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Quantitative Evaluation of Physical Assembly Support in Human Supporting Production System "Attentive Workbench"

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Abstract— **We have proposed "attentive workbench (AWB)," an assembly cell that supports the production activities of human workers. Attentive Workbench is composed of an augmented desk interface and self-moving trays with the Sawyer planar motors. In this paper, real assembly experiments using the implemented AWB system are carried out. The merit of the physical assembly support by the proposed system is evaluated quantitatively in the view of necessary time for product assembly.**

I. Introduction

In recent years, manufacturers are expected to maintain variety in their product lines while retaining the ability to quickly produce appropriate products in adequate quantities. For this reason, instead of automated assembly lines, *cell production systems* have come into wide use in this decade.

In a cell production system, a single human worker manually assembles each product from start to finish [1]. Uniformly skilled human workers enable cell production systems to accommodate diversified products and production quantity flexibly. However, in practical sense, keeping such well-trained workers is not so easy. The productivity of cell production systems is lower than automated assembly lines. In these ways, there still remain problems to be solved in cell production systems. Recently several studies try to improve cell production systems, (e.g. on-line assembly instruction system that can reduce the cost for worker training and raise the productivity [1], [2]).

We have proposed attentive workbench (AWB) [3], an intelligent cell production system. Figure 1 shows a schematic view of attentive workbench. The system recognizes the intention and condition of human workers through cameras and vital signs monitors, and presents information through projectors. The system delivers assembly parts to the workers and clears away the finished products, using self-moving parts trays. By these assembly support from both information and physical side, the system will achieve a higher yield rate and productivity, by reducing failure and time in picking up the assembly parts.

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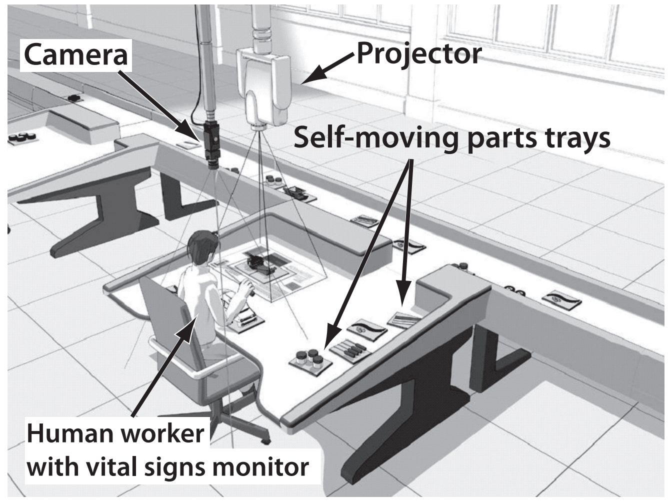

Fig. 1. Attentive Workbench (AWB).

We are also applying AWB to a deskwork support system in home environment, where fingerpointing is used as an interface between the user and AWB. In home environment, needs are focused on responding to wide variety of users' preferences. Estimation of situation, or intention of a user, is a key issue here. In this respect, we have established a method for estimating a user's intentions using dynamic Bayesian network [4].

Until now, we have mainly focused on the physical side of assembly support. In the report [5], the first prototype system of AWB had been implemented using Sawyer-type planar motors [6] as actuators of self-moving parts trays. A simple demonstration of physical assembly support had been performed. In order to improve the efficiency of the first prototype, second prototype system of AWB has been newly implemented in [7], where more high-speed planar motors and efficient motion planning method for the motors are introduced.

Feeding assembly parts to human workers by self-moving parts trays will bring about several merits to cell production systems, e.g. higher productivity, worker-friendly environment, and so on. Such physical assembly support also helps the less experienced people to enter the workforce.

In this paper, real assembly experiments using the im-

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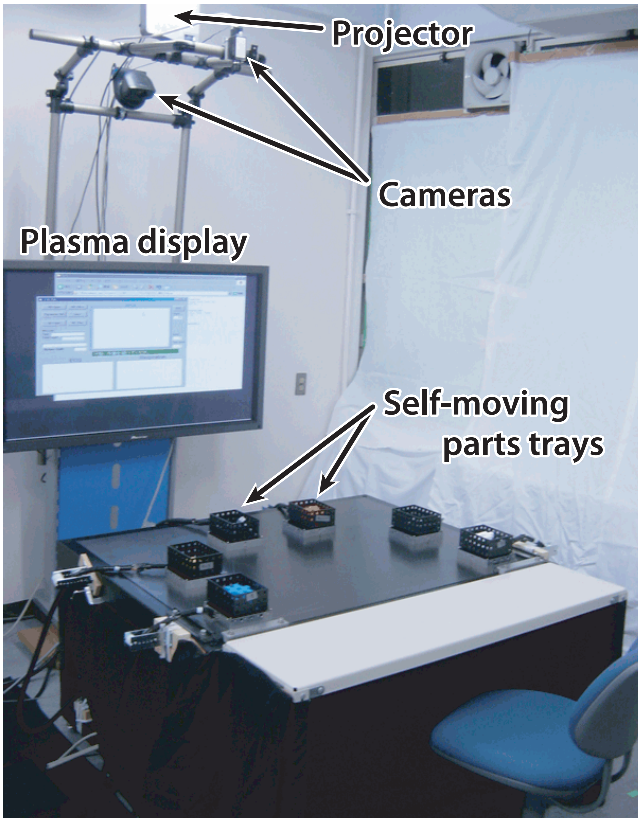


Fig. 2. Implemented prototype system of AWB.

plemented AWB system are carried out. The merit of the proposed system is evaluated quantitatively in the view of productivity.

II. Attentive Workbench (AWB)

A. System Overview

Fig. 2 shows the overview of the implemented system of AWB. The key technologies and devices of an attentive workbench consist of the following three items:

EnhancedDesk: It is a desk-type human-computer interface with augmented reality proposed by Nakanishi, Sato, and Koike [8]. Users express their intention by hand gestures, and the system recognizes them using the infrared camera [9]. Then the system presents the information using an LCD projector or a plasma display.

Estimation of the state of workers based on bio-measurement technologies: The state of human workers can be estimated from their heart rates and respirations, both measured by vital signs monitors. In this respect, Kotani et al. [10] have introduced a new method for analyzing respiratory sinus arrhythmia (RSA) as to respiratory phase.

Self-moving parts trays: We introduce self-moving trays driven by a Sawyer-type 2-DOF stepping motor [6], aiming for higher productivity than usual cell production systems. Self-moving parts trays, taking charge of physical side of assembly support, carry assembling parts and supply them to the human worker.

As shown in Fig. 2, there are six motors (i.e. six self-moving trays) on a motor platen (i.e. iron plate) with its size being 1200(mm)$\times$900(mm). The size of each motor is 135(mm)$\times$130(mm). In front of the motor platen, there is a white worktable with its size being 1200(mm)$\times$300(mm).

Motors can move 1 (m/s) at maximum for each axis. Therefore they can move more than 1 (m/s) for diagonal direction. Motors' trajectories are limited to straight line segments, due to the specification of motor controllers. They cannot move on curved line. The number of vertices on a trajectory is desired to be small, because motors must stop completely at the vertices in order to change their moving directions. Each motor has a cable that supplies both compressed air and electronic power from outside. The cables should be taken into account in motion planning to avoid them from tangling or colliding with each other.

In the previous paper [7], considering these physical characteristics and constraints of the Sawyer-type planar motors, we have introduced a new motion planning method for the self-moving parts trays based on priority scheme [11]. This method can generate efficient paths of multiple self-moving trays without mutual collision.

Fig. 3 shows an example of physical assembly support. In this system, a footswitch is used as an interface between the worker and AWB system. When the worker pushes the footswitch, the system supplies assembly parts necessary for the next assembly process. In Fig. 3-(b), two parts are used in single assembly process. Two parts trays simultaneously move to supply parts to the worker.

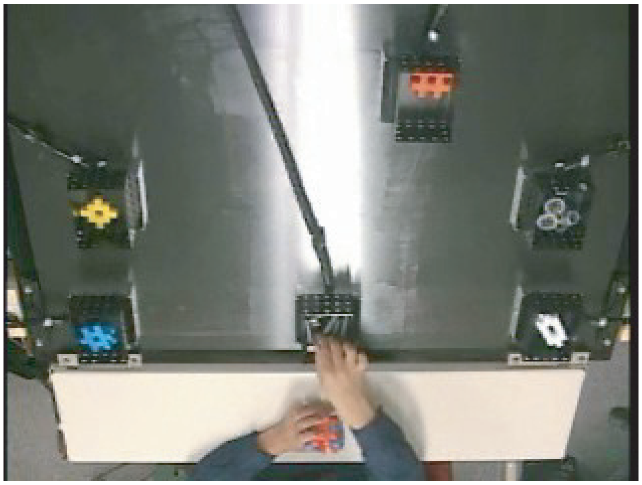
III. Experiment

As it is mentioned in the introduction, physical assembly support (i.e. automatic parts feeding to the human workers) in AWB will bring about various merits to the cell production systems. In this paper, we focus on the improvement of productivity (i.e. assembly speed) among various possible merits of physical assembly support, and evaluate it through experiments on product assembly.

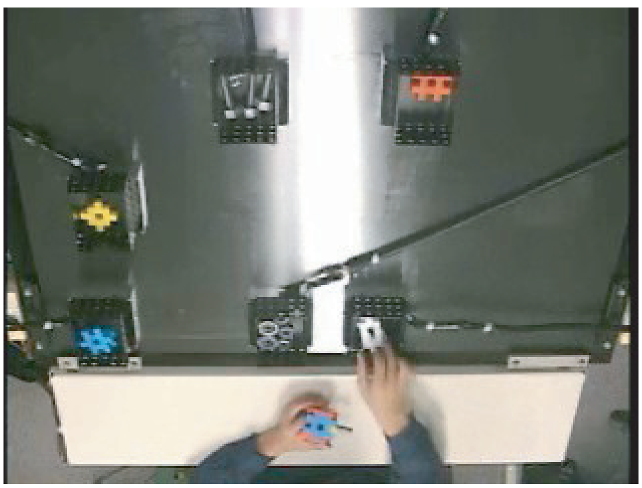
A. Sample assembly product for experiments

The improvement ratio of assembly speed will depend on the details of assembly tasks. As the assembly tasks continue for longer times, and as the assembly parts become larger and heavier, ratio of improvement of assembly speed will increase. In this section, we design an appropriate product that is suitable for experimental evaluation.

We have prepared a sample assembly product that is used in experiments, which is shown in Fig. 4. The product consists of a wooden plate referred to as "base plate", and 104 small metal pins (originally used as shelf support pins). As it is shown in Fig. 4, metal pins have five different diameter sizes; 3, 3.5, 4, 4.5, and 5mm.



(a)



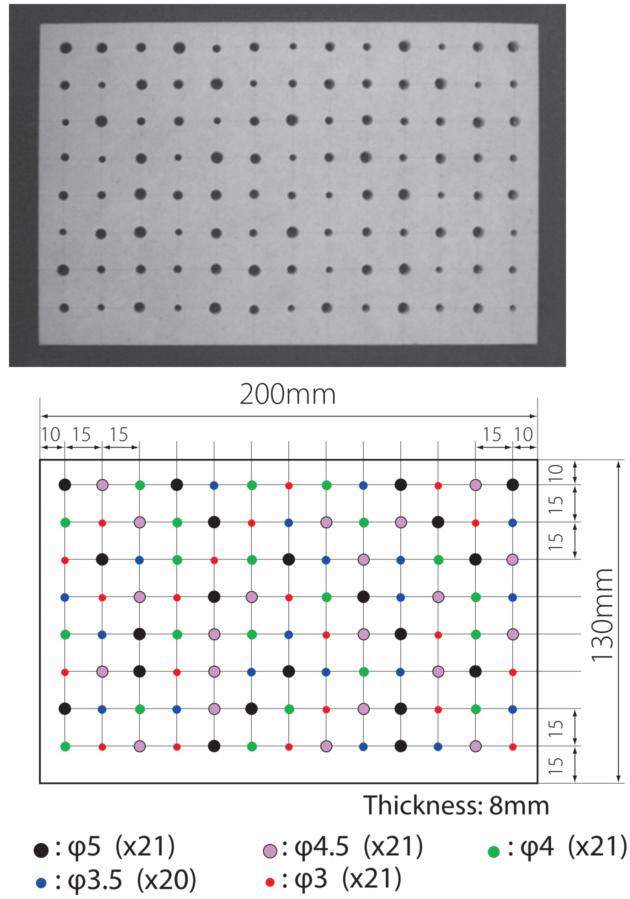
(b)

Fig. 3. An example of assembly support.

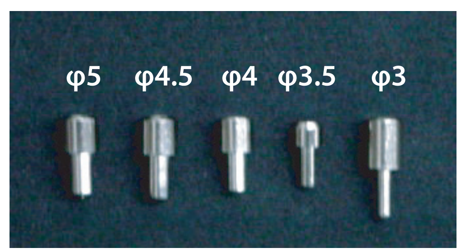
In each assembly process, the worker put a pin into a corresponding hole in the base plate. The order of assembly processes is fixed according to the "left to right, top to bottom" rule. The first pin is put to the top left hole (with 5mm diameter) in the base plate (see Fig. 4-(a)), and the assembly finishes at the right bottom hole (with 3mm diameter).

Putting a pin into a hole is very simple and easy operation, and does not require any special skills to assemble. These feature are suitable for evaluation experiments, in which each user (i.e. subject) does not always have enough skills for manual assembly tasks.

Five kinds of pins in Fig. 4-(b) look like one another very much. It is very difficult for the users to memorize the sequence of assembly process of the product. Therefore the experimental result is not so influenced by the effect of the experience curve, which will often cause noises in such experiments composed of the repetition of the same work.



(a)



(b)

Fig. 4. Assembly product. (a) Wooden base plate with 104 holes. (b) Five kinds of small metal pins.

B. experimental settings

At first, the user assembles the product shown in Fig. 4. When the user completes the assembly of it, then he/she disassembles the product. In each disassembly process, the user pull out a pin and return it to the parts tray in front of him. Same as the case with the assembly, the sequence of disassembly processes is all fixed according to the "left to right, top to bottom" rule.

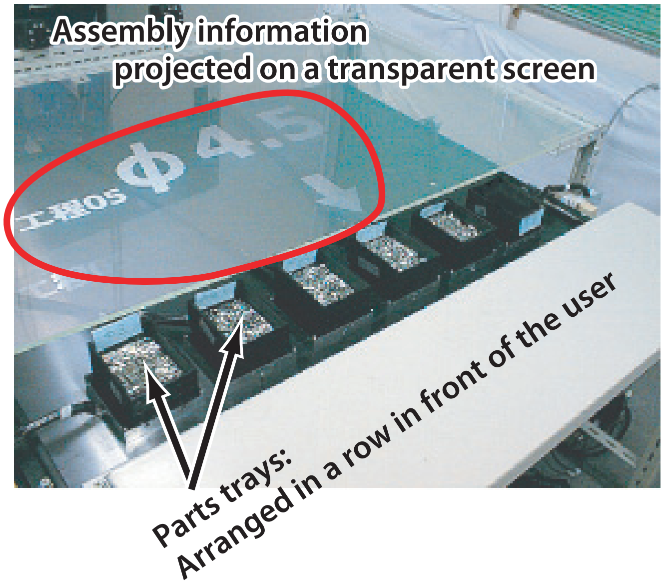


Fig. 5. Experimental settings in the case with no physical assembly support. Assembly information is projected on the desk. Parts trays are arranged in front of the user and cannot move.

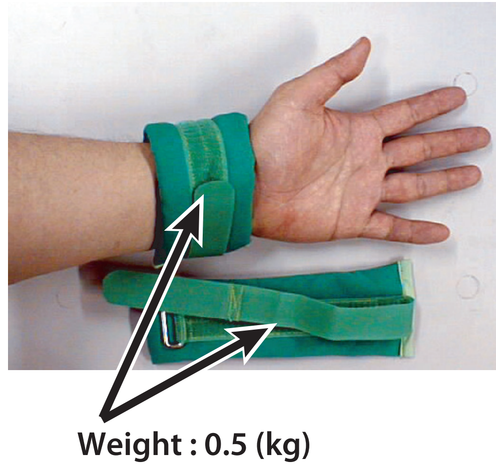


Fig. 6. Wrist weights used in the experiment in subsection III-D.

For comparison, assembly experiment of the same products without physical support is also carried out. In this experiment, self-moving trays does not move. They are arranged in a row in front of the user at intervals of approximately 20 (cm), which is shown in Fig. 5. In this case, the assembly information is presented on a transparent screen using the projector. On the screen, the name of part necessary for the current assembly process is presented, and an arrow that indicates the corresponding parts tray is shown. Similar to the case with physical assembly support, a footswitch is used as the interface between the worker and AWB system for information presentation,

We do not use information presentation in the case using self-moving trays. It is noted that the motion of trays also plays a role for information presentation.

C. Experimental result

Table I shows the average necessary time and the standard deviation for each of seven subjects to carry out single assembly/disassembly process. In the calculaion of the averages and standard deviations, each top and bottom 5% values for each subject are excluded as outliers. It is noted that these outliers are caused by some assembly errors, e.g. the subject had failed to insert the pin in the hole because of jamming and tried it again, or he stepped the footswitch by mistake before he picks up a pin necessary for the current assembly process, and so on.

In Table I, the right column with "Difference" header shows the difference of average necessary times between the case with physical assembly support and the one without it. A positive value of this column means that the necessary time is reduced by the physical support, and a negative value means that the time becomes worse by the physical support.

From Table I, we can see that the results of five subjects (A, B, C, D, and F) have the common tendency. In these five subjects, the average necessary times of assembly and disassembly in the case with physical assembly support are shorter than without physical support. The difference of average necessary time between two cases are approximately 0.08 to 0.4 (s). The paired t-test ($p < 0.05$) shows that the average of necessary assembly times for seven subjects are significantly improved ($p = 0.0152$) through the physical assembly support. On the other hand, with respect to the necessary time for disassembly, the improvement of necessary time through the physical support is not significant ($p = 0.0878$).

We can also see that the standard deviations (see Table 1) of necessary time in the case with physical assembly support are smaller than in the case without physical support. In the case with physical support, self-moving parts trays always come to the same position, which is near to the user. The user can easily pick up necessary parts. Without physical support, the trays are all located their own position, and the user sometimes has to stretch his hand more widely. This is the possible reason of the difference of standard deviation.

These results suggest that the physical assembly support (i.e. transporting the necessary parts to the human worker by self-moving parts trays) is effective in the view of productivity.

D. Experiment with larger physical payload

In order to simulate assembly with heavier load, we introduced a pair of wrist weights each of which weighs about 0.5 (kg). These wrist weights are a part of the "aged simulation set" (made by Koken Co. Ltd.), which intend to virtually experience the inconveniences felt by the elder people due to decline in body function. The subjects wears

TABLE I

AVERAGE NECESSARY TIME FOR SINGLE ASSEMBLY/DISASSEMBLY PROCESS AND ITS STANDARD DEVIATION

Subject (Age/Sex)		**(1)** With physical assembly support (s)		**(2)** Without physical assembly support (s)		**(3)** Difference ((**2**) − (**1**))	
		Assembly	Disassembly	Assembly	Disassembly	Assembly	Disassembly
A	Average	2.329	1.296	2.479	1.392	0.150	0.096
(33/M)	Std. Dev.	0.236	0.074	0.323	0.130		
B	Average	2.112	1.259	2.277	1.453	0.165	0.194
(24/M)	Std. Dev.	0.342	0.178	0.433	0.291		
C	Average	2.378	1.499	2.627	1.585	0.249	0.086
(22/M)	Std. Dev.	0.505	0.482	0.513	0.388		
D	Average	2.306	1.416	2.706	1.716	0.400	0.300
(28/M)	Std. Dev.	0.298	0.182	0.466	0.390		
E	Average	2.180	1.349	2.146	1.247	−0.034	−0.102
(25/M)	Std. Dev.	0.300	0.157	0.485	0.288		
F	Average	2.376	1.321	2.585	1.556	0.209	0.235
(23/M)	Std. Dev.	0.429	0.205	0.549	0.322		
G	Average	2.184	1.245	2.259	1.213	0.075	−0.032
(22/M)	Std. Dev.	0.447	0.178	0.439	0.223		

TABLE II

AVERAGE NECESSARY TIME FOR EACH ASSEMBLY/DISASSEMBLY PROCESS AND ITS STANDARD DEVIATION (WITH WRIST WEIGHTS)

Subject		**(1)** With physical assembly support (s)		**(2)** Without physical assembly support (s)		Difference ((**2**) − (**1**))	
		Assembly	Disassembly	Assembly	Disassembly	Assembly	Disassembly
A	Average	2.355	1.320	2.573	1.497	0.218	0.177
	Std. Dev.	0.233	0.071	0.344	0.133		
B	Average	2.120	1.257	2.290	1.491	0.170	0.234
	Std. Dev.	0.330	0.142	0.355	0.340		
C	Average	2.465	1.472	2.694	1.643	0.229	0.171
	Std. Dev.	0.499	0.468	0.532	0.380		
D	Average	2.385	1.391	2.822	1.654	0.437	0.263
	Std. Dev.	0.315	0.410	0.357	0.324		
E	Average	2.280	1.371	2.283	1.238	0.003	−0.133
	Std. Dev.	0.293	0.155	0.429	0.229		
F	Average	2.465	1.303	2.850	1.719	0.385	0.416
	Std. Dev.	0.473	0.204	0.569	0.317		
G	Average	2.178	1.248	2.340	1.310	0.162	0.062
	Std. Dev.	0.411	0.162	0.448	0.220		

the wrist weights in this experiment. Other conditions (i.e. subjects, assembly product, etc) are the same as in section III-B.

The result is shown in Table II. In the calculaion of the average values and standard deviations, each top and bottom 5% values are excluded as outliers. In six subjects (A, B, C, D, F, and G), the necessary times in the case with physical assembly support are shorter than in the case without physical support.

The tendency is similar to the previous experiment (see Table I), but the effect of the physical assembly support is shown more clearly than the previous result. The paired t-test ($p < 0.05$) shows that necessary times of both assembly and disassembly are significantly improved ($p = 0.00583$ and $p = 0.0396$ respectively) through the physical assembly support.

This suggests that the physical assembly support is more effective as the physical loads of assembly tasks for workers become larger.

IV. CONCLUSION

We have presented attentive workbench (AWB), a new cell production system in which an intelligent system supports human workers from both information and physical sides.

In this paper, attentive workbench (AWB) has been outlined first. AWB consists of an augmented human-computer interface, vital signs monitors, and self-moving parts trays driven by planar motors.

Next, we have dealt with the quantitative evaluation of the attentive workbench based on real assembly experiments. The present system have been compared with a conventional cell production, where the parts tray cannot supply assembly parts to the workers, with respect to the assembly speed. According to the experimental result, for the majority of the subjects, the necessary time for each assembly/disassembly process can be decreased through the physical assembly support. The proposed system is more effective when the physical loads of assembly tasks for the workers are larger.

Currently the number of users are still insufficient, but the result suggests that the present system is effective with respect to productivity.

In the next stage, we will carry out additional experiments with different workers.

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