A Method For Extracting Sensory Motor Skills And Designing A Training System

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ABSTRACT

Two years ago, the rapid retirement of the "baby boomer artisans" in vast numbers threatened to erode the competitiveness of Japanese manufacturers (i.e., the 2007 problem). This study proposes a practical process for extracting skills and designing a training system, to accelerate the learning of skills in production fields by younger generations (the passing down of skills from generation to generation). The proposed process can be roughly divided into a description of a task, extraction of skill, and the design of a training system consisting of the following seven steps: structural arrangement of work, clarification of work condition and target, clarification of changes in quality, extraction of variation factor by worker, setting of a hypothesis, verification of the hypothesis and determination of an appropriate range of variation factors, and selection of the training facilities and design for the training system. The process of skill extraction and training design proposed in this study was applied to the handing down of skills in welding work for PVC boards at manufacturer of photo-developing machines. A verification experiment with 18 subjects was performed to verify the effects of the training system developed. The excellent training effects and high utility of the proposed process were verified.

Keywords: Skill Transfer Management, Sensory Motor Skill

1. INTRODUCTION

Two years ago, the rapid retirement of the "baby boomer artisans" in vast numbers threatened to erode the competitiveness of Japanese manufacturers (i.e., the 2007 problem). Now, through the enforcement of the revised Law for the Stabilization of the Employment of the Aged, companies can temporarily forestall the skill drain by extending employment for their aging talent pool or hiring skilled workers who have retired from other companies. But these methods are not fundamental solutions. The permanent solution will be effective methods for handing skills down from one generation to the next.

The methods for handing down skills include the following two types: 1 training next-generation workers by converting the implicit knowledge of veteran engineers (personal know-how) into formal knowledge and 2 replacing the work of the veteran engineers with comparable work by machine (e.g., replacing highly skilled human lathe work with NC lathe work). In many cases, small and medium-sized enterprises are unable to afford the expensive investment required for the introduction of machines. Therefore, method 1 is realistic.

Other groups are developing techniques to hand down skills by VR (virtual reality) training (Hartmann et al. 2005) and by training systems focused on individual jobs (Matsumoto et al. 1993, Shida et al. 2001). Training with VR requires too much capital investment to expect widespread dispersion. For training systems for individual jobs, systems developed by universities and other research institutions through job analyses are already in use in production fields (Matsumoto et al. 2003). Yet the individual focus of most of these systems renders them unsuitable for other jobs, and the individual jobs handled by research institutes are limited in number. Thus, the best approach for the future will be to extract the implicit knowledge of skilled persons in production fields and design training systems. Yet the implicit knowledge of a skilled person, a form of knowledge "beyond words," is difficult to extract. To do so, the jobs of the skilled person must be analyzed in detail. In job analysis, researchers must begin by carefully finding "what they should look at." To hand down skills in a given production field, it may be necessary to build a process (e.g., a job analysis at a research institution to extract skills) for the analysis of jobs and the design of training in that production field. Thus, the objective of this study is to propose practical processes to extract skills and design a training system for job analysis and design of training in production fields.

2. SUBJECT OF RESEARCH

Skills in production can be divided into two categories: intellectual control skill (to correctly memorize the order of attachment of parts or job procedure) and sensory motor skill (to determine by visual, auditory and tactile senses, and to move the four limbs) (Mori & Kikuchi 1995). The latter, sensory motor skill is difficult to extract by interviews alone. For this reason, we selected sensory motor skill as subject of this study.

3. PROPOSAL FOR THE PROCESS OF EXTRACTING SKILL AND DESIGNING THE TRAINING SYSTEM

Step 1: Describing a work task

Step 1-1: Structurally arranging the work task

A "goods-change analysis" (Nakamura 2003) is an analysis to arrange the contents of a task in a structural manner. Fig. 1 is an example of the goods-change analysis in lathe work. As the figure shows, the goods-change analysis examines a task in terms of "first goods (raw materials)," "finished goods (product and residuals)," "means," and "change." We perform the analysis to improve the manufacturing process.

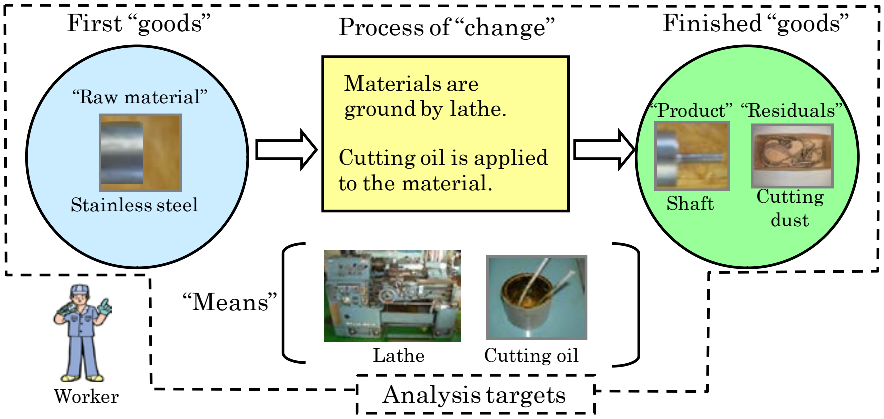


Fig. 1 Goods-Change Analysis

Step 1-2: Clarifying work conditions and targets

Next, we list up the “first goods” and “means.” In an actual task, working methods often change according to the materials and tools used. Therefore, we should determine the target “goods” in order to clarify working condition.

Step 1-3: Clarifying differences in quality

Next, we define conforming articles and types of defective products with a focus on the “finished goods.” We should also clarify the difference in “finished goods” produced by skilled and unskilled persons.

Step 2: Extracting skill

Step 2-1: Extracting variation factors by worker

Next, we change parts and materials (“first goods”) into products (“finished goods”). During the process, materials are changed by hands and tools (“means”) under various conditions. Materials are changed in different ways, as the “conditions of touch” and “stimuli” differ. Ultimately, the finished goods also differ. The quality of the product, good or bad, depends directly on:

- How the “means” (tools) come into contact with the “first goods”
- The stimuli of the “means” applied to the “first goods”

We investigate how “means” (tools) come into contact with the “first goods” in the “change” process and what stimuli are applied, and extract fluctuations between workers.

The posture and body movement of a worker may change the workmanship of final products. These factors, posture and body movement, change according to individual body types and conditions. If a worker tries to simulate the posture and body movement of another worker, minute differences in muscle movements will make it impossible to mimic with complete success. And when the movements of the copier are only superficially the same as the movements of the copied, the change between the “means” and “first goods” may not be completely the same. Therefore, the posture and body movement of a worker are presumed not to be variation factors.

Step 2-2 Setting the hypothesis

Next, we form a hypothesis by considering the process where the “first goods” become “finished goods,” as shown in Step 1-3. We investigate the cause of the difference in quality based on the condition under which the “means” (tools) come into contact with “first goods”, and on the stimuli applied to the “first goods” (variation factors in Step 2-1).

Step 2-3: Verifying the hypothesis and determining an appropriate range of variation factors

For each variation factor extracted in Step 2-1, we quantify the work of a skilled person. For verification of the hypothesis in Step 2-2, we perform experiments on variation factors extracted in Step 2-1 to clarify an appropriate range. Skilled persons work near the border of the appropriate range of each variation factor. If unskilled persons try to simulate the work of skilled persons, small changes may cause completely different results. Therefore, the work of a skilled person is not always appropriate for an unskilled person.

Step 3: Designing the training system
Step 3-1: Selecting the training facility

In the training mentioned in Step 3-2, unskilled persons learn to bring their actions closer to the appropriate actions. To do so, they need feedback on their actions. In selecting training facilities, we wish to prepare equipment to visualize the appropriate range of variation factors for the target task specified in Step 2-3.

Step 3-2: Designing the training process

We need to consider a style of training which makes trainees experience the target task within an appropriate range of each variation factor specified in Step 2-3. A person gain skills through the three phases of cognition, association, and automation. (Fitts & Posner 1967)

In the cognitive phase, a person understands a motion overall. In the associative phase, a person refines his or her motion in response to feedback. In the autonomous phase, a person learns to perform a task automatically. In other words, the cognitive phase is learning of knowledge, the associative phase is training to complete a task by moving one's body, and the autonomous phase is a repetition of motional training and actual task.

In the cognitive phase, the training method should explain the work and the changes in quality resulting from the variation factors. In the associative phase, the person learns an appropriate range for each variation factor. If there are multiple learning items, we need to divide them. From the viewpoint of divided action, we can apply two learning methods, one "total" and one "divided." The total learning method is appropriate for instant actions, such as a ball-batting action. The divided learning method is appropriate for actions composed of various elements. The divided learning method is more appropriate for manufacturing, as instant actions such as ball-batting are much less common than compound actions in a factory setting.

In designing a training system, each appropriate range of variation factors specified in Step 2-3 should be learned respectively. In the autonomous phase, the person should ideally repeat the training by executing what he or she learns.

4. APPLICATION TO AN ACTUAL TASK

4-1. Target Task

Apply the proposed process for skill extraction and training design for a vinyl chloride resin welding task (the "PVC welding task") at Company O, a photo-developing machine manufacturer. In a PVC welding task, a worker melts a PVC stick (the "weld rod") with hot air from a gun to connect a PVC board to another or pipe. The steps are as follows:

1. Hold a weld rod with the left hand and a gun with the right hand.
2. Apply hot air from the gun.
3. Weld PVC while melting the weld rod and board.

Company O relies on PVC welding to manufacture a reservoir tank for photo-developing machines. The welding technology is very important for the company's operations. The employees are rapidly aging. The company urgently needs to hand down welding skills to its younger employees. Fig. 2 shows the target task. Two PVC boards are welded vertically. This is a typical welding task in Company O.

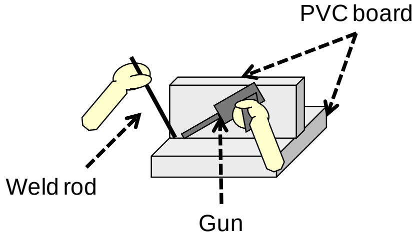


Fig. 2 Target Task

4-2. Application Of The Proposed Process

Step 1: Describing the task

Step 1-1: Structurally arranging the task

Fig. 3 shows a goods-change analysis of the target task.

The "first goods" are two PVC boards.
The "finished goods" are the same PVC boards welded vertically.
The "means" are the gun (hot air) and weld rod.
The "change" is the melting of the weld rod with the hot air from the gun and the vertical welding of the two PVC boards.

Note: The hot air from the gun is not a physical object, but it plays a role in the task. Therefore, the hot air is included among the "means."

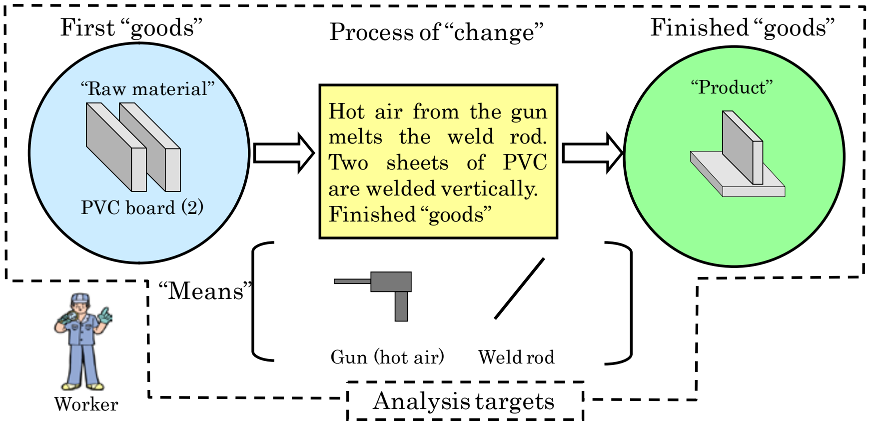


Fig. 3 Goods-Change Analysis Results

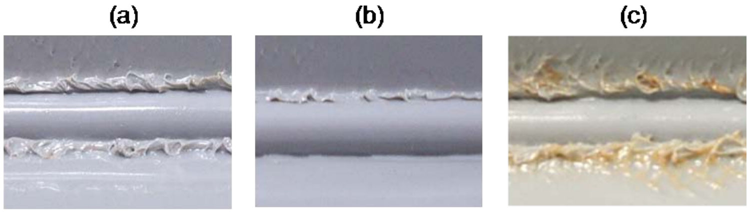
Step 1-2: Clarifying the work conditions and targets

In PVC welding, the “first goods” are PVC boards, and the “means” are the weld rod and gun. The types of “first goods” and “means” used at the factory include:

- PVC board : gray, high-temp, clear, nolyl
- Weld rod : 3S, 3W, 2S, red, white, black, clear
- Gun : fixed type, portable

The targets include the PVC board (gray), weld rod (3S), and gun (fixed type). All three are used to produce core products.

Step 1-3: Clarifying differences in quality



Conforming item Poor contact Burnt defective

Fig.4 Conforming Item and Defectives

The quality of PVC welding can be determined visually to some degree. As shown in Fig. 4-(a), both sides of weld rod show narrow irregularities (“burrs”) on conforming items.If the weld rod and PVC board fail to fuse together, there will be a gap between the PVC board and weld rod (“poor contact”). Poor contact causes leakage and poor strength. As shown in Fig. 4-(b), the burr is small in poor-contact products. On the contrary, if the weld rod and PVC board fuse together too closely, the welding point is burnt (“burnt defective”). The burr shown in Fig. 4-(c) is burnt and wider than the burr of the conforming item. The width of welded spot, including the burr, is distributed, as shown in Fig. 5 (width of the welded spot). The welded spot of the conforming item has a width of 3.84～4.57 mm (average width of conforming item±2σ). Items with widths narrower than 3.84 mm are poor contact items. Items with widths of 4.57 mm or more are burnt defectives.

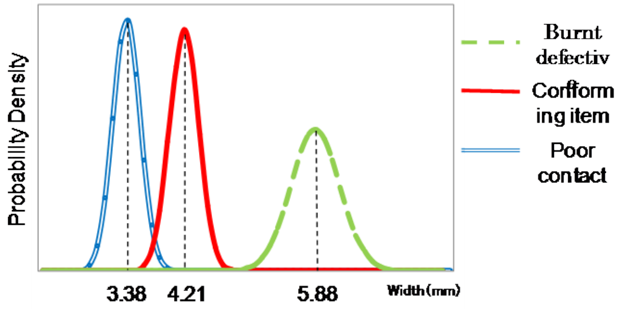


Fig.5 Width of the Welded Spot

Step 2: Extracting skill

Step 2-1: Extracting variation factors by worker

The conditions of contact between the "means" (tools) and "first goods" include the angle of the weld rod, angle of the gun, and gap between weld rod and PVC board (press of weld rod). The stimulation applied to the "first goods" by the "means" is determined by the heating duration and the distance between the gun and welded spot.

Angle of the weld rod

One end of the weld rod is welded to the PCV board and the other end is held by hand. If the weld rod slants in the direction of travel, the gun collides with the weld rod. Therefore, the weld rod should be slanted away from the direction of travel. But the angle of the weld rod at the welded spot is always 90˚ because the weld rod is slanted in the counter-direction of travel with its one end welded. Consequently, the angle of weld rod is excluded from the variation factors.

Angle of the gun

If the angle of the gun is inappropriate, too much hot air will blow onto the weld rod or PVC board. This will result in an irregularly welded spot and a poor contact product. Therefore, the angle of the gun is one of the variation factors.

Pressing the weld rod

The weld rod should always be kept in contact with the PVC board. If contact is interrupted, the welded spot will become irregular and no burr will be formed. This, again, results in a poor contact product. The weld rod should be pressed to the welded spot with as constant a strength as possible. The technique for pressing the weld rod is included among the variation factors.

Heating duration and distance of the gun

The magnitude of stimulus is determined by the heating duration and the distance from the welded spot to the tip of the gun. At the target factory, the standard time for PVC welding is set at 10 cm/min. The length of one welding spot is approximately 1 cm. The welder needs to process one spot within six seconds. A skilled welder welds fast enough to meet this condition. The heating duration is therefore considered to be six seconds, and is not included among the variation factors. The distance of the gun is included among the variation factors.

As just explained, the variation factors of the target task include the angle and distance of the gun and the technique for pressing the weld rod.

Step 2-2 Setting the hypothesis

Causes of poor contact may include:

1. The gun is too distant to properly melt the PVC (strength of stimulus).
2. Hot air is applied unevenly to the weld rod and PVC board, resulting in irregular welding (status).
3. A gap between the weld rod and PVC board causes an irregular welding spot (status).

We can list one possible cause for a burnt defective:

1. The gun is too near and excessive heat burns the PVC in welding (strength of stimulus).

Step 2-3: Verifying the hypothesis and determining an appropriate range of variation factors

Angle of the gun

The angle of gun was set from 10 to 80˚ (8 patterns, by 10˚ step). The distance of the gun for skilled welders was set at 10 mm. The heating duration was fixed at 6 seconds.

As a result, poor contact occurred at gun angles of 30˚ or less and 80˚. Therefore, we set the allowable range as 40 to 70˚. The gun angle for skilled welders was 70˚. This is the highest limit in the allowable range. Skilled welders work at the maximum value without making mistakes. By maintaining a large angle, they have an open line of view to the welding spot. But if the angle widens even a little, poor contact results. During the welding, welders look at the gun from directly above. Therefore, the gun angle cannot be checked visually during the welding. Thus, measurement of the gun angle is very difficult and not an appropriate task for unskilled persons. The appropriate range was set at 50 to 60˚.

Distance of the gun

The experiment was performed with a heating duration fixed at 6 seconds. The distance from the welding spot to the tip of the gun was in a range from 5 to 20 mm (4 patterns, 5 mm step). The gun angle was fixed at 60˚ (appropriate angle). As a result, 5 mm caused burnt defectives and 20 mm caused poor contact. Consequently, the appropriate distance was set in a range from 10 to 15 mm. The distance used by skilled welders was 10 mm.

Pressing the weld rod

The pressing force of the weld rod was distributed from 3.93 to 12.75 N. Even with a minimum force of 3.93 N, no gaps between the PVC board and weld rod resulted. The welding spot becomes irregular unless the PVC board stays in contact with the weld rod. No burrs are generated and poor contact occurs. Therefore, the weld rod should be pressed against the welding spot with as constant a pressure as possible. When holding again the weld rod, the pressure applied by the skilled welder differed by 3.45N. Meanwhile, the pressure applied by the unskilled welder differed by 4.63N. It was difficult to replicate these movements experimentally. Therefore, the angle and distance of the gun were fixed. We had both skilled and unskilled welders perform the work. We found, as a result, that poor contact occurred when the unskilled welder re-held the weld rod. Next, we researched the changes in force when the poor contact occurred. If force suddenly changed by 5.89N or more when re-holding the weld rod, gaps were generated at the welding spot and poor contact products resulted. The force applied to the weld rod was weakened rapidly, and the reaction of the weld rod in response to the applied stress resulted in the formation of a gap between the PVC board and rod. On this basis, we determined that the appropriate change in force when re-holding weld rod less than is 5.89N.

Step 3: Designing the training system

Step 3-1: Selecting the training facility

The force applied to the weld rod was measured by an electronic scale connected to a PC. The weight measured by the electronic scale was automatically transferred to Microsoft Excel once per second. Based on the data, the force was expressed by color using an application we developed earlier. A video camera was connected to a monitor to display the front of the weld rod and gun. For training purposes, a plastic transparent sheet displaying the appropriate gun angle and distance was affixed to the monitor. By viewing the monitor and plastic sheet, the trainees could check the appropriate range visually as they welded.

Step 3-2: Designing the training system

We developed a training system based on the results up to Step 2-3. The training system consists of knowledge education in the cognitive phase and action training in the associative phase (the action training is repeated in autonomous phase). For the knowledge education in the cognitive phase, we prepared a Microsoft PowerPoint presentation with a description of the relationship between the products manufactured at the target factory and PVC welding (a very important point for PVC welding). This provided trainees a resource to learn by themselves. We adopted the divided learning method for the training of the task procedures in the associative phase. The divided learning method consists of three steps:

- Training step 1: Moving the gun in the right hand
- Training step 2: Pressing the weld rod in the left hand
- Training step 3: Moving both hands

Training step 1: Angle and distance of the gun in the right hand

A trainee learns how to move the gun in his or her right hand. The trainee practices the movement of the gun while maintaining a gun angle of 50 to 60˚ and a gun distance of 10 to 15 mm.

Procedures for training step 1:

1. Hold the gun.
2. Move the gun while maintaining a gun angle of 50 to 60˚ and gun distance of 10 to 15 mm. When moving, adjust the gun angle and distance to fit the angle and distance printed on the training sheet affixed to the monitor.
3. Once accustomed to action 2, move the gun without looking at the screen. Next, ask another person to judge whether you are moving the gun correctly. If you can move the gun correctly without looking at the screen, complete training step 1 and proceed to training step 2.

Training step 2: Pressing the weld rod in the left hand

In training step 2, the trainee adjusts the force difference between before and after re-holding the weld rod to 5.89N or less (obtained from experiment), in order to keep the pressure of the weld rod stable. When the Excel cell turns blue, the trainee is performing the operation normally. If the cell is displayed in red, there is a difference in force of 5.89N or more in any one-second period. The trainee can judge instantly. If something is wrong, the trainee can identify the cause based on the positions of the colored cells after training.

Procedures for training step 2:

1. Hold a weld rod.
2. Slide the weld rod on the PVC board affixed to the top of the electronic scale.
3. Slide the weld rod on the PVC board affixed to the electronic scale until the Excel cell lights up blue stably. Slide the weld rod while checking PC screen by yourself.
4. Once accustomed to action 3, slide the weld rod without looking at the screen. Ask a third person to check whether you can press the weld rod correctly. If you can press the weld rod correctly without looking at the screen, complete training step 2 and proceed to training step 3.

Training step 3: Moving both hands

Finally, the trainee practices moving the gun in his or her right hand and pressing the weld rod in his or her left hand.

Procedures for training step 3:

1. Hold the gun in your right hand and the weld rod in your left hand. Perform the action executed in training steps 1 and 2 with both hands at the same time. While moving the gun and weld rod, watch the screen to confirm that the angle of the gun, distance of the gun, and force of the weld rod are all appropriate.

Once accustomed to action 1, move the gun and weld rod without looking at the screen. Ask a third person to check whether you are moving the gun correctly and pressing the weld rod correctly. If you can do so correctly without ever looking at the screen completely, complete training step 3.

5. VERIFICATION EXPERIMENT

5-1. Experiment Plan

We conducted a verification experiment with 18 subjects (male, age: 21-23) to verify the effects of our training system. The subjects were divided into group A (trained by skilled welders at the target factory) and group B (trained by our training system). We based the grouping on evaluations of the welding work before the training to ensure that each group had about the same welding ability in the pre-training condition. Welding work by each group after the training was evaluated.

5-2. Method For Evaluating The Effects Of The Training Systems

Weld spots were rated on a scale of one to ten based on the quality inspection of the welding spot widths at the target factory. Three welding spots were evaluated per subject. The lowest rate was adopted.

5-3. Experimental Results

Fig. 6 shows the averages and standard deviations of ratings for groups A and B. As this chart shows, the averages for groups A and B were 5.0 and 6.2, respectively.

To verify the difference in the rates of welding spot for groups A and B, we also tested the difference in the averages. The ratings of the groups were significantly different (significance level of 1%). Group B welded significantly better than group A. Thus, the effectiveness of our training system was verified.

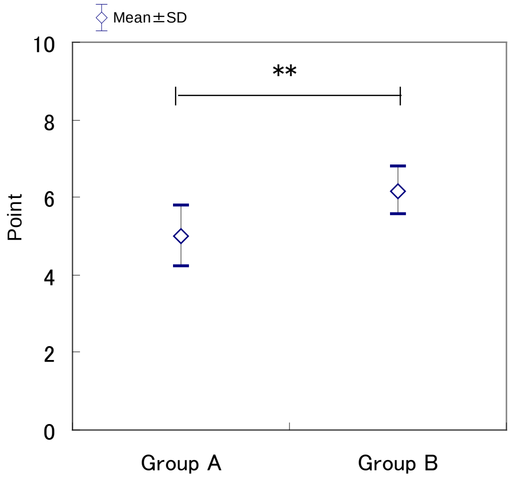


Fig. 6 Results of training

6. CONCLUSIONS

This study proposes a practical process for extracting skills and designing a system for the training of sensory motor skills in manufacturing. The proposed process can be roughly divided into a description of a task, extraction of skill, and the design of a training consisting of seven steps in total. To verify the practical utility of our skill extraction method and training system design, we applied a skill extraction and training design process (i.e., handing down skills in PVC board welding from one generation to another) for Company O, a manufacturer of photo-developing machines, etc., and developed a training system. Eighteen subjects were tested to verify the effect of our training system. As a result, we verified the effectiveness of the training system developed through the process proposed by this study. In the future we hope to apply the proposed process to production fields in order to support manufacturers with their efforts to hand down manufacturing skills from generation to generation.

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