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Research Article

Design of a New Virtual Interaction Based PLC Training Using Virtual Sensors and Actuators: System and Its Application

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This paper proposes a new virtual interaction based programmable logic controller (PLC) training system using virtual sensors and actuators. The proposed system is composed of four components including virtual sensors (for interacting between user and input devices), virtual actuators (for manipulating and controlling device or equipment), virtual PLC (for programming and generating command), and virtual networks (for interfacing the interactions and transferring the data between all the components). The proposed system is applied to a real training program of the university's training center to examine the applicability and feasibility, and the results are analyzed and discussed.

1. Introduction

Owing to rapid developments in manufacturing industry's automated production facilities, top-edge equipment required on programmable logic controller (PLC) training is becoming more expensive with shorter replacement cycles. Moreover, due to the nature of latest and expensive equipment, mishandling and/or malfunctioning can result in substantial loss, including personal injuries, equipment damages, manufacturing of defect products, and interruption of the production process. Therefore, there is a strong demand for effective training that can provide trainees with quick and safe ways to adapt to the latest equipment. Republic of Korea has some of world leading companies in manufacturing industry such as automobile, semiconductor, display, mobile phone, and shipbuilding. The most important group of technical experts in cutting-edge manufacturing industries such as Samsung Electronics and Hyundai Motor Company are PLC automation professionals. Due to the nature of manufacturing industries, PLC automation training requires very expensive latest equipment. Since inadequate manipulation or programming errors by trainees can damage the equipment and there are difficulties involved in continuously replacing and providing the latest and expensive equipment, thus the ones are not used at all or provided only with limited use for the training. Therefore, most trainees listen to explanations rather than hands-on manipulation, which places limitations compared to actually being able to operate the equipment.

In accordance with the increasing importance of training on latest and expensive equipment spurred by the rapid developments in the manufacturing industry, this paper proposes a new virtual interaction based PLC training system using virtual sensors and actuators. Based on the virtual sensors and actuators, the proposed system provides PLC trainees with a virtual interaction that is identical to actually handling various types of equipment. In order to allow PLC trainees to handle virtual equipment that models actual high-price equipment such as elevators and conveyors, providing the effects of engaging in hands-on training, the proposed system is composed of three components including virtual sensor (for interacting between user and input devices), virtual actuator (for manipulating and controlling device or equipment), and virtual PLC (for programming and generating command). For instance, virtual sensor components sense trainee's wiring and device inputs, and once it is determined by virtual PLC whether or not they are accurate, the virtual PLC generates command for the correction action, and thus virtual actuator (output device) simulates the corresponding action, whereas incorrect one produces a simulation result of faulty action. There has been hardly any research and development on the proposed training system, especially using virtual interaction based on virtual sensors and actuators for PLC automation equipment. The proposed system is applied to a real training program of the university's training center linked academia and industry to examine the applicability and feasibility, and the results are analyzed and discussed.

2. Proposed Interaction Based PLC Training System

This section describes the PLC training system developed to provide virtual interaction using virtual sensors and actuators, especially on the latest and expensive equipment to reflect the needs of the industry. That is, the proposed virtual interaction based PLC training system is designed and developed to provide training activities in a controlled virtual environment, for transferring skills involved in building and operating the latest and expensive equipment based on PLC. The quality of the virtual interaction based PLC training system depends not only on the similarity between the hardware environment and the practical environment, but also on the verisimilitude degree of reaction and the reasonability of training subjects [1, 2]. System subjects are not required to cover the entire content of the program, but the content of the subjects shall be consistent with training contents specified in the program.

2.1. System Overview. The proposed system mainly consists of four components as the following:

(i) virtual sensor;
(ii) virtual PLC;
(iii) virtual actuator;
(iv) virtual network.

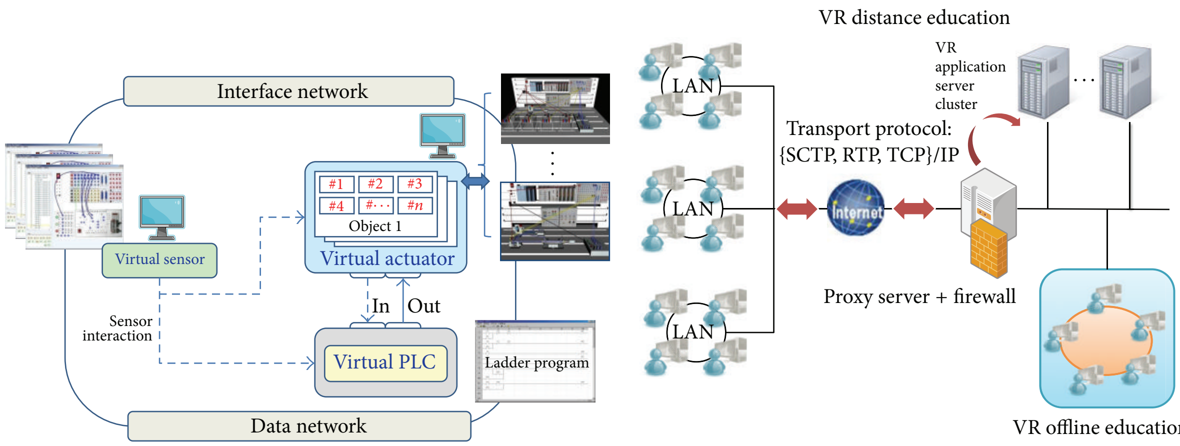
Figure 1 shows the overall block diagram of the proposed interaction based PLC training system and training networks using it.

2.2. Virtual Sensor. The virtual sensor has two units: the object-based sensor input unit and the virtual composer unit. The object-based sensor input unit has role in sensing and processing the sensor input and the virtual composer unit has a role in receiving user's (trainee's) arbitrary wiring input. This virtual composer unit receives the initial input from the user (trainee) and supports arbitrary wiring. Whereas most input wiring units accept only preassigned (correct) wiring, the virtual composer unit in the proposed system accepts any wiring configuration (even incorrect wiring) from the user. The trainee can also study materials related to a specific session and practice wiring using this virtual composer shown in Figure 2(a). In order to cover various user's arbitrary wiring input, Scene Access Interface (SAI) [3, 4] is used for the implementation. Once the trainees complete wiring, the device I/O code table as shown in Figure 2(b) is generated internally corresponding to the wiring configuration, which is delivered to virtual PLC component.

2.3. Virtual PLC. The virtual PLC replaces the actual PLC unit. To substitute the real one, the virtual PLC should have role in determining (inferring) the action and generating the command corresponding to the input as the real one does. The virtual PLC is designed based on the same structure of real PLC as it should mimic the real one. Figure 3(a) shows the structure of the virtual PCL. Next, we need a virtual ladder tool that provides a usage environment including writing PLC ladder programs similar to the actual ladder environment while satisfying the dedicated ladder tool for virtual PLC. Based on this requirement, we developed a ladder tool for programming ladders that can be loaded into virtual PLC. Figure 3(b) shows the command flowchart in the virtual PCL. Ladder diagram (LD) into instruction list (IL) can be transformed based on [5]. Specifications of the functions supported by the ladder tool are based on the international standard IEC61131-3. Figure 3(c) shows the generic virtual ladder tool implemented by this study. The virtual ladder tool supports some kinds of PLCs including Mitsubishi and LS but does not support all the kinds of PLCs.

2.4. Virtual Actuator. This virtual actuator has roles in generating three-dimensional (3D) virtual environment of the resultant output and simulating what is built. 3D virtual environment visualization including virtual equipments corresponding to the trainee's wiring input configuration (done by the virtual composer component) provides the trainee with reality and immersion as if he/she were in real factory automation environment, which may enhance the training effectiveness. Simulation produced by the virtual output component allows the trainee to experience the results corresponding to his wiring and programming to operate the equipment. Especially, the trainee can verify whether or not the equipment (or system) is integrated and operated correctly by the simulation too. Accurate wiring configuration simulates correct action, whereas incorrect wiring produces a simulation result of faulty action. For instance, virtual sensors sense trainee's wiring configuration, and once it is determined by virtual PLC whether or not it is accurate, the virtual PLC generates the resultant command, and thus virtual actuator (output equipment) simulates the corresponding action. If either the wiring or programming is incorrect, the system may give a simulation result of faulty action. All the virtual equipments are modeled and implemented based on X3D, the Web3D which is international standard graphic format [6–10]. Figure 4 shows some training examples manipulated and controlled by the virtual actuator.

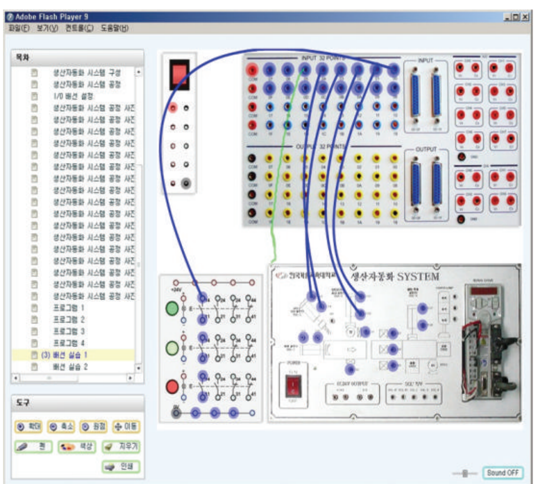
2.5. Virtual Network. This network has two units: the data network and the interface network. The interface network has role in interacting the data and command between the other



(a) Interaction based PLC training system

(b) Training networks using the proposed system

Figure 1: The overall block diagram of the proposed system.



(a) A screen shot of wiring practice using the virtual composer

		Input	Output	COMR	COMB
Power	POW			R1, R2, R3, R4, R5	B1, B2, B3, B4, B5
PLC In/Out 포트	PLC	B00, B01, B02, B03, B04, B05, B06, B07, B08, B09, B0A, B0B, B0C, B0D, B0E, B0F,	Y00, Y01, Y02, Y03, Y04, Y05, Y06, Y07, Y08, Y09, Y0A, Y0B, Y0C, Y0D, Y0E, Y0F, Y10, Y11, Y12, Y13, Y14, Y15, Y16, Y17, Y18, Y19, Y1A, Y1B, Y1C, Y1D, Y1E, Y1F	R1, R2, R3, R4	B1, B2, B3, B4
스위치유니트	SWI		A : 14, 24, 34, 44, 11, 21, 31, 41 B : 14, 24, 34, 44, 11, 21, 31, 41 C : 14, 24, 34, 44, 11, 21, 31, 41 G01, G02, G03, G04 (Bottom) (X1 과 GX는 임의 연결 성립)	R1, R2, R3, R4, R5 (쓰이지는 않음)	B1
Air분배기	AIR				
양솔레노이드	DSO	I1, I2		R1	
편솔레노이드	SSO	I1		R1	
복동 실린더	DSY				
모터	MOT	I1 (Whight)		R1	
생산화 SYSTEM	SYS	(SOL-2) M2 (TOWER LAMP) R, Y, G (SOL' V/V) S0, S1, S2, S3, S4	(SOL-1) CS1, CS2 (SOL-2) C93, C94 (SOL-3) C95, C96 (SOL-4) C97, C98 (기타 센서) S1, S2, S3, S4, S5		

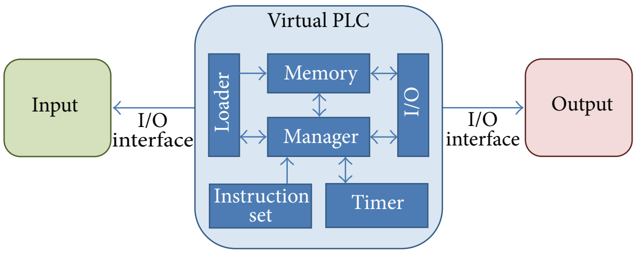
(b) An example of the internal device I/O code generated corresponding to the wiring

Figure 2: The virtual composer unit of virtual sensor.

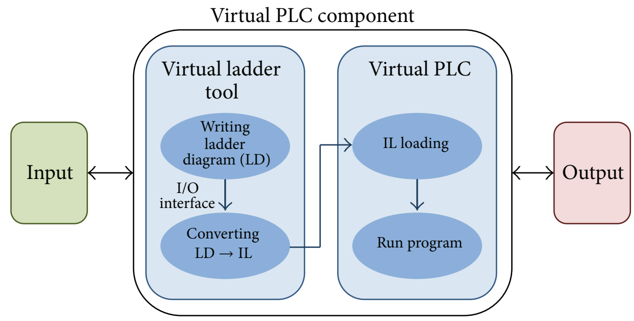
three components (virtual sensor, virtual actuator, and virtual PLC). The data network has role in transferring the data of the three components (virtual sensor, virtual actuator, and virtual PLC). In particular, this has role in networking between all the systems of the trainees as shown in Figure 1(b).

3. Application into Real Training Program and Results

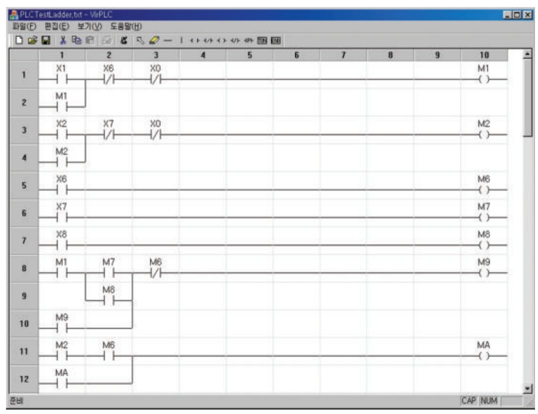
3.1. Experiments. In this section, the proposed virtual interaction based PLC training introduced in Section 2 is applied to a course entitled "GLOFA-PLC control class" [11] for training a junior-level of industrial manufacturing engineers, and it is reviewed how effective the proposed system for training is. The training session involved controlling a virtual conveyor implemented in a virtual environment to simulate a high-level, large-scale, and expensive machine that is difficult for trainees to operate for training purposes [12, 13]. The practice course was conducted in a sequence identical to practicing on a real one as shown in Figure 5(a). Figure 5(b) shows the snapshot of the real training course using the proposed system (Figure 1). Figure 5(c) shows the overall measurement process to examine the effectiveness of the proposed training system. To provide objective evaluation with the experiment, the course has been measured by two tests and a survey (T1, T2, and S1) as shown in Figure 6. Here T1 shows a test taken before the course on the first day (it is called pretest in the paper), T2 is a test taken after the course on the last day (this is like a final examination, and it is called posttest in the paper), and S1 is the Likert-scaled questionnaire taken at the end of the course on the last day. 180 trainees participated in the experiment, including professional training school teachers, industrial high school



(a) Structure of the virtual PLC



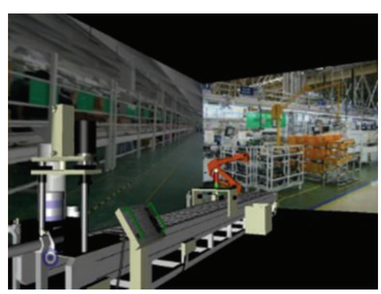
(b) Command interaction flow between input and output by the virtual PLC



(c) An example of the generic virtual tool implemented for the virtual PLC

Figure 3: Virtual PLC.

(a) Servo motors control



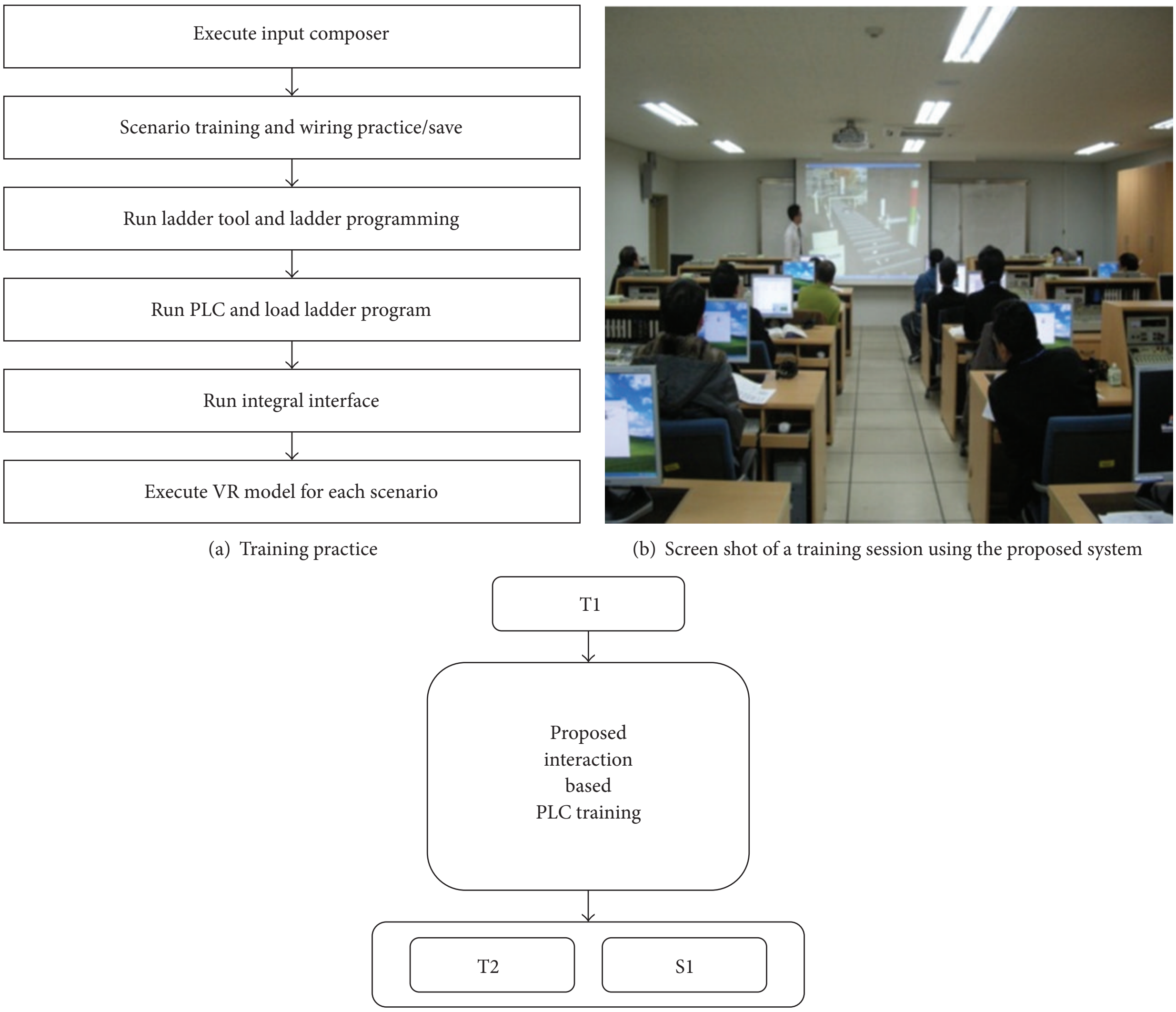
(b) Conveyor control

(c) Elevator control

Figure 4: Some training examples manipulated and controlled by the virtual actuator.

teachers, and large companies' in-house instructors. After being introduced to the proposed virtual interaction based PLC training system, the participants were trained in the conveyor control practice session. For objective quantitative evaluation, two tests are given as shown in Figure 5(c). At the first class on the first day of the course, students are asked to take a test (T1) to see the initial status of them including their levels of knowledge and skill of the students before they learn. Similarly, at the last class on the last day of the course, students are asked to take the other test (T2, and this is similar to a final examination) to see how much their levels of knowledge and skill are improved when they complete the course. The tests used for the quantitative evaluation are given in Tables 1 and 2, respectively. For qualitative evaluation, students have a survey (S1) as shown in Figure 5(c); students are asked how much they are satisfied with the VT to replace the PLC conveyor, a high-expensive cutting-edge equipment, which thus is difficult to have hands-on practice. The survey questions used for the qualitative evaluation are given in Table 3.

3.2. Discussions: Analysis of the Results Obtained Using the Proposed System. 180 of participants anonymously completed both tests and surveys at the beginning and end of the course, respectively. Results measured from total 9 classes of the course using the previously described tests and surveys were analyzed, and some were given as representative



(a) Training practice

(b) Screen shot of a training session using the proposed system

(c) Measurement process using both tests and survey

Figure 5: Overview of experimental setup to a real course.

examples. Those representative examples were provided to illustrate what and how the students learned via the proposed virtual interaction (VI) based PLC training system.

(i) Qualitative Evaluation Results and Discussion. Experiences with Likert-scale five scoring levels ((5) highly satisfied, (4) satisfied, (3) average, (2) unsatisfied, and (1) Highly unsatisfied; or (5) highly positive, (4) positive, (3) average, (2) negative, and (1) highly negative) were employed to assess students' understanding of the specific equipment or process which they want to learn. The students' satisfaction and experiences with the proposed VI based PLC training system were assessed with a Likert-scaled survey questionnaire (S1). Upon completion of the proposed VI based PLC training (course), they were asked to respond to a survey consisting of 10 questions, as shown in Table 5, and rate the level of satisfaction according to the Likert scale. These numerical values were used to calculate the mean value and the standard deviation of students' responses to each question. Table 4 shows the statistical results of students' responses to five Likert-scaled questions regarding students' satisfaction and experiences with the course using the proposed VI based PLC training system. Students' responses to Question 1 in Table 3 indicate that 85% of students were "highly satisfied" or "satisfied" with the proposed virtual interaction (VI) based PLC training system. From this result, it is confirmed that the use of the VI increased student engagement in class. Students' responses regarding the effectiveness of training content by the VI based PLC training system (Questions 2, 3, and 4) indicate that 88% of students "agreed" or "very agreed" that the VI was helpful for understanding the material covered in the course, effective compared to an actual PLC, and beneficial to practice controlling the conveyor.

The students were asked about the adequacy of amount of training provided by the VI based PLC training system (Question 5 in Table 3). Students' responses to this question

Table 1: Pre-test questions used for evaluation on the training program using the proposed system.

Number	Questions	Score (10 if Yes, 0 if No)
1	Have you received training on sequence or pneumatic system? (Yes/No)	
2	Have you used a PLC system? (Yes/No, If Yes, please indicate the system type.	
3	Can you distinguish the difference between serial and parallel communication? (Yes/No)	
4	Can you convert decimal numbers into binary and hexadecimal numbers? (Yes/No)	
5	Have you used PLC-to-PLC communication? (Yes/No)	
6	Can you use the touch screen (GOT1000)? (Yes/No)	
7	Have you performed position control using PLC? (Yes/No)	
8	Have you performed servo control using PLC? (Yes/No)	
9	Have you performed elevator control using PLC? (Yes/No)	
10	Have you performed conveyor control using PLC? (Yes/No)	

Table 2: Post-test (final test) questions used for evaluation on the training program using the proposed system.

Number	Questions	Score (10 if Yes, 0 if No)
1	Have you received training on sequence or pneumatic system? (Yes/No)	
2	Have you used a PLC system? (Yes/No, If Yes, please indicate the system type.	
3	Can you distinguish the difference between serial and parallel communication? (Yes/No)	
4	Can you convert decimal numbers into binary and hexadecimal numbers? (Yes/No)	
5	Can you use PLC-to-PLC communication? (Yes/No)	
6	Can you use the touch screen (GOT1000)? (Yes/No)	
7	Can you perform position control using PLC? (Yes/No)	
8	Can you perform servo control using PLC? (Yes/No)	
9	Can you perform elevator control using PLC? (Yes/No)	
10	Can you perform conveyor control using PLC? (Yes/No)	

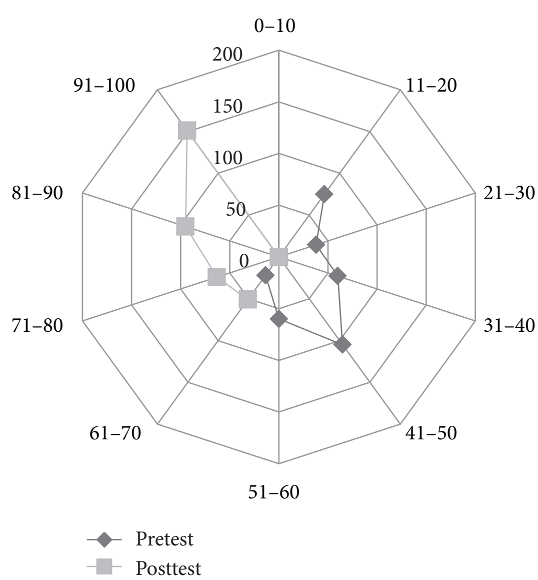


Figure 6: Test results comparison between before training (T1) and after training (T2).

indicate that about half of students (49%) were "highly satisfied" or "satisfied" with it, and they wanted to have the amount of VI abundant quantitatively as well as qualitatively. Also, 71% and 78% of students stated that they are "highly satisfied" or "satisfied" with its reality and effectiveness in replacing actual equipment using the VI based PLC training system (Questions 6 and 9 in Table 3), which even though the results were rated as "positive," more realism is needed for the VI based class. Regarding the user-friendliness, students' responses to this question indicate that about half of students (49%) were "highly satisfied" or "satisfied" with it, and they wanted to upgrade the user-friendliness.

Overall average of students' responses to self-evaluation (which is the average of Questions 3 and 4 in Table 3) was 4.14 (82.8%), and this indicates that most of students rated their participation and enthusiasm to the course as "positive." Moreover, 78% of students concerning Question 10 in Table 4 stated that they were "highly satisfied" or "satisfied" with the applicability of the training program based on the proposed system. The obtained assessment showed that more than 80% of students responded that the overall experience with their VI based PLC training system was "positive" or "highly positive," which means they "agreed" or "very agreed" that the training by the VI based course enhanced their skills and knowledge. In a questionnaire, most of the participants stated that it was very easy to watch the conveyor features on the screen; most of the students positively responded to a question that asked how useful the VI based PLC training system is to learn difficult PLC-based conveyor process in the area of automated production facilities in manufacturing engineering. The Likert survey also revealed that, as a teaching method, the industrial workers (students) welcomed the proposed VI-based PLC training course. In addition, these

Table 3: Questionnaire used for evaluation on the training program using the proposed system.

Number	Category	Level of satisfaction				
		Highly satisfied	Satisfied	Average	Unsatisfied	Highly unsatisfied
1	Learning engagement and motivation					
2	(Effectiveness of training content I) Was the virtual system helpful for understanding the materials covered in the session?					
3	(Effectiveness of training content II) Was the virtual PLC system effective compared to an actual PLC?					
4	(Effectiveness of training content III) Was it beneficial to practice controlling the conveyor using the virtual PLC system and attempt things that would not be feasible with an actual PLC?					
5	(Adequacy of amount of training) Was the amount of training you received using the virtual conveyor system adequate?					
6	(Reality of training content) Do you think practicing with the virtual system will be helpful for your field operation?					
7	(Distinction from other training materials) Was the virtual system more helpful than other training materials for understanding the training session?					
8	(User-friendliness) Was the virtual system easy and convenient to operate?					
9	(Effectiveness in replacing actual equipment) Do you think the virtual system can replace the actual equipment for training purposes?					
10	(Applicability in technical training) Do you think it would be beneficial to apply the virtual PLC system to various technical training programs?					

Table 4: The summary of statistical results obtained from the survey (S1).

Category	Survey question number	Highly satisfied (%)	Satisfied (%)	Neutral (%)	Unsatisfied (%)	Highly unsatisfied (%)	Mean
	1	21	64	7	7	0	4
	2	14	71	14	0	0	4
	3	14	71	7	7	0	3.9
	4	7	71	14	7	0	3.8
	5	7	42	29	14	7	3.3
	6	7	64	21	0	7	3.6
	7	14	42	29	14	0	3.6
	8	7	42	29	14	7	3.2
	9	14	64	7	14	0	3.8
	10	21	57	21	0	0	4

results mean that the use of the VI based PLC training system allowed them to apply the course concepts and theories to real industrial (or new) situations. This allowed the students to develop analytical skills and their abilities to interpret an issue from multiple perspectives.

(ii) Quantitative Evaluation Results and Discussion. Next, it was investigated how the proposed system improves the students' knowledge and skills. (Especially, it was focused to review how the proposed system improves the skills which they wanted to learn on the specific equipment because the knowledge required can be learned from the other learning.) Two tests (T1 and T2 in Figure 5) were given for the evaluation, and Figure 6 and Table 5 show the test results comparison between T1 and T2. From the results comparison, we can see that the students' levels of skill were greatly improved, especially students in top rank (91%–100%) were increased up to 7 times.

It was confirmed that the proposed interaction-based training system has the following uniqueness and strength

Table 5: Summary of test results (T1 and T2).

Score	T1	T2
0–10		0
11–20	34	0
21–30	20	
31–40	33	
41–50	52	
51–60	30	
61–70	11	25
71–80		32
81–90		48
91–100		75
Total	180	180

compared to the VI based PLC training system, and the training course could focus on student learning in a PLC course in which students developed their own PLC program for controlling conveyor, the latest and expensive equipment which is difficult to learn. With the VI based PLC training system, the students are not simply just users but, more importantly, they can be the process developers and designers. The VI based PLC training system, which aims at providing an efficient transfer of the skills, involved in procedural tasks. It is based on the paradigm of learning by doing, which represents a form of knowledge called Enactive Knowledge [14]. The proposed course can support trainees to practice procedural task for the latest and expensive equipment in real time (including component setup, wiring, program, control, and operation).

4. Conclusions

In this paper, a new virtual interaction based PLC training system using virtual sensor and actuator was proposed. To provide the hands-on training effects, the proposed system introduced and used virtual sensor (for sensing both user and device inputs), virtual actuator (for actuating/controlling device or equipment), and virtual PLC (for generating command) and was finally implemented with virtual networks (for interfacing the interactions and transferring the data between all the components). Based on the virtual components, the proposed system could allow trainees to operate virtual equipment that models actual (expensive and the latest) equipment such as FA conveyors as if they were moving toward the equipments and manipulate it. As well, the proposed system could offer a training environment without concerns of safety and equipment damage caused from malfunctioning and program errors as it could be conducted in virtual manner. The proposed system was applied into a real training class of our university's training center to examine the applicability and feasibility, and the results analyzed quantitatively as well as qualitatively confirmed that the system can be applicable into real training programs. The assessment showed that more than 80% of students responded that the overall experience with the proposed system was "satisfied" or "highly satisfied," showing they "agreed" or "very agreed" that their training enhanced their skills and knowledge. Therefore, if we could improve some aspects, such as user-friendliness and interface, and expand functionality, the system can be more applicable in virtual PLC training programs.

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