary labor and wasted time in the production of automobiles. For example, the industrial robot does the majority of work in welding and coating processes.

However, there are many nonautomated processes such as work requiring status judgment and cooperative work. In particular, it is difficult to use an existing industrial robot in assembly processes ; i.e., assembly work should be manually done by hand. The industrial robot is poor at completing work for which the experienced adjustment of power is necessary, work for which skill is necessary, and work that varies in a less predictable manner.

To improve the present situation, the expectation is sent to the partner robot which achieves the aimed work by doing the work that is difficult for the worker, and supporting the work which becomes a load of the worker. Recently, various robots have been developed, such as the meal-support robot My Spoon by Ishii et al. [1], a flexible assembly work cooperating system by Hayakawa et al. [2], the scrub nurse robot by Miyawaki et al. [3], Penelope by Robotic Systems & Technologies Inc. [4], and Leonardo by Hoffman and Breazeal [5]. Also, Hoffman and Breazeal proposed Cost-Based Anticipatory Action Selection[6].

Research focusing on production sites includes the investigation of the human symbiotic assist arm by Higuchi et al. [7] and the installation of work-support equipment, referred to as skill-assist equipment, on the automotive assembly line by Yamada et al. [8]. These researches aim to decrease the worker's operating physical force and load.

Authors are developing a new human-friendly/cooperative working support robot named PaDY (in-time Parts/tools Delivery to You robot) with the aim of reducing the worker's load, improving work efficiency, and preventing work mistakes (Fig. 1). The robot is not directly involved in the assembly task but does nonessential work in support of the human carrying out the task.

Another robot-partner system is Sugi's worker-support cellular manufacturing system, which supports assembly by delivering parts using self-moving trays [9]. Because the system uses a self-propelled tray that employs a Sawyer planar motor, the area that the system can deliver parts to is limited to a special platen. Therefore, it is difficult to deliver parts in the case of line production as opposed to cellular manufacturing based on desktop workstations.

PaDY measures the worker's position in real time, estimates the present task of the worker from the worker's position and work schedule, and delivers necessary parts and tools to the worker at the proper time. Specifically, PaDY obtains the worker's positional information using a laser range finder (LRF), estimates the task that the worker is doing at that time and the pace of work, and plans the timing of the delivering of parts and tools. Moreover, PaDY avoids collision of its arm with the worker by recognizing the worker's position at any time. Thus, PaDY plans the trajectory of the arm so as to hand the parts and tools to be used in the following task to the worker and controls the robot arm on the basis of this trajectory.

By introducing PaDY, the worker only has to take the delivered parts and tools and complete the work, and thus, the worker does not have to return many times to the location where the parts and tools are stored. PaDY achieves the

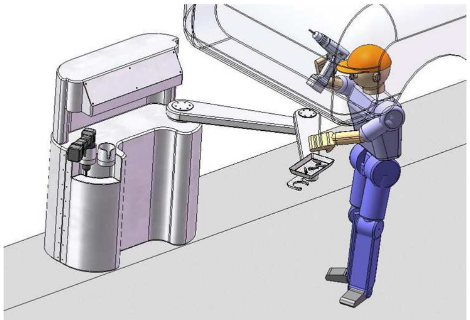


Fig. 1. The concept of parts/tools delivery system

J. Kinugawa, Y. Kawaai, Y. Sugahara and K. Kosuge, the Department of Bioengineering and Robotics, Graduate School of Engineering, Tohoku University, Aoba-yama 01, Sendai 980-8579, JAPAN, {kinugawa, kawaai, sugahara, kosuge}@irs.mech.tohoku.ac.jp

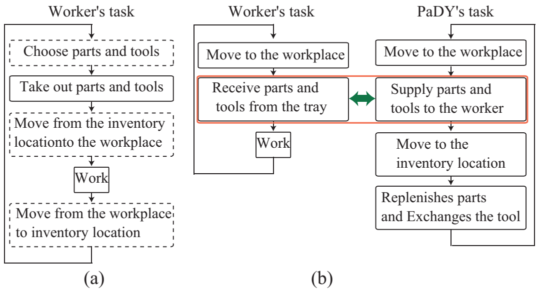


Fig. 2. Work procedure. (a):Current works, (b):Works with PaDY.

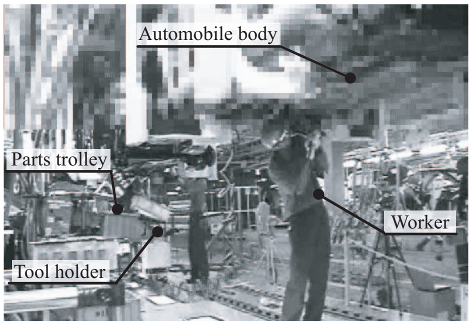


Fig. 3. Targeted work

TABLE I

WORK SCHEDULE

Procedure Number	Task
0	Task not targeted
1	Task A
2	Move to Next Workplace
3	Task B
4	Task C
5	Move to Next Workplace
6	Task D
7	Move to Next Workplace
8	Task E
9	Task F

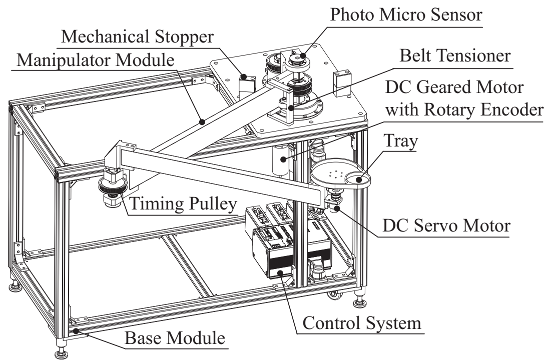


Fig. 4. Parts/Tools delivery system PaDY P1

following two goals. First, length of the working hours are shortened by optimizing the delivery timing of parts and tools according to the working process. Second, the system compares the work of the worker with the work schedule and can thus detect work mistakes. Fig. 2(b) shows the procedures of the worker and PaDY, whereas Fig. 2(a) shows the worker's procedure when working alone. The work enclosed with the dotted line in Fig. 2(a) is work that becomes unnecessary by introducing PaDY.

In this paper, a prototype of the robot arm for delivering parts and tools, the worker's motion measurement system, the method for generating the movement of the robot arm are proposed, and the effectiveness of the system were confirmed by performing experiments.

The paper is structured as follows. The following section presents the work targeted in this research. Section 3 introduces the outline and hardware design of the human-friendly/cooperative working support robot PaDY. Section 4 proposes the worker's motion measurement system and describes a statistical treatment of the work status. Section 5 explains the motion planning method. Section 6 proposes the method of modifying the delivery time in real time. Section 7 confirms the system effectiveness by experiment. Finally, conclusions and future work are discussed in Section 8.

II. TARGETED WORK

The work targeted in this research is an assembly process of an automotive production line. Specifically, we select a process of assembling parts to an automobile body that delivers overhead of the worker as shown in Fig. 3. In this process, the worker selects parts and tools from a trolley, positions it in the automobile body, and attaches them to the automobile body with special tools. In the process that we target, two or more parts and tools are used. Therefore, the worker needs to return many times to the trolley where parts and tools are kept next to the production line, and this can be regarded as lost time. Moreover, the worker needs to select parts and tools in a limited time, and this can result in mistakes being made.

TABLE I shows the schedule of work tasks when considering the actual task and the travel involved during task. We use this work schedule in our analysis. The task number n of 0-9 denotes tasks and movements in the work process. Each task comprises assembly work that is set to a constant work amount such as the amount of work for setting a part or that for tightening a screw. Six tasks (task A–F) are included in the overall process, and the workplace specified for each task in relation to the position of the automobile (the automobile coordinate system), working hours, and necessary parts and tools are specified by the work schedule. In the process, the worker goes to take parts and tools and selects necessary parts and tools at the time of movement. In addition, tasks need to be completed in the tact time. The tact time is the time that one automobile pass one worker's working space in the assembly line. Therefore, the worker needs to finish the tasks in the work schedule and prepare for the next automobile in that time. One worker's working space is $5.3[m]$ (length) × $3.6[m]$ (width). Then, this work schedule is changed depending on the kind of car models and the kind of the options.

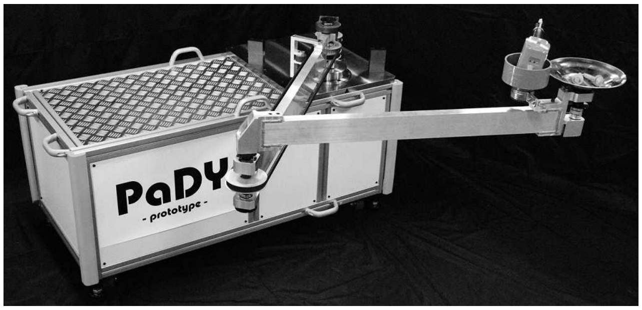


Fig. 5. Photograph of PaDY P1

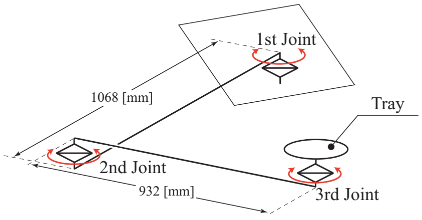


Fig. 6. DOF Configuration of PaDY

III. THE FIRST PROTOTYPE OF HUMAN-FRIENDLY/COOPERATIVE WORKING SUPPORT ROBOT -PADY (P1)

The first prototype of PaDY (P1) comprises a manipulator module that delivers parts and tools to the worker, a measurement module that measures the worker's motion, and an integrated control system (Figs. 4 and 5). The manipulator module comprises a horizontal articulated robot arm having three degrees of freedom and a tray on which parts and tools are placed as shown in Fig. 6. This section details the manipulator module.

A. FUNCTIONAL REQUIREMENTS

The following mechanical characteristics are required of PaDY.

- Coexistence with a human: The robot must work safely and deliver parts and tools to the worker using the same working space as the worker.
- Wide range of motion: The robot must have a range of motion sufficient to support work in one worker's working space ($5.3[m] \times 3.6[m]$).
- Low thrust: Because collision between the worker and robot should not pose a danger, the actuator of the robot should be of low thrust.
- Weight capacity: The weight capacity of the arm should be $3[kg]$ or less so that the robot arm can deliver parts and tools necessary for assembly at the production site.

An arm with such mechanical characteristics was developed and named VLWVWW (Very Light-Weight Very Wide Workspace) Arm. Details are presented in the following.

To cooperate with human, the robot must adjust the delivery timing to the worker's motion. In one side, it is not necessary to delivery to the accurate point, because the worker can reach to the tray around him/her.

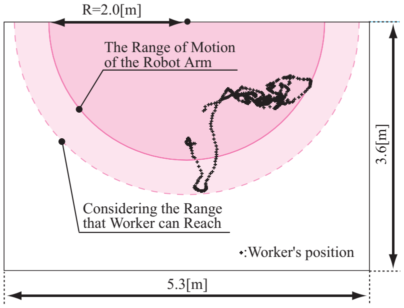


Fig. 7. Workspace of the Robot Arm and the Motion of the Worker

TABLE II
SPECIFICATION OF PADY P1

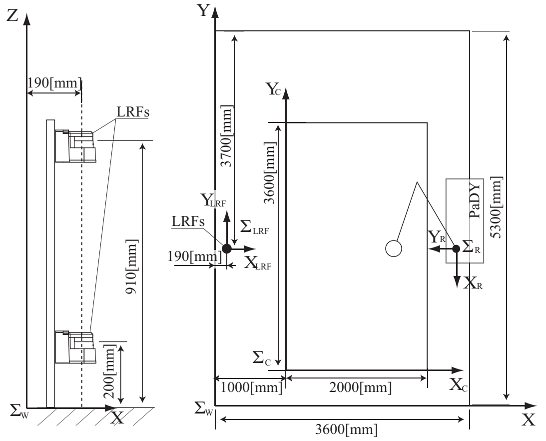
Model No.	PaDY P1
Dimension/Wieght	
1st Link Length	1068[mm]
2nd Link Length	982[mm]
Weight of Working Parts	11[kg]
Mechanism	
Link Mechanism	Horizontal Articulated
Degrees of Freedom	3
Actuator	
Motor of 1st Joint	DC Servo Motor 80[W]
Motor of 2nd Joint	DC Servo Motor 80[W]
Motor of 3rd Joint	DC Servo Motor 15[W]
Maximum Reach	2.0[m]
Maximum Load	3.0[kg]
Equipment	
sensor	LRF x 2

B. SELECTION OF MOTOR

In Japan, regulations regarding safety and sanitation, including a detailed safety plan for the use of industrial robots, have been set for industrial robots by the Ministry of Health, Labour and Welfare, Japan. In part II, chapter I, section 9, article 150-4, it is stated that "The employer shall, in the case where an industrial robot is operated (excluding when operating the industrial robot for teaching, etc., and where the work prescribed by the next article has to be carried out during operation), and when it is liable to cause dangers to workers due to contact with the said industrial robot, take necessary measures of providing a railing, an enclosure, etc., for preventing the said dangers." The rated output of power needs to be $80[W]$ or less for a robot to be excluded from the regulations. Moreover, there are similar JIS (JISB8433-1) and ISO (ISO 10218) limitations. Therefore, a robot working cooperatively with a worker in the same workspace should use a motor with a power output of $80[W]$ or less for safety reasons. Thus, we adopted a direct-current (DC) motor with rated output of $80[W]$ at the first joint and second joint of VLWVWW Arm. In addition, we adopted a light, compact DC motor with rated output of $15[W]$ at the third joint of VLWVWW Arm. We confirmed that the motors were able to move the robot arm in a kinetics simulation.

C. MOVABLE RANGE

To ensure the range of motion of the robot is sufficient to support the worker, we surveyed the worker's workspace. The motion of the worker during the targeted work was measured by LRFs as described in section 4. Fig. 7 shows



(a) (b)

Fig. 8. Arrangement of LRF and setting of coordinate system

the measurement result. The solid circle of $2.0[m]$ radius in Fig. 7 includes the trajectory at the worker's position. This circle shows the range of motion of the robot arm, which has a maximum reach of $2.0[m]$. The dotted circle of $2.5[m]$ radius is drawn assuming that the distance with the worker and the position at which he/she can reach the end effector is about $0.5[m]$. Considering the range that the worker can reach, the movable range of the robot arm can cover the worker's space sufficiently. Therefore, the length of the arm in the targeted work was set to $2.0[m]$.

D. SAFETY DESIGN

The robot works with the worker in the same workspace. Therefore, it is assumed that the two will collide at some stage. It is important that the robot is as light as possible to ensure a low impact force when the robot collides with the worker. So that the moving part of VLWVWW Arm is light, the motor of the first and second joints is designed to be part of the base module by using a timing belt drive. In addition, the first and second links are made of hollow square pipe, and they are welded at the joint. In this way, the mass of the arm is low while the strength of the arm is sufficient. The mass of the moving part of the robot is about $11.5[kg]$, and the mass of the arm is light considering its range of motion and weight capacity. Additionally, to ensure safety through the use of hardware, a torque limiter is connected to the first and second joints. We plan to cover the arm with the exterior and the cushioning material in the future. TABLE II lists the specifications of PaDY.

IV. WORKER'S MOTION MEASUREMENT SYSTEM

A. WORKER'S POSITION MEASUREMENT METHOD

For the partner robotic system to provide appropriate support, the robot should recognize the worker's motion. Research to establish a suitable method has been conducted in various fields [10]-[13]. Methods can be roughly categorized as three types: methods employing a camera, methods in which a sensor is set on the human, and methods employing laser sensors. When the worker does not move, such as when an assembly task is carried out on a table and surgeries, the method that recognizes the worker with a camera is used because a camera can obtain information when the working range is comparatively narrow. However, the camera-based approach has large time and financial costs when the worker moves over a wide area, as in the case of a worker at a production site, because two or more cameras are required. In addition, it is undesirable to attach a sensor to a worker when considering the worker's load. On the other hand, ranging sensors can be used for practical worker recognition at a production site.

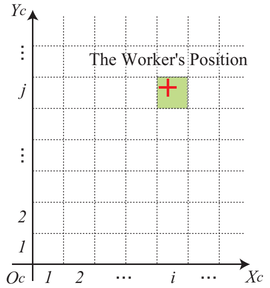


Fig. 9. The automobile coordinate system shown by the mesh with cells of constant width

Therefore, two LRFs are used for the measurement of the worker's position in this research. The LRFs are set up as shown in Fig. 8(a). After that, they measure to specify the position of the worker's waist and foot. Next, data clusters are measured employing the nearest-neighbor method [14]. The worker's cluster is specified and the worker's position calculated[15].

B. STATISTICAL TREATMENT OF THE WORK STATE

The time required for the worker to complete tasks, the worker's trajectory, and the worker's peculiarities were estimated by statistically analyzing time series data of the worker's position.

The following three frequency distributions are computed by measuring the worker's movement when the worker works on two or more automobiles to treat the time series data of the worker position statistically.

1) Existence Probabilities of the worker's position: First, in the automobile coordinate system shown by the mesh with cells of constant width in Fig. 9, the frequency at which the worker is located is measured in each cell and is divided by the total number of data of each work task. This ratio is referred to as the existence probability $E_{n,i,j}$ of the worker's position (i, j) for n-th task and is written as the following equation :

$$E_{n,i,j} = \frac{1}{M} \sum_{m=1}^{M} \left(\frac{C_{m,n,i,j}}{\sum_{i=1}^{200} \sum_{j=1}^{360} C_{m,n,i,j}} \right) \qquad (1)$$

where M is the number of automobiles worked on in the data series, $C_{m,n,i,j}$ is the number of data points measured

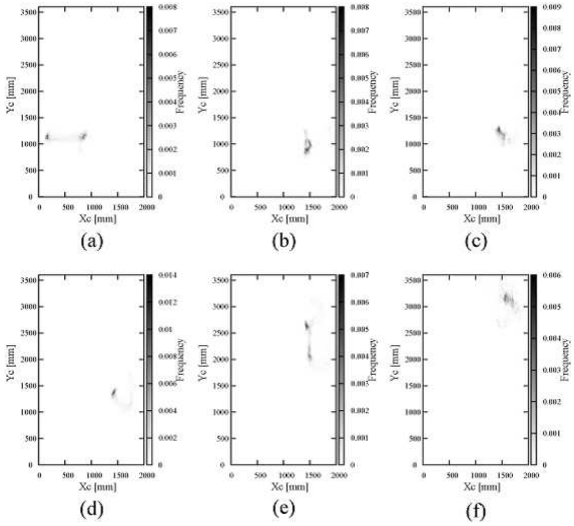


Fig. 10. Execution probabilities of the worker's position.
(a) Task A, (b) Task B, (c) Task C, (d) Task D, (e) Task E, (f) Task F.

in (i, j) coordinates for the n-th task of the m-th automobile, $\sum_{i=1}^{200}\sum_{j=1}^{360} C_{m,n,i,j}$ is the total number of worker's positional data for the n-th task of the m-th automobile.

When the procedure number n is given, $E_{n,i,j}$ indicates the probability that the worker is at a certain position.

2) Execution Probabilities of work with respect to time: The frequency that the worker is engaged in the n-th task at a certain time is computed by dividing the frequency that the worker is engaged in the n-th task at time t with the total number of measurements. This ratio is referred to as the performing rate $I_{n,t}$ of n-th task with respect to time t, and is written as the following equation :

$$I_{n,t} = \frac{W_{n,t}}{M} \tag{2}$$

where $W_{n,t}$ is the frequency that the n-th task is being undertaken at time t, the number of measurements is M.

When time t is given, $I_{n,t}$ indicates the probability that the worker is engaged in a certain task at that time.

3) Execution Probabilities of work with respect to position: Using the automobile coordinate system shown by the mesh with cells of constant width as well as the existence probabilities of the worker's position, the ratio of the probability of a worker being engaged in a certain task when the worker is in the cell is computed by dividing the frequency at which the worker is measured to be in the cell with the total number of data corresponding to a measurement in the cell. This ratio is referred to as the performing rate $R_{n,i,j}$ of work with respect to position (i, j) for n-th task, and it is written as the following equation :

$$R_{n,i,j} = \frac{1}{M}\sum_{m=1}^{M}\left(\frac{B_{m,n,i,j}}{\sum_{l=1}^{L} B_{m,n,i,j}}\right) \tag{3}$$

where $B_{m,n,i,j}$ is the number of data points corresponding to position (i, j) for the m-th automobile, L is the number of automobiles on which the worker worked in the cell.

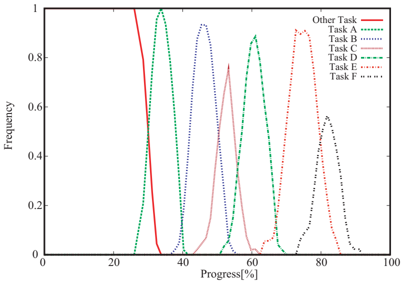


Fig. 11. Execution probabilities of work with respect to time

When the worker's position (i, j) is given, $R_{n,i,j}$ indicates the probability that the worker at that position is engaged in n-th task. This execution probabilities is defined only for cells in which the worker exists at least once in each work cycle.

C. MEASUREMENT EXPERIMENT

We measured the work of one worker for 43 automobiles. The worker's position was represented on the mesh shown in Fig. 9, and the cell width of the mesh was set to $10[mm]$ for the existence probabilities of the worker's position and $50[mm]$ for the execution probabilities of work with respect to position. The existence probabilities of the worker's position is shown in grayscale in Fig. 10. The existence probabilities of the worker's position is basically concentrated at certain place. However, there were some positions where the existence probabilities was high relating to the setting of parts in tasks A and E.

Fig. 11 shows the execution probabilities of the work with respect to time for the 43 automobiles. The horizontal axis is the time from the beginning of work normalized by the tact time (cycle period), and the vertical axis is the frequency that the worker is engaged in the n-th task at a certain time. This result shows that the execution probabilities of work with respect to time has a near normal distribution for each task.

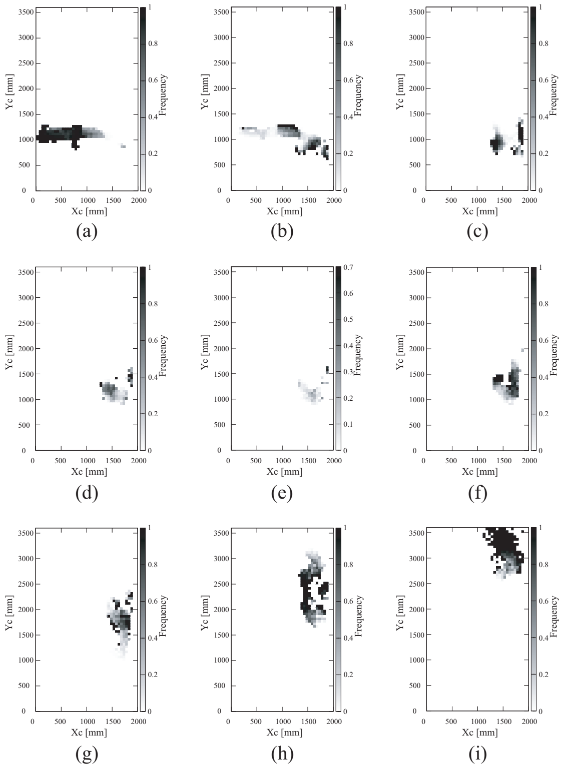
Fig. 12 shows the execution probabilities of work with respect to position. The ratio that each task is done in a certain cell is computed from the number of data in the cell. Therefore, the frequency of each cell is higher than the existence probabilities of the worker's position. This figure shows the frequency that the worker is engaged in each task on the basis of the cell that the worker is in.

The coordinate system in Figs. 10 and 12 is the coordinate system Σ_C of the automobile being worked in the production line.

V. MOTION PLANNING OF PADY

The motion of the work requested of PaDY is planned using the statistical data obtained in the preceding section. The procedure for planning the trajectory of the robot arm is as follows (Fig. 13).

i Specify the worker from the data measured with the LRF and obtain the worker's position.



(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Fig. 12. Execution probabilities of work with respect to position. (a) Procedure #1, (b) Procedure #2, (c) Procedure #3, (d) Procedure #4, (e) Procedure #5, (f) Procedure #6, (g) Procedure #7, (h) Procedure #8, (i) Procedure #9.

ii Produce the three abovementioned frequency distributions by statistically processing the worker's position.

iii Compute the delivery position and delivery time of parts and tools from the existence probabilities of the worker's position and the execution probabilities of work with respect to time.

iv Estimate the pace of work from the worker's position and the execution probabilities of work with respect to position, and modify the delivery time according to the pace of work.

v Plan the trajectory of the robot arm at the delivery position and the delivery time of parts and tools.

Details of the motion planning are as follows.

A. DELIVERY POSITION

The position at which the worker is most likely to be is obtained from existence probabilities, and the coordinates are adjusted by adding a suitable offset for the size of the worker's body. For tasks A and E, the delivery position is determined by adding the offset to the worker's initial position.

Because the delivery position is written with respect to the automobile coordinate system, when the target position of the end effector of the robot is computed, the delivery position is converted from the position of the present automobile to the robot coordinate system.

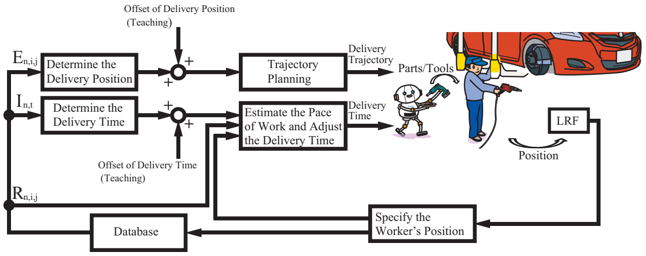


Fig. 13. Flow of processing

B. DELIVERY TIME

The frequency at which a worker is engaged in a certain task at a certain time is computed from the execution probabilities of work with respect to time. Therefore, if we assume that the worker is engaged in the task that is the highest execution probabilities, the time when the worker starts each task is computed. This time is time when the possibility that the task changes statistically is high. Therefore, when this time is made delivery time as it is, the delivery might be delayed. Then, the time of delivery is determined as the time to which suitable moving up time is added at this standard time. Although the time when the execution probabilities of work with respect to time is low can be used as the delivery time, we thought that it was not appropriate in this case, because the influence of irregular data on the movement of the robot is large owing to insufficient measurement frequency.

After delivering parts and tools to the worker, the robot stops for sufficient time for the worker to install the parts and interchange tools.

C. PART REPLENISHMENT AND TOOLING INTERCHANGE TIME

The robot should replenish parts and interchange tools between the start time of a certain task and the start time of the following task. This timing is decided in consideration of each delivery time. It is necessary to deliver parts and tools for some tasks at a time when there is not enough time to replenish parts and interchange tools. We currently decide this timing manually. In this experiment, the robot did the replenishment work before tasks A, B, C, and E.

D. TRAJECTORY GENERATION METHOD

The end effector's trajectory is generated as a straight line trajectory based on the timing of the robot's delivery of parts and tools and the delivery position determined using the abovementioned procedure.

VI. MODIFICATION OF THE DELIVERY TIME IN REAL TIME

The worker waits until the robot delivers parts and tools if the worker completes the previous task earlier than the delivery time determined from the abovementioned statistical data. To reduce this wasted time, we propose a method of modifying the delivery time according to the actual pace of work.

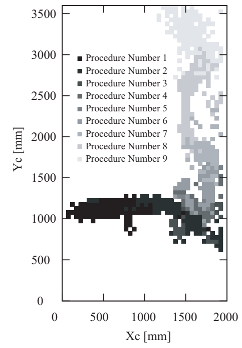


Fig. 14. Performing rate of work with respect to position

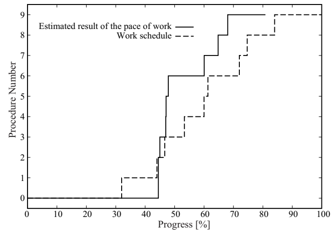


Fig. 15. Estimated result of the pace of work

A. ESTIMATING ACTUAL PACE OF WORK

The execution probabilities of work with respect to position shown in Fig. 12 is used to estimate the pace of work from the worker's position. It is judged that the worker is engaged in the task having the highest frequency in terms of the rate at which work is carried out with respect to the coordinate position at which the worker is located, and the pace of work is estimated from the transition of the task with the highest frequency. Fig. 14 shows the task with the highest frequency in each cell. The task the worker is most likely undertaking is estimated by comparing the figure with the worker's actual position.

B. MODIFICATION OF THE DELIVERY TIME

When the pace of work estimated using the abovementioned method is found to be faster than that of the schedule, the delivery time is modified according to the difference.

VII. EXPERIMENT

We conducted an experiment in which parts and tools were delivered to the worker on the production line using the abovementioned system. The robot control scheme is basic PD control. However, the replenishment of parts to the robot and the interchange of tools were done by a human now. In near future, the replenishment of parts and the interchange of tools will be automated.

The estimated pace of work is shown in Fig. 15. The pace of work determined from the work schedule and the actual pace of work when the robot supports work are shown in the figure. The robot delivered parts and tools $5.9[s]$ earlier than indicated by the work schedule at a time of $47.9[\%]$ (time normalized by the tact time). As a result, workers were able to work faster than the pace of work specified by the work schedule. The data measured by LRFs and the snapshots are shown in Fig. 16. The left side of figure shows the LRF measurement results and the state of the robot arm. The right side of figure shows the snapshots at that time. First, the robot prepared parts and tools for the tray, stood by (Progress $25[\%]$), and delivered them to the worker at the delivery time for the first parts and tools (Progress $30[\%]$). After delivering the parts and tools, the robot replenished parts required for the following task (Progress $35[\%]$), and delivered them to the worker at the delivery time (Progress $40[\%]$). Afterward, the robot replenished the parts and tools again (Progress $45[\%]$), modifyed the delivery time (Progress $47.9[\%]$), and delivered the parts and tools (Progress $50[\%]$). In addition, the robot stood by until the worker exchanged the tools (Progress $60[\%]$). The robot prepared parts and tools necessary for the following task, and stood by until the beginning of the following task (Progress $70[\%]$). It is shown that the robot and worker were able to work without interruption.

VIII. CONCLUSION

In this paper, we described the concept of the partner robot PaDY, which delivers necessary parts and tools to the worker at a production site, and proposed a basic motion planning method based on the worker's positional data statistically. Moreover, we proposed a method to modify the delivery timing of parts and tools by estimating the pace of work from the worker's statistic positional data. The effectiveness was confirmed by performing experiments.

In a future study, we intend to verify the experimental results using two or more workers instead of a single worker used in the present study. We will evaluate the effectiveness of the system overall from the experimental result of two or more times. Moreover, this modification method at the delivery time does not consider the case where there is a delay in work; i.e., it can only advance the distribution timing. We will design a method to account for the delay in work in future. Under the present situation, the estimation method used only worker's position. But it is not a best way to estimate the work pace accurately. By using work time and worker's direction to estimate, the estimate accuracy will become better. In this paper, worker's motion that was measured is without robot. We will measure the worker's motion with robot, and then we will generate a robot motion.

In addition, the robot arm should ideally avoid the worker and obstacles; however, in this study, the trajectory of the robot arm was a straight line. Therefore, we will develop a motion scheme that will not disturb the worker in future. Moreover, we intend to increase safety by realizing software-based collision detection methods.

REFERENCES

[1] S. Ishii, Meal-assistance Robot "My Spoon", *J. of the Robotics Society of Japan*, vol.21, No.4, pp.378-381, 2003. (in Japanese)

[2] Y. Hayakawa, T. Ogata and S. Sugano, "Flexible Assembly Work Cooperating System based on Work State Identifications by Self-Organizing Map", *IEEE/ASME Trans. on Mechatronics*, Vol.9, No.3, pp.520-528, 2004.

[3] F. Miyawaki, K. Masamune, S. Suzuki, K. Yoshimitsu and Juri Vain, "Scrub Nurse Robot System-Intraoperative Motion Analysis of a Scrub Nurse and Timed-Automata-Based Model for Surgery", *IEEE Trans. on Industrial Electronics*, Vol. 52, No. 5, pp. 1227-1235, 2005.

[4] Robotic Systems & Technologies Inc. , http://www.roboticsystech.com/

[5] G. Hoffman and C. Breazeal, "Collaboration in Human-Robot Teams", *1st AIAA Intelligent Systems Conf.*, Chicago, IL, September 2004.

[6] G. Hoffman and C. Breazeal, "Cost-Based Anticipatory Action Selection for Human-Robot Fluency", *IEEE Trans. on Robotics*, vol. 23, pp. 952-961, 2007.

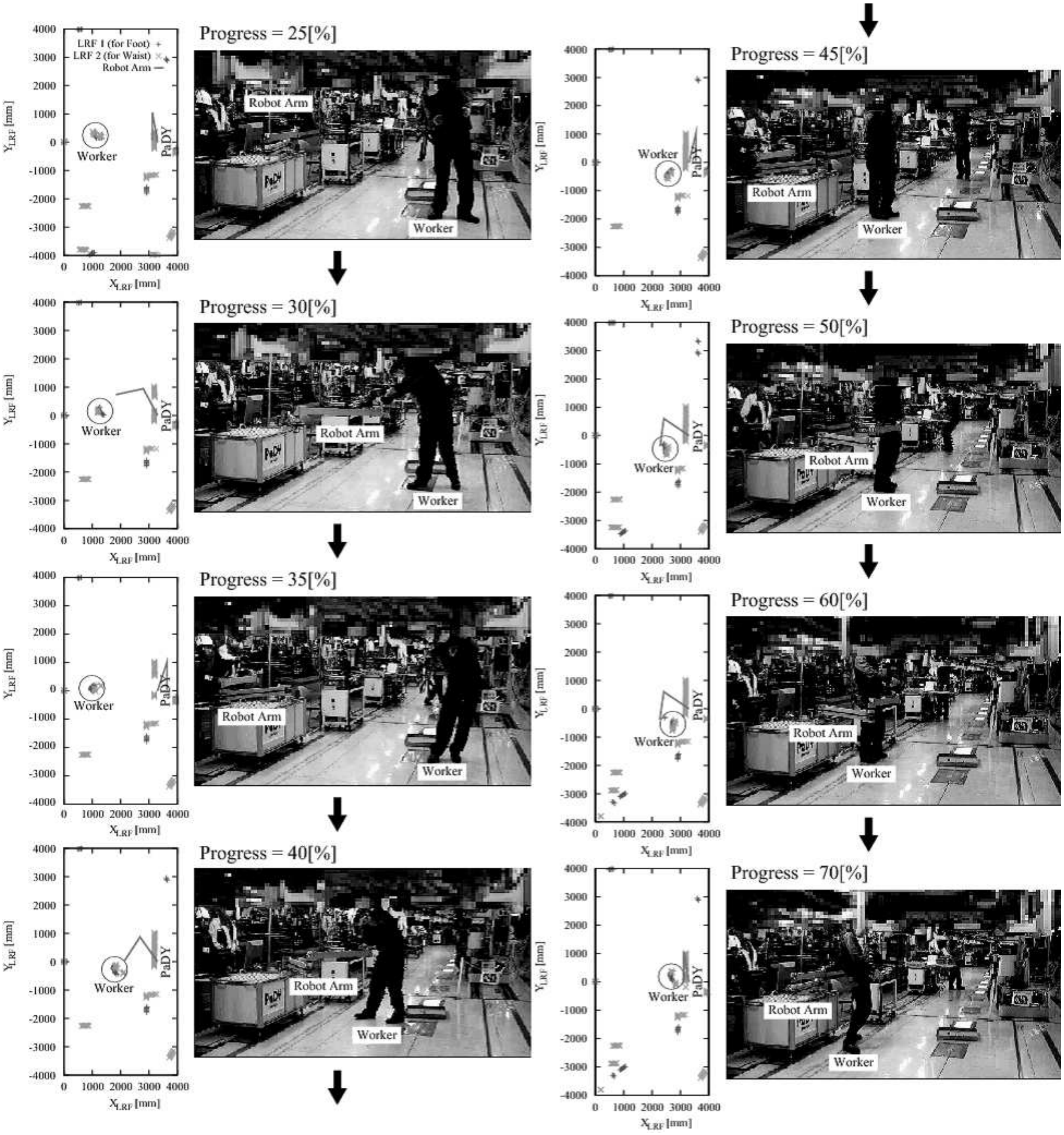


Fig. 16. Experimental result

[7] M. Higuchi, Development of a Human Symbiotic Assist Arm "PAS-Arm" : Basic Concept and Mechanism(Mechanical Systems), *Trans. of the Japan Society of Mechanical Engineers. C*, vol.73, No.730, pp.1762-1768, 2007. (in Japanese)

[8] Y. Yamada, H. Konosu, T. Morizono and Y. Umetani, "Proposal of Skill-Assist for Mounting Operations in Automobile Assembly Processes", *Trans. of the Japan Society of Mechanical Engineers. C*, 68(666), pp.509-516, 2002. (in Japanese)

[9] M. Sugi, M. Nikaido, Y. Tamura, J. Ota and T. Arai, "Motion and Arrangement Planning for Self-Moving Trays in Human Supporting Production Cell "Attentive Workbench"", *J. of the Japan Society for Precision Engineering*, Vol.72, No.11, pp.1380-1385, 2006. (in Japanese)

[10] B. Lau, K. O. Arras and W. Burgard, "Multi-model Hypothesis Group Tracking and Group Size Estimation", *Proc. of the IEEE ICRA 2009*, 2009.

[11] M. Luder, G. D. Tipaldi and Kai O. Arras, "Spatially Grounded Multi-Hypothesis Tracking of People", *Proc. of the IEEE ICRA 2009*, 2009.

[12] O. M. Mozos, R. Kurazume and T. Hasegawa, "Multi-Layer People Detection using 2D Range Data", *Proc. of the IEEE ICRA 2009*, 2009.

[13] A. Carballo, A. Ohya and S. Yuta, "Multiple People Detection from a Mobile Robot using Double Layered Laser Range Finders", *Proc. of the IEEE ICRA 2009*, 2009.

[14] P. J. Clark, et al. , "Distance to Nearest Neighbor as a Measure of Spatial Relationships in Populations", *Ecology*, Vol.35, No.4, pp.445-453, Oct. 1954.

[15] J. Kinugawa, Y. Kawaai, Y. Sugahara, K. Kosuge, "Human-Friendly/Cooperative working support Robot "PaDY" for Manufacturing -2nd Report: Human Motion Estimation using Laser Range Finders-", *ROBOMEC2009*, 1A2- E04, 2009. (in Japanese)