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A Framework of State Identification for Operational Support based on Task-Phase and Attentional-Condition Identification

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***Abstract*— This paper proposes a state identification framework to support the complicated dual-arm operations in construction work. The operational support in construction machinery filed requires the compatibility with different types of support and the commonality among various operator skill levels. The proposed framework is therefore organized into two functions: real-time task phase identification and time-series attentional condition identification. The task phase is defined by utilizing the joint load applied according to the environment constraint condition. The attentional condition is defined as one of the internal work-state condition classified by the necessity level of operational support, and is dependent on the vectorial or time-series date selected by the identified task phase. Experiments are conducted using the hydraulic dual arm system to perform transporting and removing tasks. Results show that the number of error contacts, internal force applied, and mental workload is decreased without time-consumption increase. The result confirmed that the proposed framework greatly contribute to improving each operator's work performance.**

I. Introduction

In recent years, the adaptation of construction machinery to highly skilled and complicated work has been expected. Such tasks include sorted dismantling for recycling resources, recovery work at disaster sites, and building construction with object-grasping tasks. Double-front construction machinery (DFCM, Fig. 1), which has two manipulators with a grasping mechanism, was developed [1] in response to such changes in social needs. While double-front operations might be expected to be similar to skillful human actions, the operators require sophisticated operational skills to control more than twelve joints cooperatively. This could lead to reducing the quality and efficiency of their work by making machine operation confusing. Operators concentrating on difficult machine operations are also less likely to notice nearby workers or hear warnings from coworkers.

Intelligent operator support system that provides the operational or cognitive support is given as one of effective ways to address these skill and safety issues. In particular, a work-state identification method requires the high adaptability to the applied field [2], [3]. Construction machinery field is characterized by the followings: the work environment is complicated, the shapes and positions of objects manipulated continually change, and the operational skill levels and operational methods differ from each operator. These characteristics complicate accurate and robust work-state identification. The authors have therefore proposed primitive static states (PSS) in our previous work [4], which are completely independent of the various environmental conditions and operator skill levels. PSS is defined by using on-off information for the control lever inputs and manipulator joint loads for each component of the front and attachment (ARM and HAND), based on the analyses related with the essential interactions among an operator, a work machine, and an environment and the different utilization-purpose between the attachment and front components (Fig. 1). General work states are certainly classified into each PSS by analyzing them based on on-off level of four PSS-parameters (Table 1).

Demolition experiments were conducted using VR simulator [5] to evaluate a developed operator support system based on PSS. The result showed that operational support to simplify precise work (reduction of operational gain) during

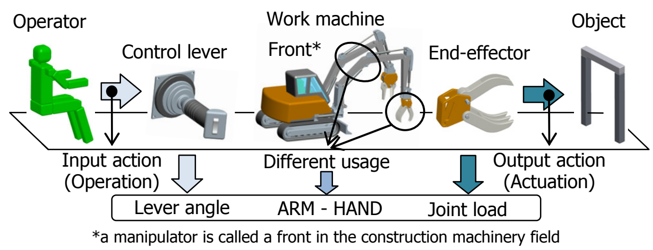

Fig. 1 An interaction model for defining the primitive static states

TABLE I
PRIMITIVE STATIC STATES (PSS)

PSS No.	Input data* HL	HO	AL	AO	Work state (example)-(HAND: grapple)
A (00)	0	0	0	0	Non-operation and load
B (01)	0	0	0	1	Reaching
C (02)	0	0	1	0	Holding using arm
D (03)	0	0	1	1	Compressing using arm
E (04)	0	1	0	0	Hand operation
F (05)	0	1	0	1	Hand operation in reaching
G (06)	0	1	1	0	Compressing using hand
H (07)	0	1	1	1	Compressing using arm and hand
I (08)	1	0	0	0	Holding of object on ground
J (09)	1	0	0	1	Abnormal state
K (10)	1	0	1	0	Holding of aerial object
L (11)	1	0	1	1	Transporting/ bending/ removing
M (12)	1	1	0	0	Grasping/ cutting of object on ground
N (13)	1	1	0	1	Abnormal state
O (14)	1	1	1	0	Grasping/ cutting
P (15)	1	1	1	1	Grasping during bending/ throwing out

*HL: HAND load, HO: HAND operation, AL: ARM load, AO: ARM operation

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cooperative transporting decreased the internal force applied and the number of error contacts, but the time consumption and mental workload increased for some operator [6]. This result indicates that operator support based on PSS do not always guarantee the positive effects. In other words, these outcomes would have resulted from the fact that PSS cannot fully identify situations where operational support would be effective for each operator by reason that PSS are abstract static states without using vectorial or time-series data. However, work-state identification that utilizes vectorial and time-series information greatly depends on the work environmental conditions or operator skill levels. This study thus focuses on effective state definitions taking fully into account operational support and an effective method of applying the vectorial and time-series data, which are independent of the above various conditions in construction machinery filed.

Conventional studies have tried to address diverseness of environmental conditions [7] and uncertainty about human factors [8], individually. This paper therefore proposes a new integrated framework of state identification for supporting, particularly, complicated dual-arm operations.

II. Analysis of Operational Support

A new state-identification framework is proposed based on analyzing operational support requirements in construction work and situations where operational support is effective.

A. Operational support requirements in construction work

1) Compatibility with different types of support: Operational support in construction work should basically improve the three different types of operational support: efficiency, safety, and quality. However, we must pay attention to the trade-off in operational support. If a support system simply reduces the operational gain to make precise work easier, the quality might improve, but efficiency would be sacrificed because of the slower motions of the manipulator. Operational support is truly required to improve the safety and quality of work while ensuring or improving its efficiency.

2) Commonality among various operator skill levels: The content of operational support greatly depends on the operator skill level. Actually, operational skills are important keyword in human-operated work machine, and we can find many researches on identifying operational skills in various areas [9], [10]. A structure common to these methods consists of learning and application processes. However, a learning process is unacceptable because the efficiency and productivity is emphasized in construction work. Additionally, skill identification in real time is difficult because construction work consists of many more tasks and the procedure is not strictly determined. Operational support is quite required the commonality among various operational skill levels. This requirement is truly important in construction machinery field in which individual operator skill levels greatly vary.

B. Situation where operational support is required

Operational support is effective when the task is difficult. The difficulty would be determined from the characteristics of tasks (work property). A result of analyzing conditions that greatly change work properties indicated that environmental restraint conditions greatly change work property (Fig. 2).

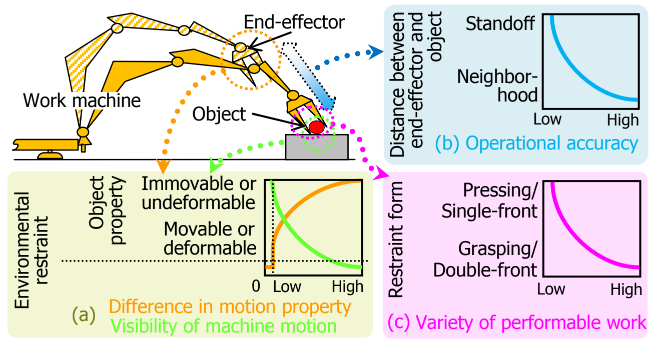

Fig. 2 Work properties depending on environmental restraint conditions

1) Without environmental restraints: Machine operation is quite easy because the motion properties of the manipulator are constant. However, when the manipulator is within the range of making contact, although the motion properties do not change, an operator requires a highly position and posture control skills because rough operation causes dangerous states such as objects breaking (Fig. 2 (b)).

2) With environmental restraints: An operator needs a highly trajectory and force control skills because the manipulator's motion properties change depending on the external force applied to the manipulator, which is due mainly to nonlinearity of hydraulic system. When a target object is not movable or deformable, operational difficulty increases much more because the operator cannot recognize the manipulator motion visually (Fig. 2 (a)). Moreover, a manipulator in an object-grasped state applies force in an arbitrary direction, whereas the manipulator in a non-grasped state only applies force in the direction of pressure at the contact point. Furthermore, the number and difficulty of performable works varies with the types of contact state (Fig. 2 (c)).

C. Proposed framework of state-identification

The previous analyses represent that only identifying the work state by using PSS is obviously insufficient to provide effective operational support. Operational support must be provided based on an internal specific condition depending on each environmental restraint condition. We thus propose a state-identification framework with real-time task phase and time-series attentional condition identifications (Fig. 3).

1) Task phase: The characteristics of each environmental restraint condition change depending on task progress. The general task sequence is represented by alternating the on-off state of environmental restraint. Besides, the conditions with environmental restraint are divided into the object-grasped and non-grasped conditions. We thus rename these environmental restraint conditions as task phase.

2) Specific condition: Specific conditions are notionally classified into four conditions by the degree of necessity of operational support: optimum, normal, attentional, and dangerous conditions, in terms of each support type: efficiency, safety, and quality. The optimal condition represents ade-

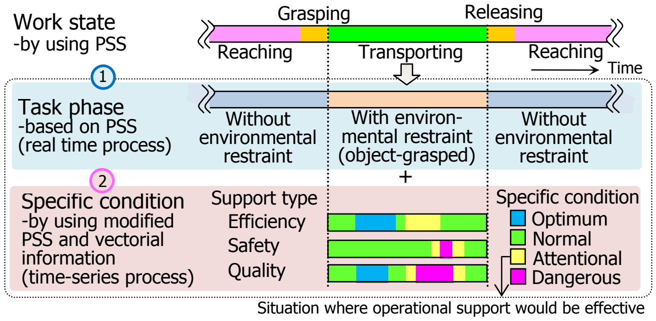

Fig. 3 Proposed framework of state identification

quate motion or load conditions. A dangerous condition represents one where a task can no longer be executed (e.g., breaking a target object).

3) Association with operational support: Two different types of support are notionally defined by using the specific conditions: from normal to optimum and from attentional to normal. Providing effective support would be difficult for the former because optimum conditions strongly relate with desired values (e.g. trajectory), which are difficult to identify. In contract, the latter's support would be effective because attentional condition is defined as a common concept which is independent of the various environmental conditions and operator skill levels. Operational support was thus defined as improving processes to change an attentional condition into a normal one. This framework could minimize lowering efficiency by providing support while the specific condition in quality or safety is identified as attentional. The proposed framework will satisfy the operational support requirements, which are the compatibility with different types of support and the commonality among various operator skill levels.

III. Embodiment of State-Identification Framework

A new state-identification framework is embodied based on analyzing the requirements of two state-identifications.

A. *Task-phase identification*

Task-phase identification requires successive state output for stable time-series data processing as well as real-time classifications of environmental restraint conditions. The method was developed based on analyzing the advantages and disadvantages of all PSS parameters. Lever-operation information does not represent task phase as stated above, so the lever operation flags was omitted from PSS. In contrast, joint load information is essential for classifying environmental restraint conditions. ARM load (on) represents an object-contacted task phase. ARM and HAND loads (on) represents an object-grasped task phase. In case of HAND load (on), ARM load was unavoidably generated due to the link structure. To avoid frequent state changes, the HAND load (on) and ARM load (off) states was omitted from PSS.

From the above modifications, three states, called as filtered PSS (f-PSS), were defined: the non-load, the object-contacted, and the object-grasped states (Table 2). F-PSS can identify task phases directly and continually in real time. Their descriptions in a dual-arm task are defined as follows:

TABLE II
Filtered PSS (f-PSS) and Corresponding PSS and Work State

f-PSS No.	Input data* AL	HL	Task phase	Work state (Corresponding PSS)
A (0)	0	0	Non-load	Non-operation and load/ reaching (PSS: 00, 01, 04, 05)
B (1)	1	0	Object-contacted	Compressing/ holding (PSS: 02, 03, 06, 07)
C (2)	0/ 1	1	Object -grasped	Grasping/ transporting/ removing (PSS: 08, 09, 10, 11, 12, 13, 14, 15)

* AL: ARM load and HL: HAND load

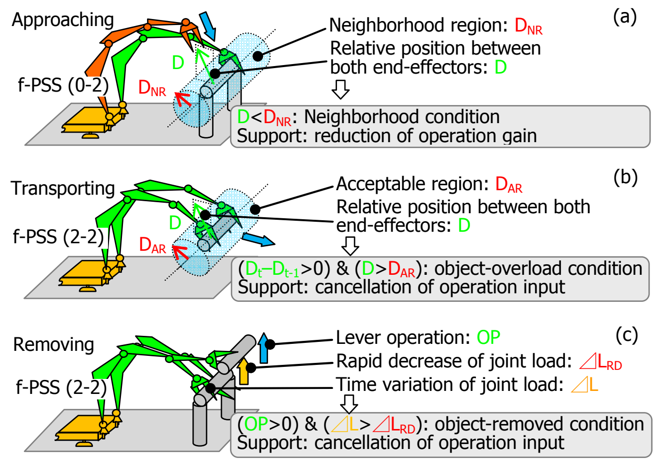

Fig. 4 Attentional-condition identification

f-PSS (0-2) represents that one manipulator is f-PSS (0) and the other manipulator is f-PSS (2).

B. *Attentional-condition identification*

Attentional-condition identification requires definite and robust state output as well as the commonality among various environmental conditions and operator skill levels. Operational difficulty in construction machinery is essentially due to the fact that precise depth perception is generally feeble, internal force applied cannot visually recognize, and rapid or large change of force applied to a manipulator hinders safe and precise operations. Thus, attentional conditions are notionally divided into three conditions: object-neighborhood, object-overload, and object-removing conditions (Fig. 4).

1) Object-neighborhood condition: To achieve both a fast approach in standoff and precision operations in the neighborhood, reducing the operational gain according to the distance between an object and the end-effector is effective. In the house-demolishing task, which mostly involves removing long straight objects, when the left arm has grabbed an object and the right one is approaching to grasp it, the position of the left hand is assumed as where the object is. A situation where the relative distance between both end-effectors is less than a neighborhood region in f-PSS (0-2) is defined as an object-neighborhood condition (Fig. 4 (a)).

2) Object-overload condition: To avoid generating large internal force during a closed-loop system among an object and manipulators forming, cancelling operation input according to the gap between both end-effectors is effective. A situation where the gap between both end-effectors is larger than an acceptable region and it has increased in f-PSS (2-2) is defined as an object-overload condition (Fig. 4 (b)).

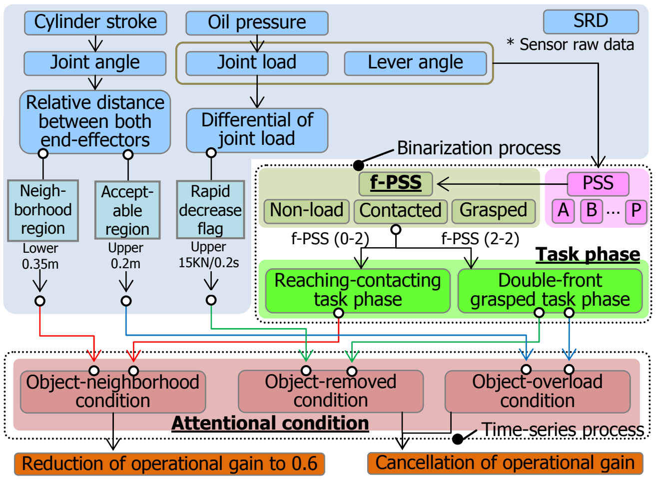

Fig. 5 Developed framework of state identification

3) Object-removed condition: To ensure safety work when generating intensive variation of force applied to a manipulator, cancelling operation input according to the differential of the applied force is effective. A situation where lever operation and rapid decrease flags are detected in f-PSS (2-2) is defined as an object-removed condition (Fig. 4 (c)).

C. *Overview of operational support system*

The proposed support system consists of three basic modules and two identification modules (Fig. 5). The system obtains three types of sensor data 30 ms frequency. From the f-PSS defined by binarizing sensor data, the system identifies two task phases. By utilizing the identified task phase and vectorial and time-series data, the system identifies three attentional conditions. The system reduces or cancels operational gain depending on the identified attentional condition.

A neighborhood region, an acceptable region, and a rapid decrease flag are defined according to the specification of each machine. These thresholds are thus determined by using the attachment length, the attachment-fork length, and the results of pre-experiments. This paper focuses on a framework of state-identification which is independent of the various skill levels and environmental conditions, under a fixed machine specification. A theoretical definition method of attentional condition would be addressed as a future work.

IV. Experiment

Experiments were conducted to evaluate the proposed framework by using a hydraulic dual arm system (Fig. 6).

A. *Experimental tasks and conditions*

1) Experimental tasks: A transporting and removing task utilizing two arms were conducted (Fig. 7). In the transporting task, a long hardwood stick was placed on the ground. An operator maneuvered the arms to reach without contacting the ground and grasped the stick with the two end-effectors. The operator then transported the stick to the target position without bending it, and released it there. In the removing task, an operator removed a long hardwood stick that was attached to a framework consisting of columns and beams.

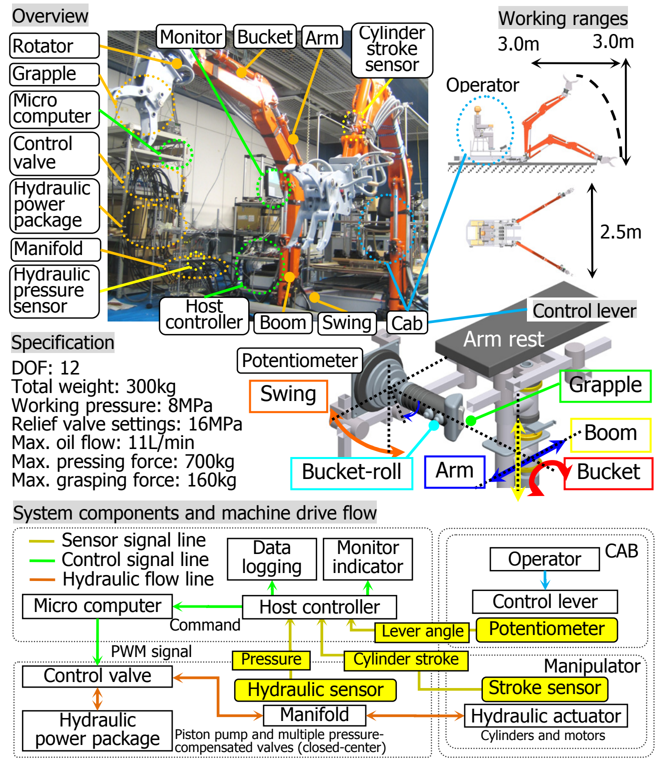

Fig. 6 Developed hydraulic dual arm system

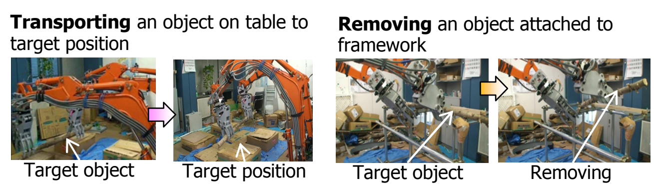

Fig. 7 Experimental tasks (transporting and removing)

2) Experimental conditions: The proposed framework (f-PSS support) was evaluated by comparisons with two other conditions: with no operational support (off support) and with operational support based on PSS (PSS support (a conventional method)). As PSS support cannot apply vectorial data, the operational gain was reduced to 0.6 during grasping and reaching states (one manipulator was PSS (10) and the other was PSS (1, 4, and 5)) and during cooperative transporting with two manipulators (both manipulators were PSS (11, 14, and 15)). Ten healthy adults (20-25 years old) without any experience at any kind of construction machinery operations and one skilled operator were used as the subjects. The subjects randomly carried out these tasks three times.

B. *Results of identifications*

1) Task phase: Figure 8 shows that the common f-PSS flow (f-PSS (0-0), (2-2), and (0-0)) was identified without interruption under all experimental conditions. This result confirmed that f-PSS could identify task phases independently of the various operational skill levels and work states. The figure also shows that the skilled operator simultaneously seized an object with both manipulators, whereas novice operators grasped objects using manipulators individually. In the removing task, the novice operator re-grasped an object three

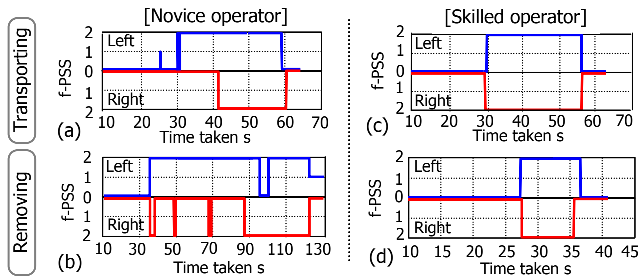

Fig. 8 Identification results of task phase

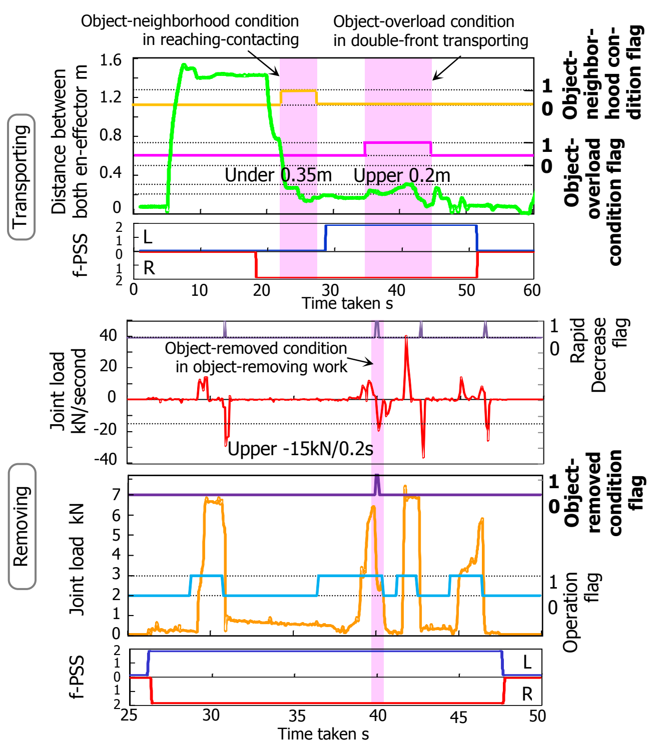

Fig. 9 Identification results of attentional condition in task phase

times (right hand) and one times (left hand) (Fig. 8 (b)).

2) Attentional condition: Figure 9 shows that the system adequately identified attentional conditions by processing the time-series data depending on the identified task phase. The definition of an attentional condition during transporting task adequately changed according to the identified f-PSS. The object-removed condition during removing task was easily defined by a combination of some relative flags.

These results confirmed that our proposed framework of state identification could appropriately recognize situations where operational support would be effective.

C. *Results of operational support*

The time taken (Fig. 10) was measured as an evaluation item of efficiency. The number of lever operations and error contacts in reaching (Fig. 11), the force applied to both end-effectors in cooperative transporting (Fig. 12), and the displacement of the end-effector after an object-removing (Fig. 14) were measured as evaluation items of safety and quality. Operator's mental workload was quantified by utilizing NASA-TLX [11] (Fig. 13).

*: $p<0.1$, **: $p<0.05$, ***: $p<0.01$, ****: $p<0.005$, $^{+}$: $p<0.001$

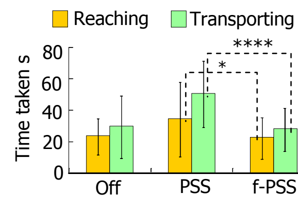

Fig. 10 Time taken

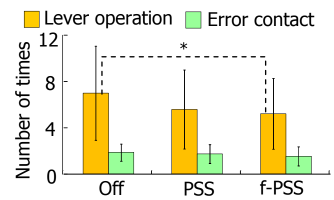

Fig. 11 Error operation in reaching

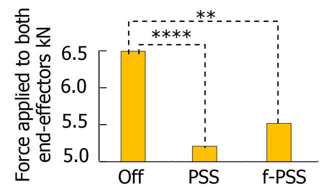

Fig. 12 Force applied to both end-effectors in transporting

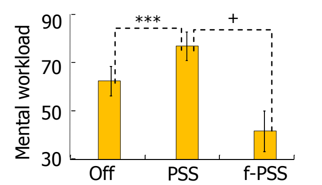

Fig. 13 Mental workload measured by NASA-TLX

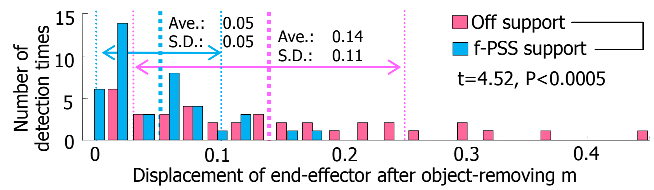

Fig. 14 Displacement of end-effector after object-removing

1) Effectiveness of PSS support: In PSS support, time consumption increased much more than that in off support although the number of error contacts and lever operations and force applied to both end-effectors decreased (Figs. 10-12). This result is mainly due to the gain reduction in all regions. The reduction of efficiency greatly increased the operator's mental workload (Fig. 13). These results reconfirmed that PSS could not adequately identify situation where operational support would be effective.

2) Effectiveness of PSS support: On the other hand, in f-PSS support, time consumption was maintained at the same level as that in off-support while improving the evaluation items of safety and quality (Figs. 10-12). This outcome results from the following facts. The f-PSS support enables operators to achieve quick operations in the standoff region and accurate operations in the neighborhood region during reaching task, and moreover, to recognize lowering work quality through reduced operational gain in cooperative transporting task. These effects greatly decreased the operator's mental workload (Fig. 13). Reducing operator's mental workload is important in actual construction work, which consists of long working hours and harsh working environments, because the mental workload directly affects work performance. Moreover, the displacement of end-effector after object-removing greatly decreased below 0.2 m (Fig. 14). The result of t-test indicates that this support significantly improved work performance. These experimental results confirmed that the proposed support system satisfied the operational-support requirements in construction machinery and improved the safety and quality of work while ensuring efficiency and commonality with the various operational skill levels.

V. Discussion

For the inspection of the support effect in the each subject, the ratios of the off-support divided by the on-support (PSS and f-PSS supports) about the above evaluation index for every subject were calculated. Figure 15 shows that the larger positive value represents that the support was more effective and the negative value represents that the support had an adverse effect. Figure 15 also shows the results of four examples which are easy to express the problems of PSS support and the advantages of f-PSS support.

1) Compatibility with different types of support: The results for operator B and D are typical examples to represent the advantage of f-PSS. In PSS support, the number of lever operations and error contacts in reaching and the overloads in transporting, which evaluates the work quality, surely decreased and the time taken, which evaluates the work efficiency, increased. In contrast, f-PSS support improved all evaluation items. This result confirmed that f-PSS realized the compatibility with different types of support.

2) Commonality among various operator skill levels: Work performance of operator A was improved in both PSS and f-PSS support. This subject would be a poorly skilled operator. For operator C, PSS support reduced not only the efficiency but also the safety and quality. This subject would be a highly skilled operator. These results indicate that the PSS support degrades highly skilled operator's work performance. On the other hand, f-PSS support improved the work performance of both operator A and C whose operational skills greatly differ. This result confirmed that f-PSS support realizes the commonality among various operator skill levels.

These results of analyses reconfirmed that our proposed framework realized the operational support requirements in construction work, compensate the disadvantages of PSS, and provide effective operational support.

VI. Conclusion and Future Works

This paper proposes a framework of state identification to support the complicated dual-arm operations of construction machinery. The operational support in construction machinery filed requires the compatibility with different types of support and the commonality among various operator skill levels. The proposed framework is therefore organized two sequential functions: real-time task phase identification and time-series attentional condition identification. The task phase is defined by utilizing the joint load applied according to the environment constraint condition. The attentional condition is defined as one of the internal work-state condition classified by the necessity level of operational support, and is dependent on the vectorial or time-series date selected by the identified task phase. Experiments are conducted using the hydraulic dual arm system to perform transporting and removing tasks. Results showed that the number of error contacts, internal force applied, and mental workload is decreased without time-consumption increase. The experimental result confirmed that the proposed framework greatly contribute to improve the operator's work performance.

The thresholds to define attentional conditions were experimentally defined. A theoretical or general definition method of attentional conditions requires in future work. A long-term experiment in an actual field is also required.

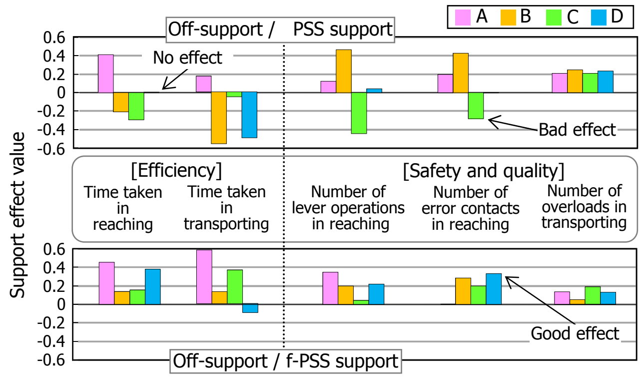

Fig. 15 Difference of improving work performance in different operators using PSS and f-PSS support

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