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Partner Ballroom Dance Robot -PBDR-

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Abstract : In this research, we have developed a dance partner robot, which has been developed as a platform for realizing the effective human-robot coordination with physical interaction. The robot could estimate the next dance step intended by a human and dance the step with the human. This paper introduce the robot referred to as PBDR (Partner Ballroom Dance Robot), which has performed graceful dancing with the human in EXPO 2005, Aichi, Japan.

Key Words : human-robot cooperation, estimating human intention, ballroom dances, dance step estimation.

1. Introduction

Robots are expected to execute various tasks in many fields of human environments, such as in a home, in an office, in medical and welfare fields etc. However it is not easy for robots to execute tasks by themselves in the environments because the environments contain many kinds of uncertainty. Human-robot cooperations have been studied as one of the solutions, in which robots execute tasks based on commands from humans who recognize the environments, situations of tasks and so on. In most of human-robot coordination systems, which have been developed by several researchers, the robots move passively based on force/moment applied by a human and execute tasks in cooperation with the human [1]-[3]^{etc}. These systems are effective to execute simple tasks such as handling of an object. If robots could behave not only passively but also actively based on human intentions, information on the environments, knowledge of tasks etc., more effective human-robot coordination could be realized than the conventional passively controlled ones.

Some researchers have proposed human-robot coordination system, in which robots move actively based on information from humans and the environments. Shibata has developed a seal-type robot "PARO", which interacts with humans and could heal them mentally [4]. Fujita et al. has developed an autonomous dog-type robot referred to as AIBO for entertainment [5]. Tashima has studied interactive pet robots with emotional models [6]. These robots behave based on external information such as sound, light and physical interaction detected by touch sensors etc. Since most of these robots have been developed for entertainment or mental healing, we would not have many physical interactions with robots. To realize complicated tasks, however, physical interaction between the robots and the humans would be required. In this research, we discuss human-robot coordination with physical interaction between a human and a robot to realize tasks effectively.

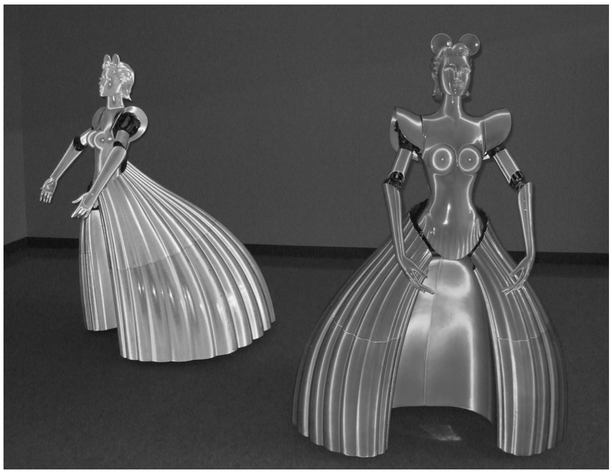

Fig. 1 Partner Ballroom Dance Robot.

Especially, in this paper, we restrict our attention to a dance partner robot performing ballroom dances with a human as an example of human-robot coordination with physical interaction. In ballroom dances, a dancer needs to have a physical interaction with a dance partner. Each dancer has to estimate the intention of the partner, and moves based on partner's intention, information on the environments, knowledge of dances, etc. to dance gracefully. Therefore, the ballroom dance is a good example for human-robot coordination based on the physical interaction between the human and the robot.

In the following part of this paper, first, we introduce a dance partner robot referred to as PBDR (Partner Ballroom Dance Robot), shown in Fig.1, which has been developed for a platform for investigation of the effective human-robot coordination. Next, we explain designing hardware structure of PBDR and its control architecture, referred to as CAST (Control Architecture based-on Step Transition), for moving the robot based on the human intention and knowledge of dances. PBDR has performed ballroom dancing with a human dancer at the prototype robot exhibition organized by NEDO, held in Aichi EXPO 2005.

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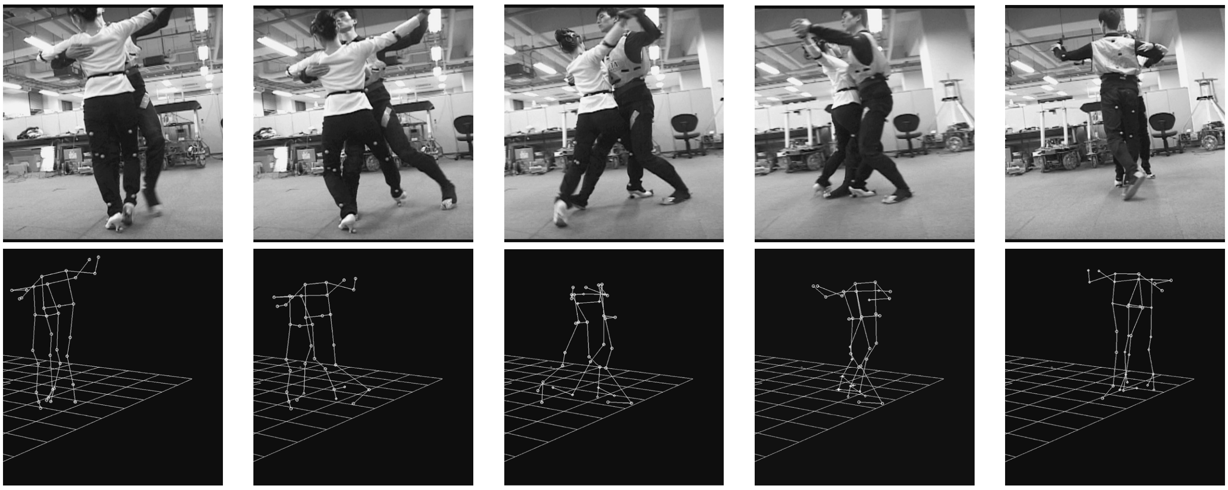


(a) (b) (c) (d) (e)

Fig. 4 Dancing motion analysis using motion capture system.

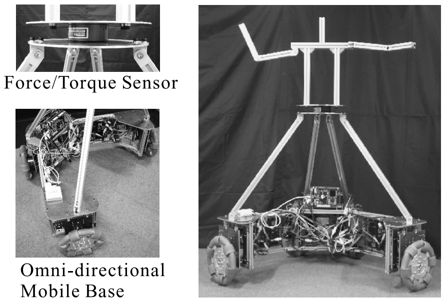


Fig. 2 Prototype of dance partner robot.

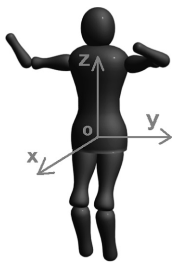


Fig. 3 Coordinate system for female dancer.

2. Partner Ballroom Dance Robot

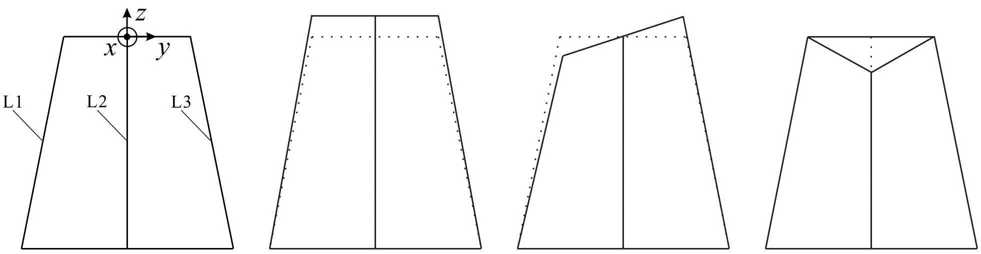
In this section, we introduce the dance partner robot, referred to as PBDR. The original concept of the dance partner robot was proposed in [7]. We considered that estimating human intention and moving based on the intention could be essential functions for robots which could help humans and become good partners for humans. The main purpose of our research is to investigate the effective human-robot coordination. As an example of human-robot coordination systems, we have developed a dance partner robot, which performs ballroom dancing with a human. In ballroom dances, a dance couple consists of a male dancer and a female dancer, and he decides the next step and leads her. On the other hand, she estimates the step intended by him based on his leading, and move along the step with him.

The dance partner robot acts as a female dancer and realizes ballroom dances with a human dancer. Therefore the robot has to estimate the next step intended by the human, and generate dancing motions to follow the human. The prototype robot, shown in Fig.2, was developed as a platform for testing the estimation algorithm. The force/moment information applied by the human is indispensable for the robot to estimate the next step intended by the human and to coordinate its motion with the human. Therefore, the robot had a Body Force Sensor [8], which is a force/torque sensor installed between the upper body and the lower body of the robot. And the robot also had an omni-directional mobile base mechanism with special wheels developed by RIKEN [9] to realize various dancing motions. The omni-directional mobile base includes a large space to avoid collisions with human legs in dancing. The human could move own legs with freedom in the space. Although the prototype robot could dance with the human by estimating human's step successfully, it could generate only two dimensional motions, i.e. x-y plane in Fig.3, because it was designed simply for testing.

However, human dancing motions are three dimensional motions. In order to have closer interaction with the human dancer, the robot should generate three dimensional motions like a human dancer. In this paper, a new-type dance partner robot is developed, which has not only the previous functions but also upper body motions. In addition to the new hardware functions, the robot should give friendly feelings to humans in order to be a good partner for humans. Therefore an exterior of the robot is designed, which promotes friendship between the robot and humans. In section 3, the hardware modules and the exterior are designed and integrated to develop the friendly partner robot PBDR.

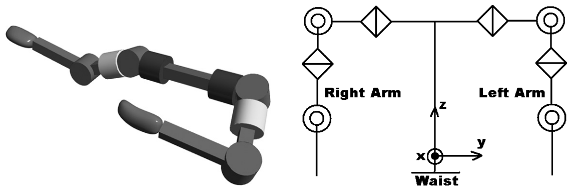
3. Design of Hardware Modules and Integration

Before designing hardware structure, dancing motions by human dancers are analyzed, as shown in Fig.4. The following facts are found by the analysis. Each dancer holds the partner with keeping own back and arms at a specific shape, referred to as "Dance Frame". And each dancer turns own face leftward. With respect to upper body motions, three kinds of motions are mainly observed. The first one is a translational motion along z axis in Fig.3, referred to as "Rise and Fall". The second one is a rotational motion around x axis, referred to as "Sway". The third one is a rotational motion around y axis, referred to as "Backward Pose".



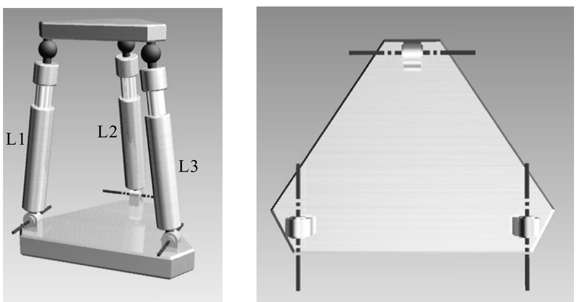
(a) Initial pose (b) Rise and fall (c) Sway (d) Backward pose

Fig. 7 Motion of parallel mechanism.



(a) Dance frame (b) Actuator configuration

Fig. 5 Design of arms.



(a) (b)

Fig. 6 Parallel mechanism for upper body motions.

(a) Body (b) Arm

Fig. 8 Mannequin, which give us a hint for designing exterior.

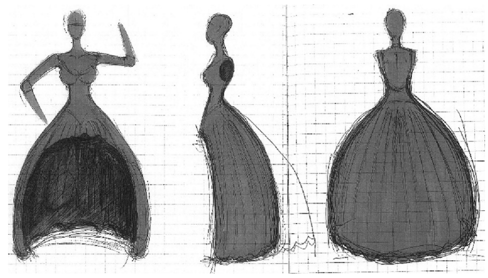


Fig. 9 Drawing of PBDR exterior.

Considering the analysis, robot's arms are designed so as to move the arms to "Dance Frame", as shown in Fig.5, whose degrees of freedom are 4×2. And a neck is designed using a revolute joint with one degree of freedom for changing the direction of robot's face. With respect to upper body motions, parallel mechanism is adopted for motion generations. In Fig.6(a), the upper plane corresponds to robot's waist, and the lower plane corresponds to robot's mobile base. Link L_1, L_2, and L_3 are linear actuators with ball screws. Each linear actuator is connected to the upper plane with a ball joint. On the other hand, each linear actuator is connected to the lower plane with a revolute joint, which has one degree of freedom around a direction shown in Fig.6(b). Generally, parallel mechanism has many degrees of freedom. By using the revolute joint, its degrees of freedom are reduced. The reduction enables the parallel mechanism to generate motions with 3 DoF when link L_1, L_2, and L_3 are actuated. The parallel mechanism could generate upper body motions, i.e. "Rise and Fall", "Sway", and "Backward Pose", as shown in Fig.7.

Moreover, a beautiful exterior that gives friendly feelings to humans is designed. A dress designer, Tatsuya Oconogi, considers that humans will accept the robot whose face is pretty with big ears, and shape of its body is like a slender woman as shown in Fig.8. According to his idea, the exterior is designed, as shown in Fig.9 and Fig.10. The actuators for robot's arm are arranged appropriately so as to fit within the slim arm in Fig.8(b). And the details of parallel mechanism and mobile base are designed so as to create a large space for human legs motions and to fit within the exterior like a slender woman. It is very important for developing partner robots to design parts and integrate them appropriately with due consideration for not only their hardware functions but also exteriors. Fig.11(a) shows the whole of CAD model, and Fig.11(b) shows robot's hardware structure. Thus, the hardware of PBDR, as shown in Fig.1, is developed by integrating a Body Force Sensor, an omni-directional mobile base, dual arms with 4×2 DoF, a neck joint with 1 DoF, a parallel mechanism with 3 DoF, and the beautiful exterior.

4. Modeling Software Modules and Integration

In this section, we explain modeling software modules based on the features of ballroom dances. The modules are integrated into robot's control architecture, referred to as CAST.

4.1 Features of Ballroom Dances

In order to realize ballroom dances, the robot should be controlled based on features of ballroom dances. Therefore we consider the features of ballroom dances at first.

In ballroom dances, a male dancer pairs up with a female dancer, and dances with her on the dance floor. Ballroom dances consists of many kinds of dances such as Waltz, Tango,

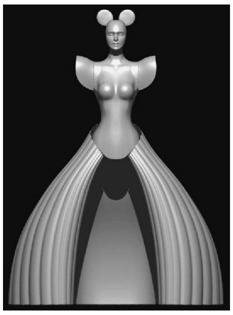
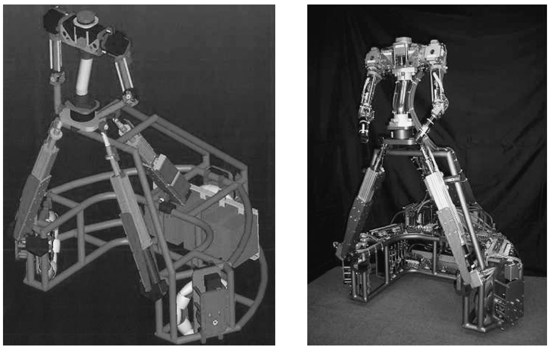


Fig. 10 CG design of PBDR exterior.



(a) CAD model (b) Structure

Fig. 11 Hardware structure of PBDR.

Rhumba, Quickstep, Cha-Cha-Cha, Blues, and so on. Furthermore each dance consists of many dance steps. The features of ballroom dances are summarized as follows.

- Ballroom dances have some kinds of dances, and each dance consists of many kinds of steps as shown in Fig.12. Each step has a characteristic motion.
- Ballroom dances are realized by the transition of some steps, which are determined by the male dancer. He decides the next step based on the information on environments, transition rules of steps and so on, and he leads the female dancer. She estimates his step based on force/moment applied by him, transition rules of steps and so on.
- Each dancer coordinates own motions with partner's in dancing.

According to the features, ballroom dances are modeled for the robot.

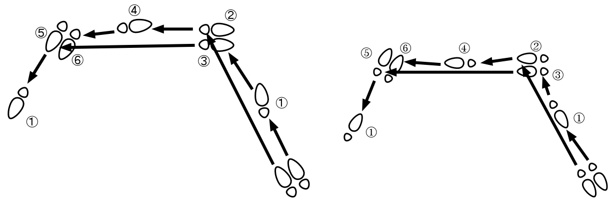
4.2 Modeling Software Modules for Ballroom Dances

4.2.1 Dance Step Trajectories

For generating robot's motions which follow dance step motions, we require the trajectory of each step. We get these trajectories from measurements of human dancing motions by using a motion capture system. A memory module for dance step motions, referred to as "Step Motion", is formed based on the measurements.

4.2.2 Transitional Relationships among Steps

A human dances steps using right foot and the left foot by turns, as shown in Fig.12. Therefore, the human chooses the next steps not at random but based on the previous step. There exist transitional relationships among steps. As examples of steps, we take up five steps in Waltz, i.e. Closed Change Left



(a) Male dancer (b) Female dancer.

Fig. 12 Example of dance step motions.

(CCL), Closed Change Right (CCR), Natural Turn (NT), Reverse Turn (RT), and Square Turn (ST). If a human dances CCR that finishes with the right foot, the next step must be either CCL or RT, which starts with the left foot. According to the footwork of each step, the transitional relationships, referred to as "Step Transition", are created, as shown in Fig.13. In this figure, arrows which are derived from each step show possibilities of the transitions.

4.2.3 Dance Step Estimation

PBDR has to estimate the next step, intended by the human, based on transitional relationships among steps and force/moment applied by the human shown in Fig.14, which are measured using a Body Force Sensor. For the step estimation, we utilize the time series of force/moment data as shown in Fig.15. we have to consider the uncertainty of data such as time-lag and variation for each repeated trial, as shown in Fig.16, because a human can not always apply the same force/moment to the robot exactly in each repeated trial of dancing. In order to treat the time series data including the human uncertainty, Hidden Markov Models (HMMs) are used for the estimation models. HMM is a stochastic method for modeling observed data with uncertainty [10]. The detail of designing the estimation models, referred to as "Step Estimator", is described in [11].

4.2.4 Motion Generation

In order to realize cooperative dancing with the human, the robot would need to generate at least two kinds of motions. One is the motion to follow dance step trajectories based on Step Motion. And the other is the motion to coordinate robot's motion with human's. The motion generation module, referred to as "Motion Generator", is designed so as to realize two kinds of motions.

4.2.5 Error Recovery of Step Estimation

An error recovery problem for step estimation has to be considered for the case that the robot mistakes step estimation. The error will be detected by measuring human legs motions because the characteristics of each step are mainly appeared at legs after starting the step. The error recovery module, referred to as Error Recovery, enables the robot to continue dancing with the human even if the step estimation is failed.

4.2.6 Collision Avoidance with Other Dance Couples

There exist other dance couples on the dance floor. Therefore collision avoidances with them should be considered. If other couples' motions are recognized, the human-robot couple can avoid the collisions. A module that recognizes other couples' motions, referred to as Couple Detector, gives the useful information for step estimation to the robot because the human will select an appropriate step based on other couples' motions. Even if the human can not select the appropriate step, Couple Detector enables the human-robot couple to avoid the collisions

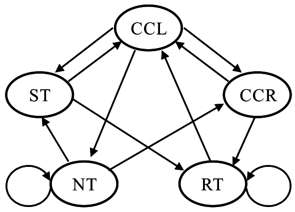


Fig. 13 Transitional relationships among five steps in waltz.

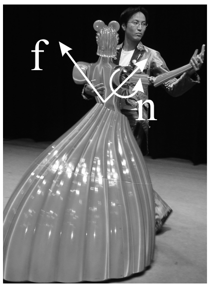


Fig. 14 Physical interaction between human and PBDR.

by adjusting their own dance step stride based on the information on environments.

4.2.7 Other Modules

In order to realize more interactive dancing with the human, many modules should be considered, e.g. a module that generates cooperative upper body motions in dancing based on physical interaction between the human and the robot, a module that synchronizes robot's motions with dance music, a memory module that stores parameters for human dance skill and renews the parameter at regular intervals, and so on.

4.3 Control Architecture "CAST"

Each module should be integrated appropriately because functions only one module can provide are limited. A control architecture, referred to as CAST (Control Architecture based on Step Transition), is designed by integrating modules. At first, Step Motion and Step Transition, both of which are memory modules for knowledge about ballroom dances, are put together into a main memory module, referred to as "Knowledge". Knowledge is indispensable for the robot to realize ballroom dancing. Next, Step Estimator is put into the control architecture. Step Estimator needs the information from Step Transition and the sensory information, i.e. force/moment applied by the human, to estimate the next step intended by the human. And the estimation results are sent to Motion Generator and Error Recovery. Error Recovery judges the error occurrences of step estimations based on the sensory information, i.e. human legs motions, and sends True/False signal about the current step to Step Estimator for re-estimating human's step. Couple Detector, which detects other couples' step motions based on the sensory information on environments, gives probability of collision for each step to Step Estimator, which is the useful information for step estimation. Couple Detector also calculates an appropriate length of dance step stride based on human-robot couple's step motion and other couples' step motions, and sends the appropriate stride to Motion Generator for avoiding the collision with other couples. Motion Generator creates robot's desired motions based on Step Motion, the estimated step, force/moment applied by the human, and the appropriate stride. Finally, the desired motions are sent

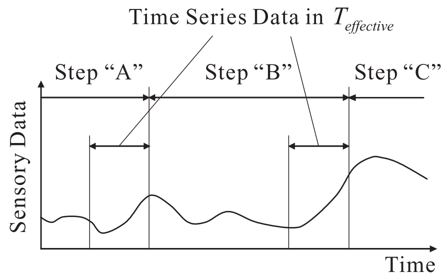


Fig. 15 Time series data for step estimations.

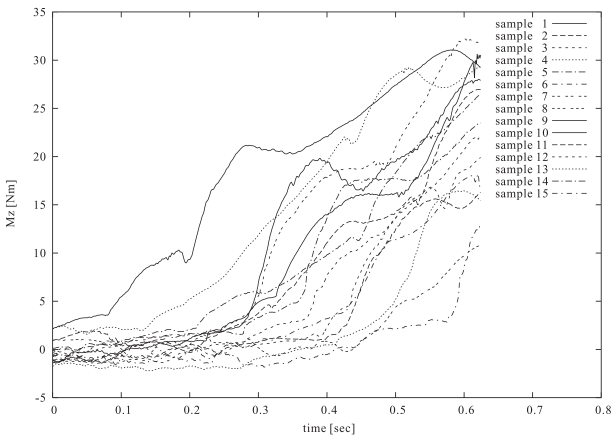


Fig. 16 Sensory data with time-lag and variation for each trial.

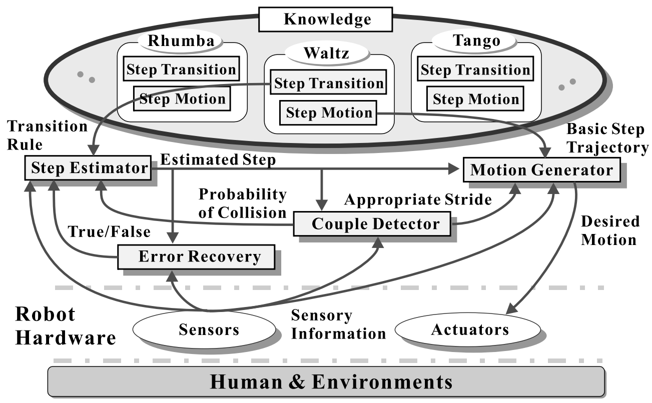


Fig. 17 Control architecture CAST.

to actuators of PBDR by Motion Generator. Thus, the control architecture CAST is designed as shown in Fig17, which realizes ballroom dancing between the human and the robot. As a matter of course, other modules can be added into CAST by integrating them appropriately.

5. Experiments

To illustrate the validity of designing hardware structure and control architecture, ballroom dancing by a human and PBDR was demonstrated at the prototype robot exhibition organized by NEDO, which was held in Aichi EXPO 2005. For testing the step estimation module, simplified CAST is used, which has Knowledge, Step Estimator, and Motion Generator. Error Recovery, Couple Detector, and Other Modules will be addressed in the future works. The experimental result of the robot dancing Waltz with the human is shown in Fig.18. In Fig.18, the robot realized a sequence of steps: CCL in Fig.18(a)(b), NT in Fig.18(c)(d)(e), CCR in Fig.18(f), RT in Fig.18(g)(h)(i), CCL in Fig.18(j), and ST in Fig.18(k)(l), as examples of steps in

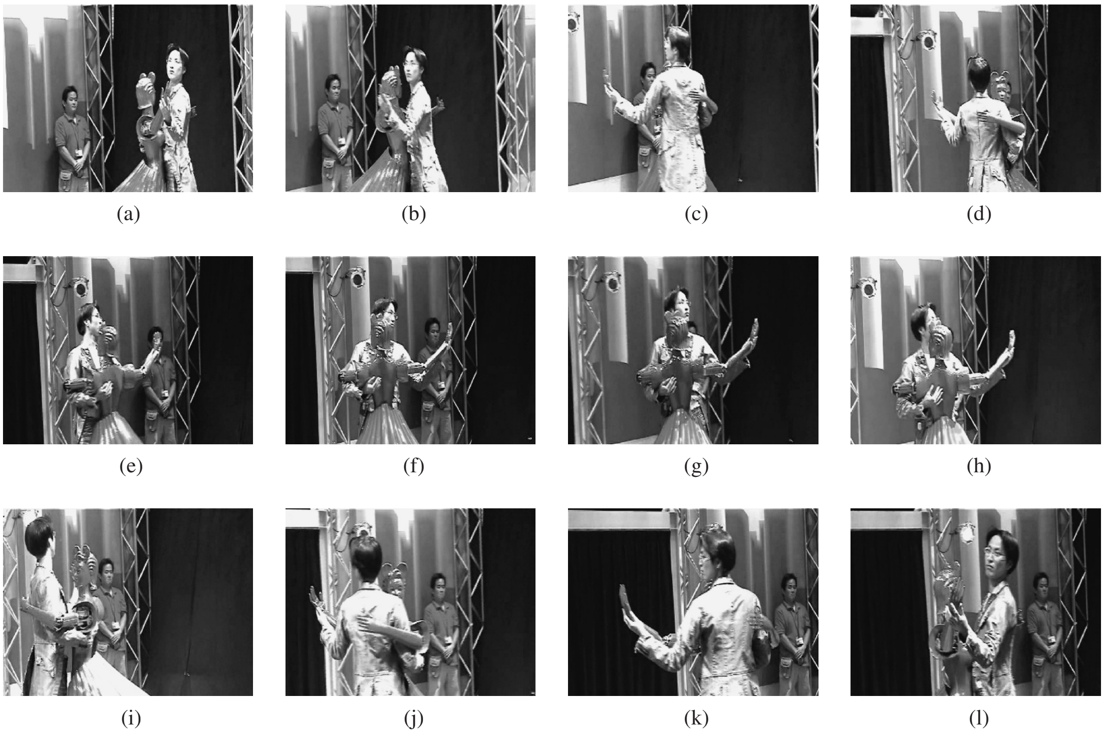


Fig. 18 Dacing waltz by human and PBDR.

Waltz. The robot realized the transitions of steps by estimating human's step successfully. PBDR could also give friendly feelings to visitors according to the results of questionnaires. Moreover, PBDR was selected for the 2007 Good Design Award in Japan.

6. Conclusion

In this paper, we discussed human-robot coordination with physical interaction. As an example of the effective human-robot coordination, we introduced a dance partner robot, referred to as PBDR. Its hardware structure and control architecture CAST are developed by integrating modules appropriately, which are designed based on measurements of human dancing motions. PBDR could dance Waltz with a male dancer by estimating his step successfully at the prototype robot exhibition organized by NEDO, held in Aichi EXPO 2005. Designing both of hardware parts and software modules based on measurements, and integrating them appropriately with due consideration for their specifications, functions, and exteriors, are very important issues for developing partner robots, which will help humans and be good partners for humans in the future.

Acknowledgments

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Mitsuru Endo

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Mizuo Koizumi was born in 1968. Since 1991, he has been working as a mechanical engineer at the Nomura Unison Co., Ltd. He is an Assistant Manager in the Department of Development Engineering, and is currently engaged in development of Factory Automation equipments. He developed mechanical components of the Partner Ballroom Dance Robot.

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Tatsuya Oconogi was born in 1963. He entered ISSEY MIYAKE INTERNATIONAL Inc. in 1984, and took part in the Paris Collection as a Chief Designer in 2000. He was a freelance designer from 2002 to 2003, and founded TroisO Co., Ltd., in 2003. He is a Director and a dress designer at TroisO Co., Ltd. He designed the exterior of the Partner Ballroom Dance Robot.