The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Human-Robot Collaboration in Cellular Manufacturing: Design and Development

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***Abstract*—The challenge of this work is to study the design and development of human-robot collaboration (HRC) in cellular manufacturing. Based on the concept of human collaborative design, four main design factors are being identified and developed in an active HRC prototype production cell for cable harness assembly. Human collaborative design aims to optimize the system design for the advantage of collaboration between human and robots based on human considerations. Task modeling approach is developed to study and analyze the task in order to identify the collaboration tasks to develop the collaboration planning. In the collaboration safety development, five safety designs, cover both hardware and control design, are proposed and developed in the prototype system. Risk assessment is conducted to verify the safety design. Two main experiments were conducted as preliminary study to investigate mental workload in HRC. A multimodal information support system is developed in the study of man-machine interface in this work to provide a comprehensive human-robot interface to facilitate human operator. The system performance evaluation had proven the improvement of prototype production cell with HRC design for cellular manufacturing.**

I. Introduction

HUMAN-robot collaboration (HRC) is a dream combination of human flexibility and machine efficiency. As the rapid change in manufacturing requirements due to short production cycle and highly flexible design, conventional automation technology has come to a bottle-neck, where HRC might be a potential candidate to solve this industrial dilemma.

A. Human-Robot Collaboration in Industrial Environments

The main discussion in this work refers to HRC, which it might sometime being regarded as the same research subject with human-robot interaction (HRI). But in fact, both terms carry different meanings; where HRI is a more general term that includes collaboration meaning but HRC is exclusively refer to working together to achieve a common goal. While a lot work had been done in HRI to provide a clear idea on HRI [1], [2], the definition and research direction of HRC are still in hot debate. This work proposes a challenge to apply HRC in industrial environments, specifically cellular manufacturing systems.

Cellular manufacturing, also known as cell production, is a production unit, where a single operator or a small team of workers performs multiple tasks on unfinished components to produce finished products [3], [4]. The human-centered characteristic stresses on the human operator's multiple skills and flexibility. However, in order to improve the productivity, introducing assistive robots into the system is the next logical step [5], [6]. This rationale has motivated the study of HRC for the development of cellular manufacturing systems in this work.

Introduction of assistive robotic devices in production environments might not be a new research subject. In 1996, Edward Colgate had introduced collaborative robots or cobots [7], mechanical devices that can provide guidance to human operator's motion. Later in 2002, E. Helms et al. had presented robot assistant as a direct interacting, flexible device that provides sensor based, actuator based, and data processing assistance [8]. PowerMate, an intuitive robot assistant for handling and assembly tasks were developed by the same group in 2005 [9]. These research efforts had proven the potential of HRC in industrial environments. However, the research view point was always focusing on hardware functionality development [10], [11], which resulting machine-driven collaboration. Hence, the aim of this work is to take up the challenge to study HRC in production with the focus on human collaborative design.

B. Active HRC Prototype Production Cell

This work involves the development of a novel active HRC prototype production cell for design validation and case study. The close range collaborative production cell design is shown in Fig. 1. A mobile platform with two robot manipulators is designed to assist the operation. In this paper, a cable harness assembly is illustrated as production cell operation. More details on the prototype production cell design are presented by F. Duan et al. [12].

Based on the prototype production cell development, the study of HRC is presented as follows. Section II gives an overview explanation on the concept of human collaborative design in HRC with the four main design factors developed in this work. Section III starts the design factors discussion on collaboration planning by task modeling. The second design

Manuscript received March 1, 2009. This work is part of 'Strategic Development of Advanced Robotics Elemental Technologies' project supported by NEDO.

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factor, collaboration safety is explained in Section IV. Section V presents the human operator's mental workload in collaboration. Man-machine interface is presented as the forth design factor in Section VI. The developed prototype production cell had undergone system performance evaluation as described in Section VII. Finally, Section VIII concludes the work with suggestions for future development.

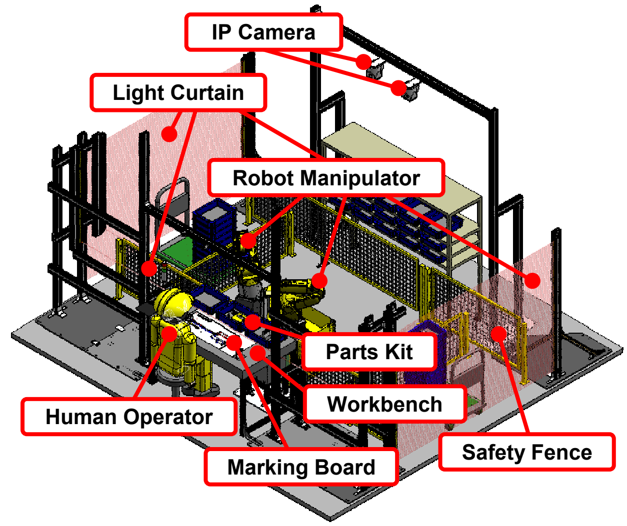

Fig. 1. Active HRC prototype production cell design.

II. Design for Collaboration

In the implementation of cellular manufacturing systems, U. Wemmerlov and D. J. Johnson had illustrated 'soft' (people) issues exceeds 'hard' (technical) issues (38 vs. 30) in the survey on factors considered of great importance to cell operation and implementation [4]. The 'human' factors should of the center of consideration in HRC design. The concept of human collaborative design in HRC is to optimize the system design for the advantage of collaboration between human and robots based on human considerations. Four main design factors are identified and studied in this work.

1) *Collaboration Planning by Task Modeling:* Andrea Bauer in her survey paper on human-robot collaboration [13] illustrated the internal mechanisms of a cognitive robot leading to joint actions as collaboration (Fig. 2). A set of actions is generated by 'action planning' to achieve the joint intention. However, the 'action planning' for the human operator is far more complex due to human nature. In this work, task modeling approach, which adopted from human ergonomics study [14], is used for the planning of collaboration action of a human-robot system.

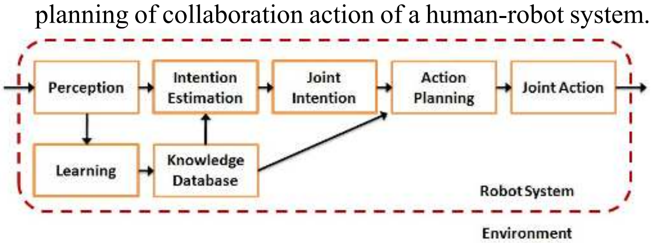

Fig. 2. Overview of the mechanisms leading to joint action [13].

2) *Collaboration Safety:* The close range active HRC design in the prototype system development has prioritized safety as the uppermost consideration. In this study, safety study and design are conducted along the whole development span, from the early design stage until the production operation stage to ensure the collaboration safety.

3) *Mental Workload in Collaboration:* K. Watanabe had shown in his work [15] that mental workload occurs even though safety features have been ensured in the system. This influencing factor can greatly affect the productivity. In this work, a preliminary study was conducted to lay down a new path to analyze the human physiological factors in collaboration with robot systems.

4) *Man-Machine Interface:* Based on the taxonomy that classified HRI by Yanco and Drury [16], the HRC of cellular manufacturing system in this work can be classified as in Fig. 3. Two main interactions shown in Fig 3: Human to robot team, and internal robot team. Internal communications within robot team are very straight forward as both are connected within the same system. But the interaction between human and robot team can be complicated as it involves man-machine interface. A multimodal information support system is developed in this work to provide a comprehensive man-machine interface for the human operator to interact with the system.

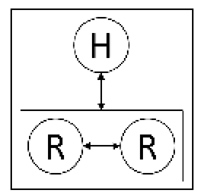

Fig. 3. Classification value: One human, robot team [16].

III. Collaboration Planning by Task Modeling

To optimize the working efficiency of HRC, one of the basic ideas is to assign the human operator only to focus on tasks that required human skills and let robots handle all tasks that able to be automated. However, to achieve this, first the tasks have to be studied and analyzed. In this work, task modeling approach is utilized for collaboration planning [17]. The whole production operation is being decomposed by task analysis technique to obtain the HTA model (Fig. 4).

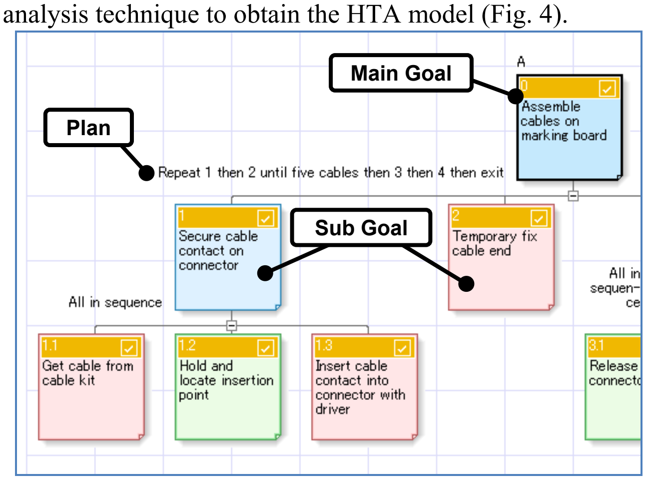

Fig. 4. HTA model (partially) of a cable harness assembly (Human-Robot: Blue; Human: Pink; Robot: Green).

The possible collaboration tasks become more apparent from the HTA model. Based on E. Helms et al. four man-machine cooperation classifications (*independent operation*, *synchronized cooperation*, *simultaneous cooperation*, and *assisted cooperation*) [8], the collaboration tasks are indentified as shown in Table I. Collaboration roles can then be assigned to human-robot (Table II) based on the agents' capability to optimize the task assignment in accordance to human collaborative design. Finally, a graphical representation of the task model can be produced with color tagging for collaboration roles (Fig. 4).

TABLE I
COLLABORATION IDENTIFICATION FROM HTA TABLE

Super-ordinate	Task components	Collaboration Identification
1	*Prepare parts kit* 1.1 Arrange parts into tray 1.2 Check parts //	*Independent operation* by robot manipulators to prepare the part kit
2	*Assemble cables on connector* 2.1 Secure cable contacts on connector 2.2 Temporary fix cable ends // 2.3 Set connector on marking board	*Assisted cooperation* by robot manipulator to hold the connector and indicate assembly points while human worker insert the cable contacts
3	*Arrange cables on marking board* 3.1 Form cables on marking board 3.2 Paste marking tape on cables 3.3 Fasten cables with cable tie	*Independent operation* by human worker due to the requirement to handle flexible cables
4	*Assemble cables on terminal* 4.1 Secure cable ends on terminal 4.2 Set terminal on marking board	*Assisted cooperation* by robot manipulator to hold the terminal and indicate assembly points while human worker insert the cable ends
5	*Assemble metal plate* 5.1 Secure cables on metal plate 5.2 Set metal plate on marking board	*Assisted cooperation* by robot manipulator to hold the metal plate while human worker fasten the cables with cable ties

TABLE II
COLLABORATION ROLE ASSIGNMENTS (TASK 2)

Super-ordinate	Task components	Collaboration Roles
2	Assemble cables on connector	Human-Robot
2.1	Secure cable contacts on connector	Human-Robot
2.1.1	Get cable from cable kit	Human
2.1.2	Hold and locate insertion point	Robot
2.1.3	Insert cable contact into connector with driver	Human
2.2	Temporary fix cable ends	Human
2.3	Set connector on marking board	Human-Robot
2.3.1	Release connector	Robot
2.3.2	Get and place connector on marked location	Human

IV. COLLABORATION SAFETY

Five main safety designs proposed and developed in the prototype production cell covers both hardware and control design.

1) *Human area and robot area* – The whole production cell is divided into *human area* and *robot area* by safety fence, photoelectric sensors and light curtains [18] in order to have safe working areas and to monitor border crossing for safety.
2) *Safety robot working zones* – As shown in Fig. 5, the double light curtains arrangement has divided the area between human operator and robot manipulators into A, B and C zones to control the behavior of the robots based on the collaboration requirements. Robots are allowed to operate in high speed movement in Zone A but low speed movement in Zone B. In Zone C, the restrictions in *robot safety design* are applied.

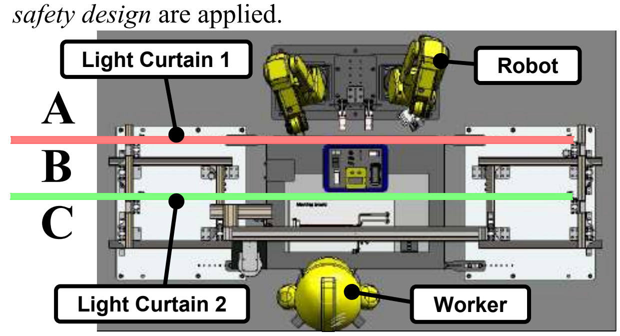

Fig. 5. Three safety robot working zones.

3) *Robot safety design* – The robot speed is limited to below 150 mm/s and the robot working area is restricted within the pink region in Fig. 6. The robot speed [19] and area restrictions are setup based on risk assessment to minimize the collaboration risks.

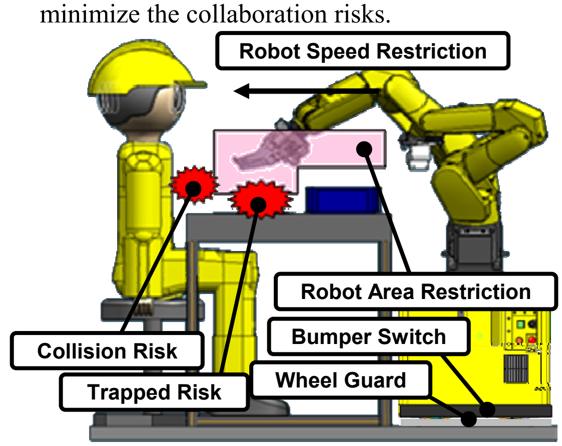

Fig. 6. Robot speed and area restrictions.

4) *Operator safety monitoring system* – Vision system by two IP cameras is developed to monitor the human operator safety (Fig. 7). The IP cameras track the color marks on the head and shoulders of the human operator to measure the body posture and position to estimate the human operation conditions [20].
5) *Operational sequence safety control* – The control system coordinates the collaboration flow between the human operator and robot system (Fig. 8). It is connected

to the operation database that contains production operation contents and instructions, operation sequences and safety strategy. The system will check the safety conditions when receive input from the human operator and sending command to the robot system based on the collaboration sequences. With this, the human operator is fully aware of all robot movements to ensure safety.

Fig. 7. Operator safety monitoring system.

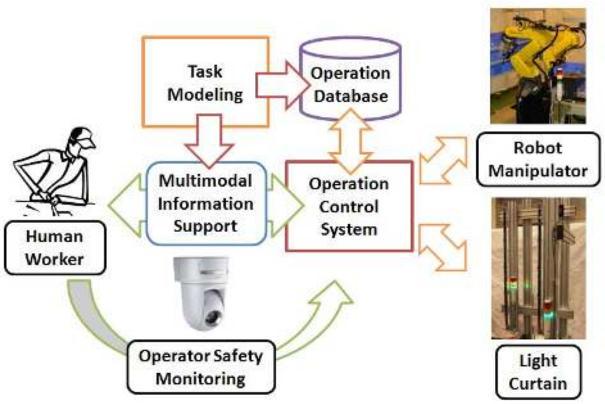

Fig. 8. Operation control system model.

Risk assessment had been conducted on the HRC based on industrial standards ANSI/RIA R15.06 [21] with reference to ISO 13849-1, to evaluate the safety performance of the developed system. The assessment results are tabulated in Table III (before safety system) and Table IV (after safety system).

TABLE III
RISK ASSESSMENT (BEFORE SAFETY SYSTEM)

Task Description	Hazard	Prior to safeguard: Severity	Exposure	Avoidance	Risk category	PL_r (Category)
Cable harness assembly	Trapped Risk – *Hands*	S2	E2	A2	R1	*e (4)*
	Trapped Risk – *Head*	S2	E1	A2	R2B	*d (3)*
	Collision Risk – *Hands*	S2	E2	A2	R1	*e (4)*
	Collision Risk – *Head*	S2	E1	A2	R2B	*d (3)*

Two collaboration risks were being studied, 'trapped risk' and 'collision risk' for both operator's hands and head cases (Fig. 6). From the assessment, it had shown that the safety system can improve the avoidance ability (A2 to A1) and minimize the severity (S2 to S1), which effectively reduce the potential collaboration risks in the system.

TABLE IV
RISK ASSESSMENT (AFTER SAFETY SYSTEM)

Safety design	Validation: Exposure	Avoidance	Severity	Risk category	PL_r (Category)
Human area and robot area					
	Trapped Risk – Hands				
Safety robot working zones	E2	*A1*	*S1*	R3A	*b (1)*
	Trapped Risk – Head				
Robot safety design	E1	*A1*	*S1*	R4	*a (B)*
	Collision Risk – Hands				
Operator safety monitoring system	E2	*A1*	*S1*	R3A	*b (1)*
	Collision Risk – Head				
Operational sequence safety control	E1	*A1*	*S1*	R4	*a (B)*

V. MENTAL WORKLOAD IN COLLABORATION

In HRC, even though safety has the top priority to safeguard human operator from any danger, working closely with robots can still produce mental workload to the operator. This mental workload can influence the operator physiologically and affect the productivity. In this work, preliminary mental workload study has been conducted to investigate the design parameters of that affect mental workload in HRC. Two main experiments were conducted on five operators to evaluate the mental workload by physiological and subjective measurements. Skin potential reflex (SPR) data was recorded as physiological measurement (amplitude ratio and occurrence rate) as it is an effective indicator of nervousness. As for parallel comparison, rating scale method (0 – 6 scores) was used as subjective measure to investigate the 'fear' and 'surprise' levels. Detailed experiments setting and discussion are available in reference [15].

A. Experiment I: Robot Motion Speed

The first experiment had the objective to investigate the effect of robot motion speed in collaboration. The robot moved in front protruding according to the speed profile in Fig. 9.

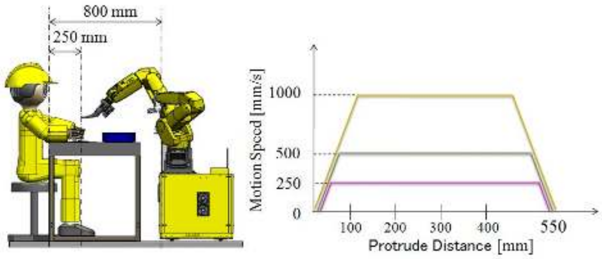

Fig. 9. Experiment I setup and robot motion speed profiles.

The results in Fig. 10 shown that mental workload increased as the robot motion speed increased. As a design guideline, the robot motion speed should be kept low to keep the mental workload low.

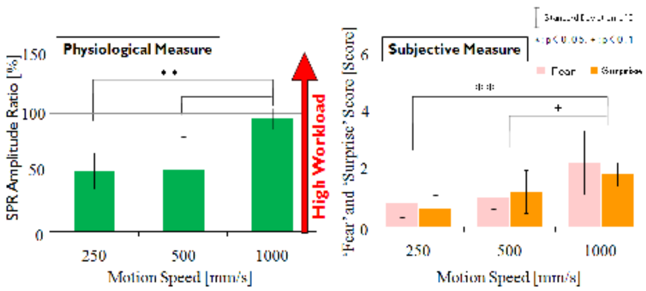

Fig. 10. Physiological and subjective measurements of Experiment I.

B. *Experiment II: Human-Robot Working Distance*

Experiment II was conducted to investigate the effect of human-robot working distance. The robot was performing bin picking movements in three different working distances (Fig. 11).

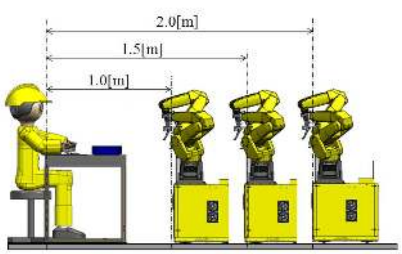

Fig. 11. Experiment II setup.

From the result in Fig. 12, the mental workload reduced as the distance increased. It was proven that a safe distance between human and robot is important to keep low mental workload during collaboration.

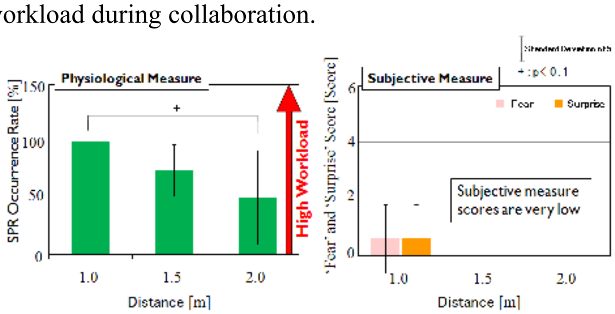

Fig. 12. Physiological and subjective measurements of Experiment II.

VI. Man-Machine Interface

The communication between human and robot systems in this work is built on a man-machine interface system. The interface system is originated from a multimodal assembly information support system [22]. From the information support, expert assembly instructions are presented in a multimodal interface (Fig. 13) to guide the human operator in performing the operation. From the task modeling development, a structural information database is developed to match the media data with the operation tasks. This system has facilitated the information support and content generation, and ergonomic study on the multimodal interface for HRC in the prototype system. The system performance evaluation is discussed in the following section.

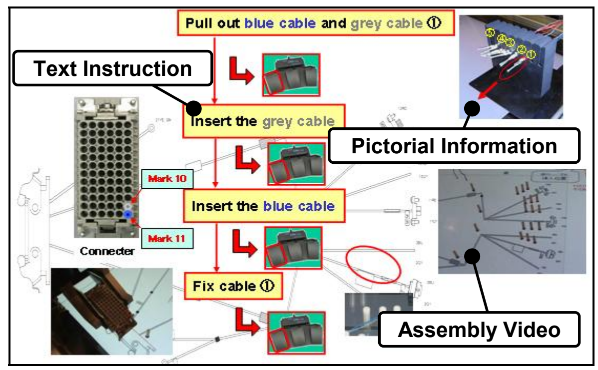

Fig. 13. Multimodal information support system interface.

VII. System Performance Evaluation

The prototype system performance evaluation was conducted on a cable harness assembly operation. The evaluation was carried out based on the comparison results between conventional manual assembly setup (Exp I) and the new HRC setup (Exp II) (Fig. 14). Five novice and expert operators had performed three assembly trails for both production setups to obtain the assembly durations.

From Fig. 15, the overall performance was proven better (shorter assembly duration) in HRC setup (Exp II). Novice and expert operators had almost the same assembly duration, which meant minimum assembly duration was possible even for unskilled operators. On the first trial, comparing to conventional setup (Exp I), the assembly duration of novice operators were only 50% in HRC setup (Exp II), which proven double productivity. In term of assembly quality, 10% to 20% of assembly error (insertion error) was observed in conventional setup (Exp I), while in HRC setup (Exp II) the error was totally being prevented by robot assistance (collaboration).

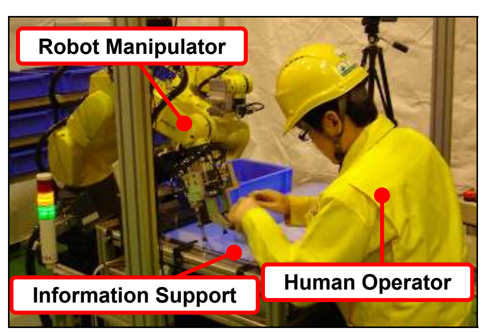

Fig. 14. Human-robot collaboration production cell setup (Exp II).

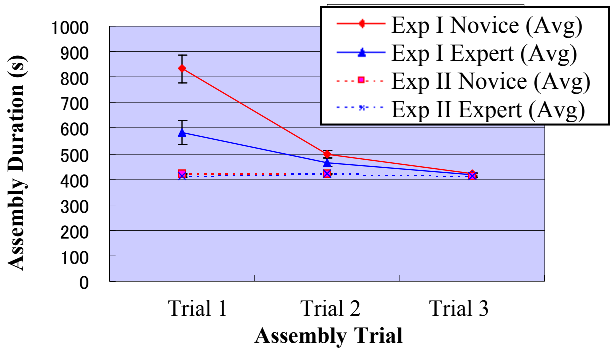

Fig. 15. Results of assembly duration in Exp I and Exp II.

VIII. Conclusions and Future Work

The purpose of this work is to study on HRC design in cellular manufacturing based on an active HRC prototype production cell development. Based on the concept of human collaborative design, four main design factors are being identified and developed in this work. The achievements of this development can be summarized as follows with suggestions on future work.

1) *Human Collaborative Design:* The main concept is to optimize the system design for the advantage of collaboration between human and robots based on human considerations.
2) *Collaboration Planning by Task Modeling:* The task modeling approach is developed to study and analyze the task in order to identify the collaboration tasks to develop the collaboration planning to optimize the collaboration design. Quantitative study on approach can improve the effectiveness of the modeling.
3) *Collaboration Safety:* Safety design is ensured in both robot design and operational control system in the safety development. The risk assessment had improved the credibility of the safety development.
4) *Mental Workload in Collaboration:* The experiments had proven the need of mental workload study in collaboration. The preliminary study had established a new direction to further analyze mental workload in collaboration.
5) *Man-Machine Interface:* In this work, a multimodal information support system is developed to provide a comprehensive man-machine interface to facilitate human operator.
6) *System Performance Improvement:* The performance evaluation had proven the improvement of prototype production cell in HRC design. Further development will focus on more operation comparisons and efficiency measurement.

Acknowledgment

Highest gratitude is expressed to GCOE for research support and research partner, FANUC for the excellent cooperation and technical support.

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