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Development of a Direct Teaching System for a Cooperative Cell-Production Robot Considering Safety and Operability

Seonghee Jeong, Yoshihiro Nakabo, Takuya Ogure and Yoji Yamada

Abstract— **A direct teaching system emphasizing safety and operability for SP02, an upper-body humanoid that cooperates with a human in a cell-production workspace has been described. The system has a direct teaching device, which enables an operator to teach a multi-D.O.F manipulator at comfortable posture despite large changes in the pose of an end-effector. The double-checked safety-related part(SRP/CS) introducing a safety module satisfies the safety performance defined in the international safety standard. To make the teaching easier to perform, impedance parameters in a variable impedance control are set through several direct teaching experiments. Through a simple direct teaching experiment, the safety performance of the SRP/CS and the teaching performance of the direct teaching system was successfully confirmed.**

Fig. 1. Cooperative work of SP-02 with a human worker in a cell workspace

I. INTRODUCTION

In the manufacturing field of IT devices and home appliances, the cell-production method, where one or multiple workers carry out an entire manufacturing process namely: processing, assembly, and inspection are becoming increasingly common. The cell-production method is capable of adapting to a large variety of small-volume production techniques and fluctuations in demand because few types of equipments are required for each cell and changes to the setup are not complicated.

In recent cell-production workspaces, however, as the needs of society change, the miniaturization of parts and modularization of assembly processing has increased, and hence limits to improvements in work efficiency and reductions in the quality of work have become serious problems. Several methods have been proposed to improve work efficiency and work quality by supporting a human working in a cell-production workspace physically and informatively[1][2]. However, in recent years, with a declining birthrate and aging society, there has been a shortage of highly skilled experts and an increase in training costs through frequent model changes. Moreover, a labor shortage during a period of economic growth or a reduction in workers during a recession brought about by a large fluctuation in production depending on the economic situation are also serious problems.

To cope with these problems, we have developed a small-sized upper-body cell-production robot, SP02, as shown in Fig.1, which makes it possible to flexibly rearrange workers in line with large production fluctuations in addition to improving work efficiency and quality by supporting a human worker. SP02 is aimed at taking the place of the function of a worker on a usual cell work-processing line where multiple workers cooperate on an assembly. Since it is a humanoid type robot and does not need any special external equipment, t can be easily introduced to a cell workspace where a human carrying out work. This makes it possible to easily construct a cell-production workspace resembling two human workers carrying out work cooperatively.

This paper focuses on a direct teaching system for SP02 in a cell-production workspace. The direct teaching method has the benefit of intuitive operation as compared to using a GUI or a pendant in teaching a complicated robot manipulator with a multiple degrees of freedom(D.O.F). For this reason, it has been introduced to many fields of industry to improve the efficiency of teaching tasks in particular the car industry.

In a cell-production workspace targeted in this paper, a robot basically performs cooperative work with a human worker. Thus, it is normally necessary to teach a robot frequently according to the work situation and breakdown of the work on the human side. In this case, it is important to perform teaching tasks naturally and safely when planning or modifying a work procedure and for operation recovery and re-teaching without the need for the robot to pause in its work for a long period. To realize this, it is necessary to devise a direct teaching device that enables a worker to a teaching task efficiently and smoothly without discomfort and fatigue, and a safety measure that guarantees the safety of a worker who performs a teaching task besides on a robot. To meet these requirements, we have built a direct teaching system takes into consideration safety and operability, by designing a teaching interface emphasizing the feeling of a human worker and by introducing a technique of functional safety based on an international safety standard.

S.Jeong, Y.Nakabo, T.Ogure and Y.Yamada are with Safety Intelligence Research Group, Intelligent Systems Institute, National Institute of Advanced Industrial Science and Technology, 1-1-1, Umezono, Tukuba, Japan sh.jeong@aist.go.jp

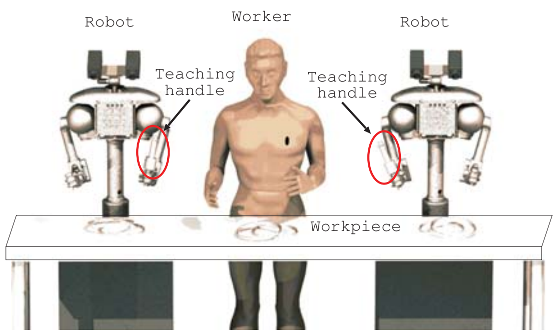


Fig. 2. Image of direct teaching in a cell-production system

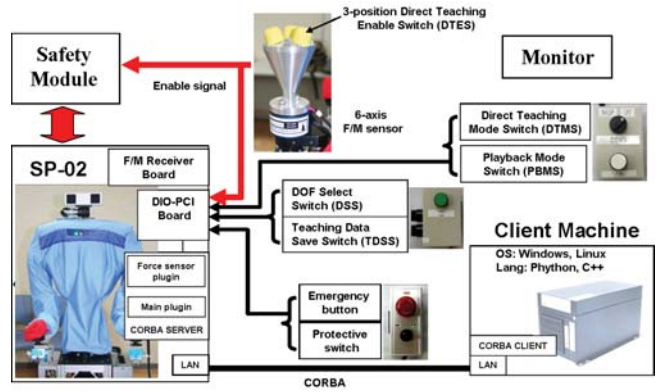


Fig. 3. System configuration of the direct teaching system of a cell-production robot SP02

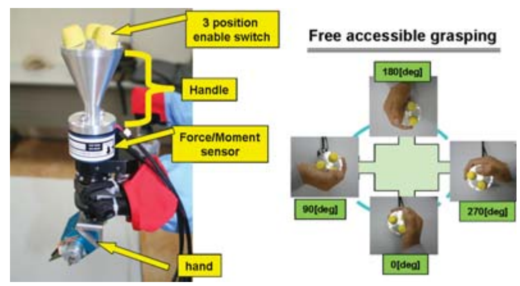


Fig. 4. Direct teaching device with a freely accessible handle and a 3-position enabling switch

In section 2, a structure of a proposed direct teaching system is described, and then a direct teaching device is described in section 3. The mechanism related to safety, and the direct teaching control, are explained in sections 4 and 5, respectively. Finally, some experimental results to evaluate the safety and operability of the proposed system are displayed in section 6.

II. Direct Teaching System

A conceptual scheme of direct teaching in a cell-production workspace is illustrated in Fig. 2. In the cell-production workspace, workers and robots are located next to each other and perform their tasks in their own workspace or common workspaces. A worker teaches a robot in accordance with his work situations.

The total configuration of the direct teaching system for SP02 is shown in Fig. 3. The system consists of the teaching target robot, SP02, a direct teaching device, various mode change switches, a client machine, a monitor, and a safety module. A brief description of each component is described as follows.

- SP02: A teaching target robot with a 6 D.O.F dual arm. A force receiver board, a digital input/output interface for mode change switches, and a direct teaching control plug-in are integrated. It performs the following motion of an end-effector based on the information obtained from the teaching force applied using a direct teaching device.
- Direct teaching device: A 3-position enable switch, a teaching handle, and 6-axis force/moment sensor are integrated. It detects the teaching force of a worker and provides it to the robot.
- Safety module: Observes the status of the robot and the enabling switch and executes various safety measures.
- Operation switch: Provides signals to select the teaching D.O.F.(DSS), saves teaching data (TDSS) and changes teaching mode (DTMS).
- Client machine: Manages a teaching and playback procedure via a CORBA interface.
- Monitor: Displays the status of the robot and teaching information.

In the following section, the direct teaching equipment, safety-related part and direct teaching control, which are the main technological components in the system, are explained in more detail.

III. Direct Teaching Device

In a direct teaching task for a robot with a multi-degree of freedom that causes a large change in the posture of its end-effector, e.g. SP02, a direct teaching device designed taking into consideration the operability of a human is required. It is important that a worker can easily access and operate the device without feeling any discomfort and perform a teaching task continuously in the case of a lengthy task without feeling excessive fatigue.

Fig. 4 shows the direct teaching device developed by considering the requirements mentioned above. The device has a handle that is shaped so that it can be gripped by a human hand, and three enabling switches for enabling a direct teaching control on top of the handle. A 6-axis force/moment sensor to detect teaching force is attached to the bottom of the handle and fixed to the end-effector. The shape of the handle is designed so that it is accessible from every direction and always produces a teaching force. Three enabling switches are located at 120 [deg] intervals, which enables a worker to press one of them even if there are large changes in the posture of the end-effector. Using this device, a worker can clasp the handle from a direction he/she wants

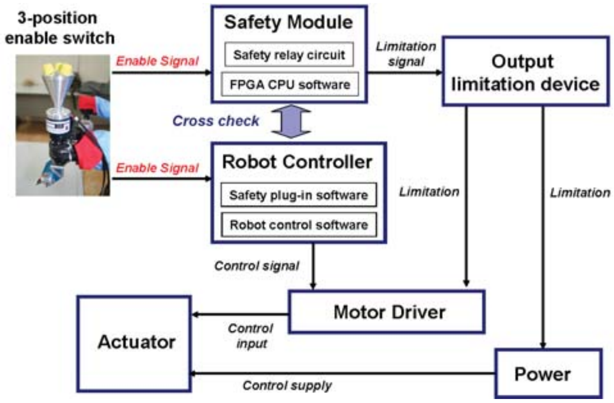


Fig. 5. Safety related part in the direct teaching system

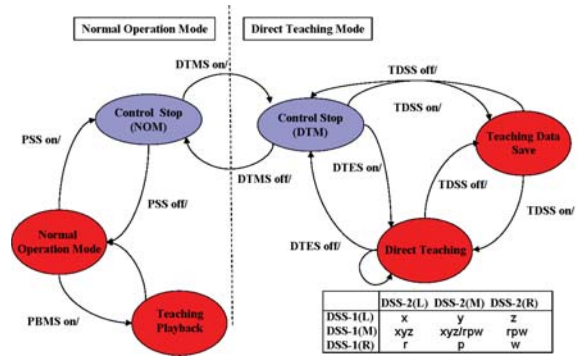


Fig. 6. Status transition diagram for a direct teaching task

to access and operate the enabling switch with a pose that does not place stress upon his/her wrist and thumb.

IV. Safety Related Part

In a direct teaching system, since a worker operates an end-effector by coming in direct contact with a robot, the safety of the worker must be the first consideration. The international safety standard of an industrial robot ISO 10218-1[3] requires the installation of a 3-position switch that three states(ON-OFF-ON) in a teaching system for a robot. Moreover the performance requirement of the safety-related part(SRP/CS) should be satisfied beyond category 3 defined in ISO 13849-1[4] unless the result of risk assessment necessitates other performance requirements. From the result of risk assessment of SP02 in a cell-production procedure[5], we have concluded that a SRP/CS of a direct teaching system should be built to specifications beyond category 3. A SRP/CS of category 3 would be designed so that a single fault in any of the parts does not lead to the loss of the safety function, and whenever reasonably practicable, the signal fault would be detected at or before the next demand upon the safety function[4]. Following these safety requirements, we have designed a SRP/CS of a direct teaching system for SP02.

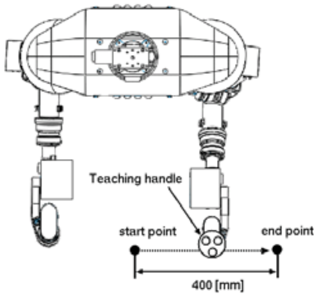
Fig. 5 shows the SRP/CS of the direct teaching system in SP02. A direct teaching enabling signal from the 3-position switch is inputted to the robot controller and the safety module simultaneously. This is a double checked system in which a control command for an actuator is not generated unless the enabling signal is confirmed in both the controller and the safety module. Thus, even if a single fault in the enabling system occurs, the safety function of the robot, an emergency stop or braking, is maintained. The enabling signal is observed during a cycle time of control, 5 [ms], so that a fault can be detected within the cycle time. Therefore, the SRP/CS on the enabling system satisfies the category 3 requirements. In the case of a harmful event when control is lost through a fault in the force/moment sensor, the safety module normally checks the robot's status and accomplishes an output limitation when there is a dangerous situation.

A teaching task is generally composed of a teaching procedure undertaken by a worker and a playback procedure performed by a robot. For switching between procedures, an operation plan should be devised that takes in to full consideration any mistakes made by the human worker. In other words, in the situation when a human is present in a robot's workspace, a playback procedure should not be executed. Fig. 6 shows the status transition diagram of the system considering the above safety condition. In the figure, the direct teaching procedure and the normal operation procedure including the playback motion are separated by a control stop mode, and automatic operation of the robot is not permitted unless the control stop mode is released. In addition to this, by locating a mode change switch outside a robot's workspace, the case of a human worker mistakenly switching to a playback procedure inside a robot's workspace can be avoided.

V. Direct Teaching Control

To accomplish a teaching task efficiently, it is important to build a direct teaching control that enables intuitive operation and has comport operation. In this paper, impedance control[6][7][8] is applied as a direct teaching control, and to achieve further improved operability, a teaching supporting mode so that a worker can freely select the degree of freedom of the end-effector to teach is introduced. Yamada[7] pointed out the importance of operational feeling in a power-assist system and proposed impedance control for the improvement of operational feeling by changing the impedance of the end-effector according to task phases.

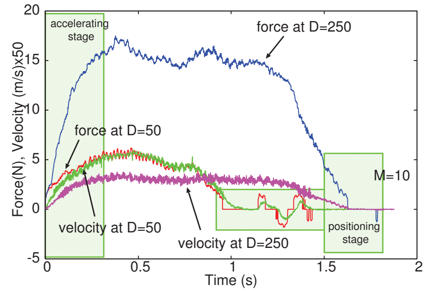
A variable impedance control method is also used in this study to improve the operability. By setting appropriate impedance parameters emphasizing the worker's operational feeling, a worker can move an end-effector intuitively and agilely to an intended direction and shift to a positioning task smoothly. The teaching support mode provides four switching modes namely individual teaching, position teaching, pose teaching, and position/pose teaching, by combining two switches, DSS-1 and DSS-2. Using the relevant mode, a worker can freely select the D.O.F of the end-effector to teach the robot according to a task condition, and thus the intention of a worker can be more exactly imparted to the



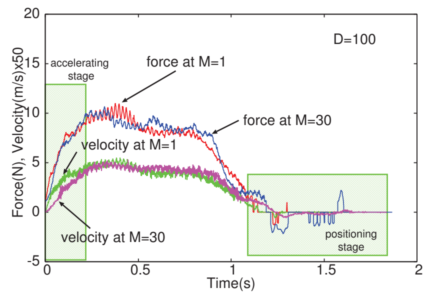
(a) Upper view

(b) Direct teaching scene

Fig. 7. Experimental setup for decision of impedance parameters



(a) M_o= 10(kg), D_o= 50, 250(Ns/m)



(b) D_o= 100(kg), M_o= 1, 30(Ns/m)

Fig. 8. Experimental result of a direct teaching control applying various impedance parameters

teaching system.

We described here a method to select a suitable impedance to improve teaching operability. In this paper, the Virtual Internal Model (VIM) proposed by Kosuge[9] is adopted as an impedance control. Since a robot is passively moved following teaching force based on direct teaching control, the motion equations for an end-effector in the VIM method is given as

$$\boldsymbol{M}_o\ddot{\boldsymbol{x}}_d + \boldsymbol{D}_o\dot{\boldsymbol{x}}_d = {}^{rh}\boldsymbol{F}. \qquad (1)$$

where $\boldsymbol{M}_o$, $\boldsymbol{D}_o$ are inertia, viscous coefficient in a Cartesian space, respectively, and ${}^{rh}\boldsymbol{F}$ is operation force. Here, setting $\boldsymbol{M}_o = diag[m_i]$, $\boldsymbol{D}_o = diag[d_i]$, $i = 1, 2, ..6$, a discrete solution of (1) is obtained:

$$x_{i,d}(k+1) = x_{i,d}(k) + \frac{m_i}{d_i}(1 - e^{-\frac{d_i}{m_i}T})\dot{x}_{d,i}(k) + \frac{dT + m_i e^{-\frac{d_i}{m_i}T} - m_i}{d_i^2} f_i(k) \qquad (2)$$

where dT is the cycle time.

Impedance parameters used in the direct teaching of SP02 are obtained by considering the operability of an operator through several teaching experiments. Experimental setup is shown in Fig. 7. In the experiment, an operator moves the end-effector along its y axis to 0.4 m from an initial position by direct teaching and then performs positioning. Other D.O.F of the end-effector are restricted during the teaching.

Fig. 8 shows the velocity of the end-effector according to the teaching force in the case of changing $\boldsymbol{M}_o$ and $\boldsymbol{D}_o$ individually. In Fig. 8(a), if $\boldsymbol{D}_o$ has a large value at constant $\boldsymbol{M}_o$, it is difficult to increase the velocity despite a large teaching force in the accelerating and moving stage. On the other hand, in the positioning stage, while the positioning is likely to be achieved at large $\boldsymbol{D}_o$, it becomes difficult at small $\boldsymbol{D}_o$. Fig. 8(b) shows the result in the case of changing $\boldsymbol{M}_o$ at constant $\boldsymbol{D}_o$. From the figure, it can be seen that the velocity by teaching force is affected only slightly by the $\boldsymbol{M}_o$. However, in the accelerating stage, while the velocity increase as a low rate when $\boldsymbol{M}_o$ is large, it is high when $\boldsymbol{M}_o$ is small. In the positioning stage, the positioning task is smoothly accomplished in the case of small $\boldsymbol{M}_o$. From the results, the selection of the desired $\boldsymbol{M}_o$ and $\boldsymbol{D}_o$ of the end-effector can be summarized as follows.

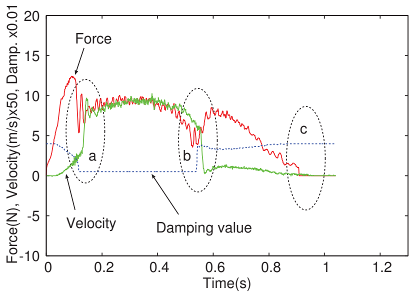
1) Select a small value of $\boldsymbol{D}_o$ in the moving stage with a high speed.
2) Select a large value of $\boldsymbol{D}_o$ and a small value of $\boldsymbol{M}_o$ in the positioning stage.

Based on the above summary, first, the desired viscosity of the end-effector is chosen as follows.

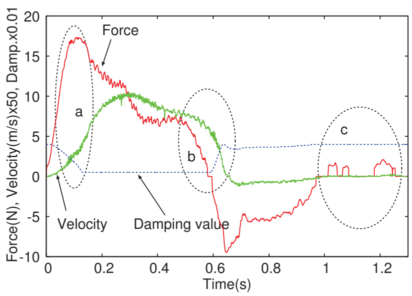
$$\begin{array}{lll} if & |v| \le v_l & D_o = D_h \\ if & v_l < |v| < v_h & D_o = \frac{D_l - D_h}{v_h - v_l}(|v| - v_l) + D_h \\ if & |v| \ge v_h & D_o = D_l \end{array} \qquad (3)$$

where the subscripts h and l represent a large value and a small value respectively. Equation (3) signifies that a large $\boldsymbol{D}_o$ is used in a low speed region, a small one is used in a high speed region, and in the intermediate region the value of $\boldsymbol{D}_o$ is linearly changed. This is then likely to increase the speed using a small teaching force, by reducing the viscous effect when moving the end-effector a large distance, and also increase positioning accuracy, by slowing down the reaction of the end-effector. In the intermediate region $\boldsymbol{D}_o$ is changed linearly so as to reduce discontinuous feeling at the moment of switching between low and high speed.

Fig. 9 shows the experimental results through applying viscous values to (3). Two values of $\boldsymbol{M}_o$ are used as fixed values in each experiment. The result in the case of small



(a) M_o= 1(kg), D_o= variable



(b) M_o= 30(kg), D_o= variable

Fig. 9. Effect of M_o on direct teaching control with a variable D_o

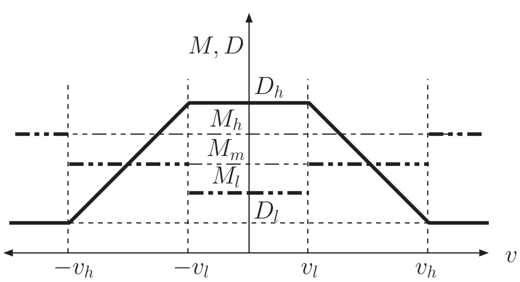


Fig. 10. Values of M_o and D_o according to the end-effector velocity

$\boldsymbol{M}_o$ and various $\boldsymbol{D}_o$ is shown in Fig. 9(a). In the figure, it can be seen that the velocity of the end-effector suddenly changes against the teaching force in the accelerating stage (a) and the decelerating stage (b). This may be a reason that causes a drop of operability in both stages. In stage (c), positioning is smoothly accomplished without vibrating the end-effector because $\boldsymbol{D}_o$ is relatively larger than $\boldsymbol{M}_o$. On the other hand, in the case of large $\boldsymbol{M}_o$, the velocity is smoothly changed in (a) and (b) as shown in Fig. 9(b). However, the end-effector decelerates after passing the target point as shown in stage (b), and positioning adjustment is repeatedly conducted in stage (c) because of the large value of $\boldsymbol{M}_o$.

Referencing the above results, we set a different value of $\boldsymbol{M}_o$ to each phase as for $\boldsymbol{D}_o$. An image of the set values of $\boldsymbol{M}_o$ and $\boldsymbol{D}_o$ according to the velocity of the end-effector is illustrated in Fig. 10. A relatively large $\boldsymbol{M}_o$ was selected

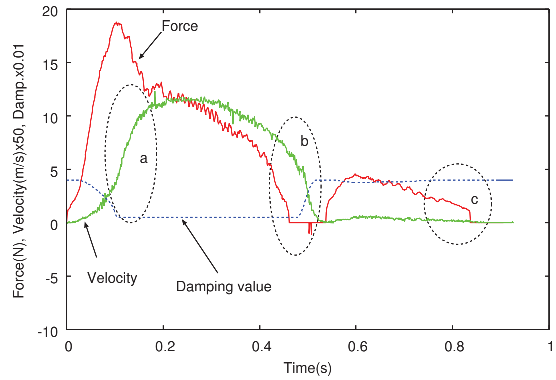


Fig. 11. Experimental result of a direct teaching control applying variable M_o and D_o according to the velocity of the end-effector

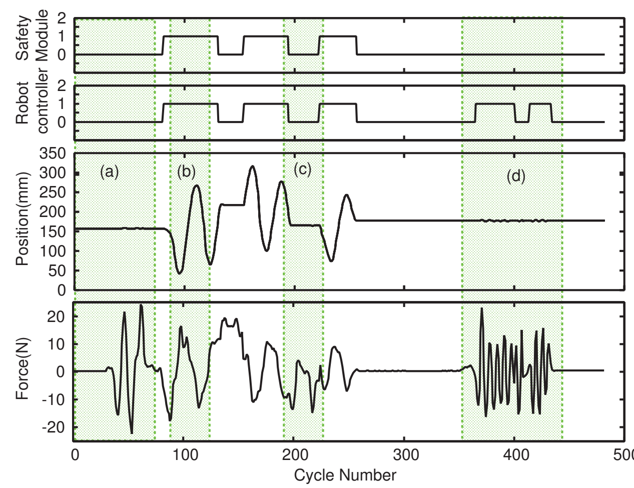


Fig. 12. Experimental result of the safety confirmation of the system

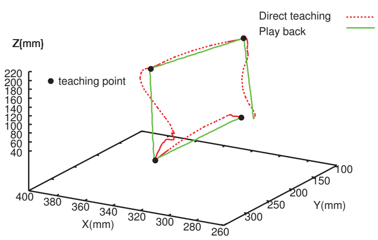
to achieve smooth motion for the end-effector for good operability in the middle and high velocity regions, and a small value was selected to improve positioning performance in the low velocity region. Fig. 11 shows the experimental result of the direct teaching, applying the various $\boldsymbol{M}_o$ and $\boldsymbol{D}_o$. From the figure, it can be observed that the velocity of the end-effector changes smoothly in regions (a) and (b) and decelerates before passing the target point. Finally, the positioning is completed without the need for wasteful adjustment motions in region (c).

VI. System Evaluation

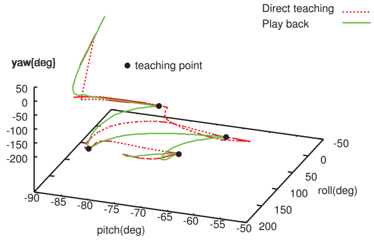
In this section, two experiments are conducted: one to confirm the safety performance of the SRP/CS, and the other to confirm the teaching and playback performance of the direct teaching system.

First, for the confirmation of the SRP/CS, the safety performance of the combination of the 3-position enabling switch and the safety module is verified. Fig. 12 shows the experimental result related to the y axis of the end-effector. In section (a), the enabling signals in both the robot controller and the safety module are OFF when the switch is released,

(a) Direct teaching scene with SP-02



(b) Position



(c) Rotation

Fig. 13. Experimental result of the direct teaching and playback of SP-02

and therefore, the end-effector does not execute following motion even though the force sensor detects the teaching force. In section (b), one of the switches is pressed, both the controller and the safety module detects that the enabling signal is ON, and the end-effector therefore executes following motion according to the teaching force. In section (c), the 3-position switch is pressed hard, and the enabling signal turns OFF again, with the result that the end-effector does not move despite detecting teaching force. In the last section (d), the switch is pressed under the condition that the enabling signal to the safety module is intentionally isolated. For this section, the robot controller detects the enabling signal but the safety module does not. Therefore, the direct teaching control is not effective, and the end-effector does not move. From the results, it is thus confirmed that the safety performance of the SRP/CS, which consists of the 3-position enabling switch and the safety module, is effective.

The experimental results of direct teaching and playback with SP02 are shown in Fig. 13. Figure 13(a) shows a scene of direction teaching with SP-02. In the experiment, the end-effector is set to the position/pose teaching mode and an operator moves the end-effector to a teaching point by operating the direct teaching device and saves the point by pushing a teaching data saving switch (TDSS). After teaching four points, the operator starts the playback procedure by switching a mode change switch (DTMS). A position control API provided with SP02 is used in the playback motion, which interpolates two points linearly. From the experimental result, it can be determined that the four positions (Fig. 13(b)) and poses (Fig. 13(c)) taught by the proposed direct teaching system are exactly represented by the playback motion.

VII. Conclusions

In this paper, a direct teaching system emphasizing safety and operability for SP02, which cooperates with a human in a cell-production workspace. The system has a direct teaching device suitable for a multi-D.O.F manipulators and a double-checked SRP/CS introducing a safety module. To improve the operability of an operator, a variable impedance control is applied based on direct teaching experiments. Through a simple direct teaching experiment, the safety performance of the SRP/CS and the teaching performance was successfully confirmed. As a future work, evaluating and further improving the operability of an operator and building a SRP/CS that includes a force sensor satisfying the standards required for functional safety will be developed.

VIII. Acknowledgments

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References

[1] S. Seki, "One by One production in the 'Digital Yatai'-Practical User of 3D-CAD Data in the Fabrication", *Journal of the Japan Society of Mechanical Engineering*, Vol.106, No.1013, pp.32-36, 2003.

[2] Y.Hayakawa, I.Kitagishi, and S.Sugano, "Human Intention Based Physical Support Robot in Assembling Work",*in Proc. of the IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp.930-935, 1998.

[3] ISO 10218-1:2006, Robots for industrial environments–Safety requirements– Part 1: Robot.

[4] ISO 13849-1:1999, Safety of machinery– Safety-related parts of control systems–Part 1: General principles of design.

[5] T.Ogure, Y.Nakabo, S.Jeong, Y.Ymamada, "Hazard Analysis of an Inderstrial Upper-body Humanoid",*Industrial Robot*, No.35, Vol.5, 2009(in press).

[6] N.Hogan,"Impedance Control: An Approach to Manipulation: PART I-III", *Trans. of the ASME, Journal of Dynamic System Measurement and Control*, vol.107, no.1, pp.1-24, 1985.

[7] Y.Yamada, H.konosu,"Proposal of Skill-Assist: A system of Assisting System for Human Workers by Reflecting Their Skills in Positioning Tasks",*in Proc. of IEEE International Conference on Systems, Man and Cybernetics*, pp.IV11-16, 1999.

[8] R.Ikeura, H.Inooka,"Variable impedance control of a robot for cooperation with a human",*in Proc. of IEEE International Conference on Robotics and Automation*, pp.3907-3102, 1995.

[9] K.Kosuge, K.Furuta, T.Yokoyama,"Virtual Internal Model Following Control of Robot Arms",*in Proc. of IEEE International Conference on Robotics and Automation*, pp.1549-1554, 1987.