Robotic Dance in Social Robotics—A Taxonomy

Hua Peng, Changle Zhou, Huosheng Hu, Fei Chao, and Jing Li

***Abstract*—Robotic dance is an important topic in the field of social robotics. Its research has a vital significance to both humans and robotics. This paper presents a review of the state of the art in robotic dance. Robotic dance is classified into four categories: cooperative human–robot dance, imitation of human dance motions, synchronization for music, and creation of robotic choreography. The research methods in each category are discussed. Future research areas are highlighted.**

***Index Terms*—Cooperative human–robot dance, robotic choreography, robotic dance, synchronization for music, taxonomy.**

I. Introduction

DANCE as a form of performing arts includes a wide range of social behaviors [1], [2], is an important means of communication [3], [4], is a useful tool for psychological and physical therapy [5]–[8], and is a natural means of emotional expression [9], [10]. According to Hanna [1]: *TO DANCE IS HUMAN, and humanity almost universally expresses itself in dance. Dance interweaves with other aspects of human life, such as communication and learning, belief systems, social relations and political dynamics, loving and fighting, and urbanization and change.*

Robotic dance has attracted interest in the field of social robotics, and dancing robots can perform many kinds of robotic dances [11], [12]. In general, robotic dance has many social effects in society: 1) It is a kind of interactive social behavior, in particular human–robot interaction [13]–[17] and animal activity [18], [19]; 2) it is a way to express the emotions or intentions of robots through nonverbal communication [20], [21]; 3) it is a treatment and therapy for a wide range of illnesses, including autism [22]–[24], developmental disorders [25], [26], and attention deficit and cognitive disabilities [27], [28]; 4) it is a tool to enrich the need of growing spiritual cultures of society; 5) it enhances entertainment and commercial performances [29]–[31]; and 6) it can promote the inheritance and dissemination of human culture [32], [33].

Robotic dance can also contribute to research in robotic applications: 1) Develop the robotic ability to interact with human effectively according to different tasks, environments, and human activities [34]–[44]; 2) enhance the socially interactive characteristics of robots [16], [45]–[47] and their coordinative ability with environments [16], [48]–[58]; 3) expand the learning ability and the motion skill of a robot [32], [33], [59]–[63], for a high degree of autonomy; and 4) promote the robot innovation capability [13]–[15], [58], [64]–[69] and the advanced development of artificial intelligence technology.

Dancing robots involve the exploration of the physical hardware structures, kinematics, dynamics, and the automation of a robot so it can dance. On the other hand, robotic dance is an expressive form of the art of dance performed by robots and is focused on how to make a robot dance as a human does, and how a robot creates and performs beautiful dance.

This paper reviews the state of the art in robotic dance developed by artificial intelligence methods after 1990. Fixed programmed methods are not included. Eighty-four papers are included in the analysis. The details of the used search terms, the searched databases, and the included publications are illustrated in Table I. Our initial analysis identified that the three main research questions in the field are: 1) How can a robot dance as a human does? 2) How could a robot effectively interact with people? 3) How can a robot be enabled to bring joyfulness to people's lives? It also identified that the classification schemes for robotic dance are not robust.

The main contributions of this paper include the following:

1) a novel framework for classifying robotic dance;
2) a hierarchical tree-structure to highlight research categories;
3) an analysis of research subcategories;
4) a discussion of the findings with respect to robotics;
5) potential research directions of robotic dance.

The rest of this survey is organized as follows. Section II presents the tree-structure taxonomy based on the current research content of robotic dance, in which four main categories are identified, namely cooperative human–robot dance, imitation of human dance motions, synchronization for music, and creation of robotic choreography. Meanwhile, each category is introduced and analyzed, respectively, in this section. In Section III, the four categories of robotic dance and dancing robots are discussed, and future research areas are highlighted.

II. Taxonomy

Focusing on the intelligent methods, Fig. 1 summarizes the current state of art of robotic dance using a tree-structured

Manuscript received May 5, 2014; revised July 29, 2014 and October 14, 2014; accepted November 17, 2014. Date of publication February 16, 2015; date of current version May 13, 2015. This work was supported by the National Key Basic Research Program of China (973 program) under Grant 2013CB329502; the National Natural Science Foundation of China under Grant 61273338, Grant 61363073, and Grant 61203336; and the Major Program of National Social Science Foundation of China under Grant 11&ZD088. This paper was recommended by Associate Editor C. M. Lewis. *(Corresponding author: Changle Zhou).*

H. Peng is with the Fujian Provincial Key Laboratory of Brain-like Intelligent Systems, and the Cognitive Science Department, Xiamen University, Xiamen 361005, China, and also with the College of Information Science and Engineering, Jishou University, Jishou 416000, China (e-mail: 6195340@qq.com).

C. Zhou and F. Chao are with the Fujian Provincial Key Laboratory of Brain-like Intelligent Systems, and the Cognitive Science Department, Xiamen University, Xiamen 361005, China (e-mail: dozero@xmu.edu.cn; fchao@xmu.edu.cn).

H. Hu is with the School of Computer Science and Electronic Engineering, University of Essex, Colchester CO4 3SQ, U.K. (e-mail: hhu@essex.ac.uk).

J. Li is with the College of Musicology and Dancing, Jishou University, Jishou 416000, China (e-mail: lijing_47@sina.com).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/THMS.2015.2393558

TABLE I
SEARCH STRATEGY OF LITERATURE SURVEY

Searched Terms	Searched Database	Source Publications
"robotic dance"		*Journals:*
OR	ACM	The International Journal of Robotics Research; SICE Journal of Control, Measurement, and System Integration;
"robot dance"		IEEE Transactions on Industrial Electronics; Computer Graphics Forum; Journal of Three Dimensional Images;
OR	IEEE	International Journal of Hybrid Information Technology; Information and Media Technologies; TELKOMNIKA Indonesian
"robot choreography"		Journal of Electrical Engineering; Neural Computing and Applications; IEEE Transactions on Haptics; Design Studies.
		Conferences:
OR	EI	IEEE International Conference on Robotics and Biomimetics (ROBIO); IEEE/RSJ International Conference on Intelligent
"robotic dancing"		Robots and Systems (IROS); IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN);
OR	ProQuest	ACM/IEEE International Conference on Human–Robot Interaction (HRI); IEEE International Conference on Robotics and
"robot dancing"		Automation (ICRA); Conference on Designing for User eXperiences (DUX); International Conference on the Simulation and Synthesis of Living Systems; IEEE International Conference on Automatic Face and Gesture Recognition (FG);
OR	IEL	International Conference on Neural Information Processing(ICONIP); International Conference on Entertainment Computing (ICEC); IEEE International Conference on Multisensor Fusion and Integration for Intelligent Systems (MFI);
"dancing robot"		Iberian Conference on Information Systems and Technologies (CISTI); IEEE International Conference on Control and
OR "robotic choreography"		Automation(ICCA); International Conference on Autonomous Agents and Multiagent Systems(AAMAS); IEEE International Conference on Systems, Man, and Cybernetics(SMC); Workshop for Young Researchers on Human-Friendly Robotics (HFR); IEEE-RAS International Conference on Humanoid Robots (Humanoids).
		Book sections:
		New Frontiers for Entertainment Computing.
		Theses (M.S.) and dissertations (Ph.D.):
		Carnegie Mellon University; FEI TU of Kosice.

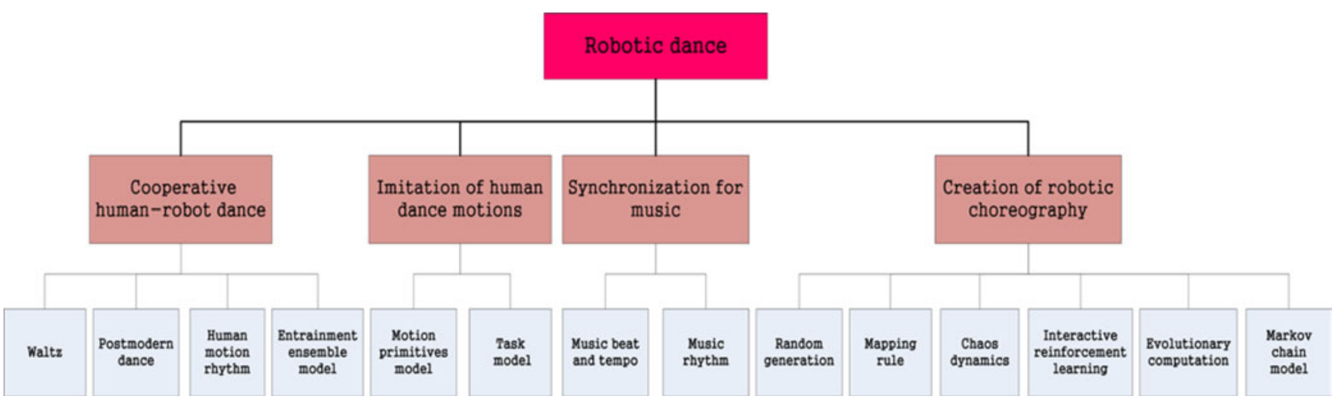


Fig. 1. Hierarchical taxonomy for robotic dance.

taxonomy. Robotic dance is classified into four categories (see Table II): cooperative human–robot dance, imitation of human dance motions, synchronization for music, and creation of robotic choreography. Each category subclass has interactive and real-time characteristics. The interactive characteristics identify if a bidirectional interaction exists between the robot and a human during robot dancing. The real-time characteristics identify if the design of the robotic dance is produced dynamically. To stimulate robots during dance performance, sensors are included and their types are also used in the categorization scheme.

A. Cooperative Human–Robot Dance

Cooperative human–robot dance is a research area in human–robot interaction, in which human dance behaviors influence the robot and robot dance behaviors impact the human. Due to its dynamic nature, the robotic dance cannot be predicted before it is performed, and the current dance motion is confirmed only by the current state and/or some source of stimulus. This section discusses four subclasses under the category of cooperative human–robot dance.

1) Waltz Performance: Waltz is a typical representation of a ballroom dance, with ten dance steps that contain basic motions and rhythms, and transitional relations of each dance step. Aimed at human–robot coordination with physical interaction [34], two dance partner robots—Ms-DanceR [34], [35] and PBDR [36]—have been designed to dance waltz with humans via tactile sensing.

Ms-DanceR serves as a prototype of PBDR; they have similar hardware structures [35], [36], [70], body dynamics [71], [72], and control architectures [35]–[41]. For waltz performance (see Fig. 2), Control Architecture based on Step Transition (CAST) is the core of cooperative human–robot waltz and has three forms:

TABLE II
ROBOTIC DANCE TAXONOMY

Research	Subclass	Interactive	Real-time	Stimuli	References
Cooperative human–robot dance	Waltz	Yes	Yes	Tactile	[34]–[41], [70]–[72]
	Postmodern dance	Yes	Yes	Visual	[45]–[47]
	Human motion rhythm	Yes	Yes	Visual, Tactile, Others	[16]
	Entrainment ensemble model	Yes	Yes	Visual	[42]–[44]
Imitation of human dance motions	Motion primitives model	No	No	Visual	[32], [33], [59]–[61]
	Task model	No	No		[62], [63]
Synchronization for music	Music beat and tempo	No	Yes	Auditory	[16], [48]–[58]
	Music rhythm	No	Yes		[56], [64]
Creation of robotic choreography	Random generation	No	No	Others	[65]
	Mapping rule	No	Yes	Visual, Auditory, Tactile	[66], [67]
	Chaos dynamics	No	Yes	Auditory	[68]
	Interactive reinforcement learning	Yes	No	Human subjective aesthetic evaluation	[82]
	Evolutionary computation TEC	No	No	Common fitness function	[83]
	IEC	Yes	No	Human subjective aesthetic evaluation	[13]–[15]
	Markov chain model	No	No	Auditory	[58]

Fig. 2. PBDR and its waltz performance [11].

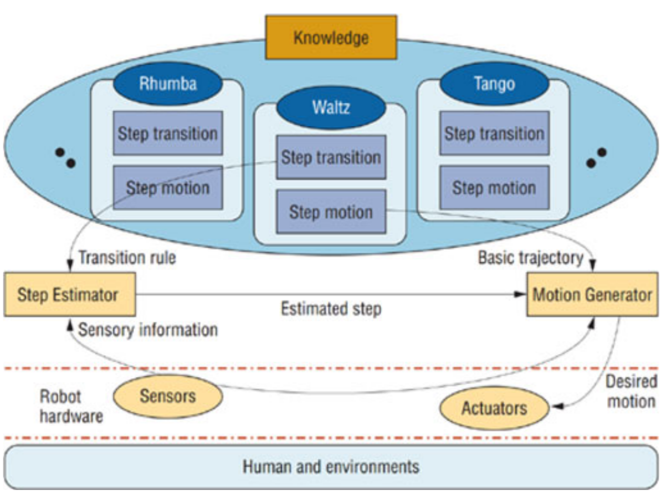


Fig. 3. Early CAST [11].

early form [35], [38], [41] (see Fig. 3), medium form [37], [39], [40], and advanced form [36]. CAST has been designed to be flexible and extensible so that more functional modules could be integrated to realize more interactive human–robot dance [36].

In CAST, "step estimation" not only determines effectiveness, but also helps to improve robotic intelligence by perceiving human intentions. Three methods of realizing "step estimation" are proposed: production rules based [35], neural network based [38], and HMM based [41]. The Hidden Markov Model (HMM)-based method has been shown to be more effective than the others with respect to the success rate of estimation.

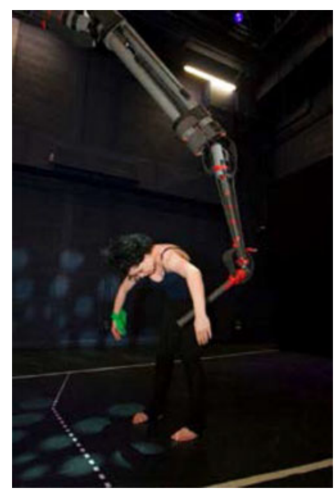


Fig. 4. SpiderCrab robot and its dance [45].

Both Ms-DanceR and PBDR have omnidirectional mobile bases (not legs); therefore, balancing is not a problem. However, a success rate of "step estimation" cannot reach 100% because of the difficulties of modeling and predicting human intentions. It is an open question if the robots can estimate a human's next step effectively when all ten waltz steps are included.

2) Performance of Postmodern Dance: Many forms of dance focus on structured movements. Ballet dance, for example, has extremely strict criteria on dance actions. Conversely, postmodern dance strives to eliminate all structures and grammars from dance movements. Dancers must forget their usual vocabularies and grammars of movements so that they can perform in a purely expressive way.

Bryden *et al.* [45] investigated human–robot interaction with the intention of developing artificial personalities. A system was constructed to perform a cooperative human–robot postmodern dance [46] based on Laban Movement Analysis by using a SpiderCrab robot [47] (see Fig. 4). The system consists of three parts: sensory input subsystem, robot controller subsystem, and improvisation subsystem. By capturing a human dancer's motions with the sensory input subsystem, the perceived

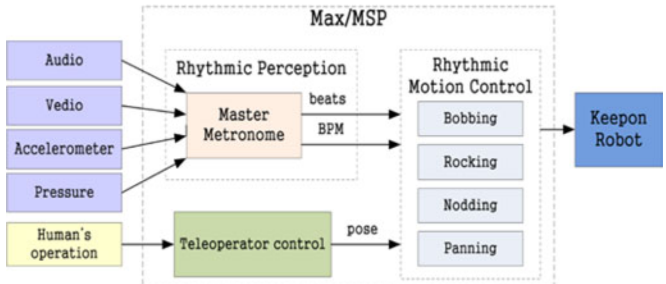


Fig. 5. Keepon's dance control architecture.

movements are mapped to the robot in the improvisation subsystem, which has three modes of responding to human movements: copy, follow copy, and oppose. Finally, the robotic dance motions are performed by the robot controller subsystem.

Essentially, the cooperative dance is improvisational based on the visual interaction between the SpiderCrab robot and a human. Robotic dance motions are determined by the dance motions of the human dancer and its current mode, so its dance is innovative and unpredictable. After dance performances, the human dancer feels that the robot is a real dance partner because of its responsive behaviors to a human's expressive offers [45], [46]. In this way, the interaction as a bidirectional expressive communication channel is very effective. Although the robot will slow its movement when it dances with a human, it is unable to detect the position of the human dancer for collision avoidance. If the improvisation subsystem has more modes, the robot's interaction with its human dance partner improves.

3) Dancing With Human Motion Rhythm: The rhythmic, synchronous, and regulatory characteristics are three important properties of human social interactions. In general, rhythmic interactional synchrony can make dancing more natural, comfortable, and effective. The robot should be capable of perceiving, modeling, and synchronizing with environmental and human interaction rhythms. Dance can be seen as a means of nonverbal social interactions. Michalowski [16] studied the rhythmic human–robot social interaction based on the creature-like robot Keepon [17] and proposed a general approach to designing rhythmic intelligence in social robots using the theory of rhythmic interactional synchrony.

Keepon has a snowman-like body and four degrees of freedom (bobbing, rocking, nodding, and panning). Fig. 5 shows its dance control architecture. To explore the rhythmic human–robot social interaction, Keepon uses a graphical programming environment named Max/MSP [73], which creates clocks and metronomes, process audio signals, and design the graphical user interface. In Max/MSP, a human teleoperator can control Keepon's pose or attentional direction and see the robot's view over an interface. A metronome can generate a series of beats separated by a given time interval to realize the desired beats per minute (BPM). The frequency of the master beat, which is the rhythm perceived by Keepon, can be obtained from multiple sensory modules [16], including audio sensors, visual sensors, accelerometers or pressure sensors.

Furthermore, there is a cluster of Max/MSP objects according to every Keepon's DOF. It can generate Keepon's rhythmic movement centered at its current direction of attention by using the beats of the master metronome, the current pose or the direction of attention, and the BPM. Thus, Keepon can perform synchronously dance movements that fluently and dynamically change the tempo according to the perceived rhythms (see Fig. 6). After observing Keepon's rhythm of movements, children will dance in a coordinated rhythm. Therefore, a rhythmic human–robot social interaction is realized.

The dance control architecture has resulted in a whole rhythmic behavior mechanism and has integrated several techniques for perception, generation, and synchronization. It becomes an effective medium of rhythmic human–robot interaction, and the dance-oriented interactions are useful to develop rhythmic perceptual and behavioral technology. However, Keepon has only four dancing movements: bobbing, rocking, nodding, and panning; therefore, its expressive ability is limited.

4) Entrainment Ensemble Model: The ability of communication is crucial for establishing a long-term interaction, especially body-based communication. However, it is a great challenge to keep a sustained dance interaction between a human and a robot.

Tanaka and Suzuki proposed an entrainment ensemble model (EEM) to address this problem [42]. As the basic element of EEM, an entrainment factor is a specific pair of motor behaviors between a human and a robot. For example, the relationship of a robot's nod in the rhythm of a human's clapping is an entrainment factor. By the compatibility and variation of the defined entrainment factors, a long-term dance interaction between human and robot is built. An EEM-based dance interaction system is used to explore the dance interaction between QRIO and toddlers in a daily life environment [43]. The result shows that EEM can make QRIO more attractive to toddlers in the dance interaction [44].

EEM builds many kinds of relationships as entrainment factors, and each relationship reflects a mapping from a human behavior to a robotic dance motion, regardless of whether the human behavior is a real dance movement or not. Thus, a robot can imitate human dance motions if the robotic dance motion is the same as the human movement with respect to some entrainment factors. Certainly, the robot can respond through some dance motions to some human behaviors if they are different in the definition of an entrainment factor. To enable humans to be active in the long-term dance interaction, EEM switches different modes of robotic dance motions across its entrainment factors so that the robot can produce complex and unpredictable dance behaviors innovatively.

However, EEM only responds to human behaviors (i.e., a passive model for robotic dance). Due to the lack of a module that estimates human intentions, it has limited intelligence and cannot predict next behavior or movement of human. Additionally, EEM has not stored any knowledge of human dances; therefore, the robotic dance may consist of meaningless actions.

B. Imitation of Human Dance Motions

To preserve and disseminate the traditional cultures of folk dance, robotic technology of imitating human dance motions is proposed; the technology not only enables robots to act like humans, but is also useful for training. The ability of

Fig. 6. Keepon dances with the perceived rhythms [17].

imitation learning can make robots quickly adapt to a new environment.

Because of the similarity of the form between a biped humanoid robot and people, the biped humanoid robots have been widely used in robotic dance research. Significantly, a unidirectional interaction exists from human to robot although both participate in the procedure of imitation. The robotic dance can only be performed after the robot has imitated all human dance motions, so the dance in this case is not in real time.

1) Motion Primitive Model: In the model, a motion primitive is a symbolic description of basic dance fragments, and dance is regarded as a sequence of primitive motions. After human dance motions are acquired from a motion capture system, they are extracted or segmented to some motion primitives. Then, these motion primitives are converted and retargeted to a specific humanoid robot platform for implementation. Two key problems needed to be solved. One is how to segment primitive motions effectively from the captured human dance motions, and the other is how to generate suitable robotic dance motions based on these primitives to realize the same human dance motions.

For segmentation, motion primitives and the structure of the whole human dance motion were detected based on the local velocity of minimum frames of the human hands and feet [32]. However, the essence of a dance was not detected robustly, and the captured human dance motions were divided into too many segments [59]. Shiratori *et al.* considered the center of mass and musical rhythm besides hands and feet in [59], [60], which can divide the sequence of dance motions into the appropriate segments (motion primitives).

To address generation, Nakazawa *et al.* [32] used the techniques of dynamic balancing and inverse kinematics, and Nakaoka *et al.* [33], [61] considered the methods of satisfying the physical constraints and dynamics consistency of the robot. The latter is more advanced, and is applied to generate the imitated dance motions for the robot on the whole body [61] and legs [33]. However, balance control in both approaches is not good enough due to the absence of various waist motions support, foot trajectory control, and yaw moment compensation.

Furthermore, the current methods used in the design of motion primitive model are not sufficient. First, upper body only includes arms [61] or hands [59], [60], and many important body parts for expressing the characteristics of dance are not included, such as the neck and waist. Second, there are only three kinds of leg motion primitives: STAND, STEP, and SQUAT [33]. While suitable for some folk dances, they are not sufficient for imitating others. Third, it is not clear how to synthesize the motion primitives of all body parts into a coordinated dance motion of a whole body for a robot.

2) Task Model: The Learning-From-Observation (LFO) paradigm is a technique that enables a robot to understand and learn to do a task just by observing human demonstrations [74], [75]. To achieve a framework of imitating human dance motions based on the LFO paradigm, abstract task models are introduced. While each action consists of both nonessential and essential parts, the robot only needs to mimic the essential parts in human dance motions because each person's body has different dimensions. Thus, the abstract task models are used as a tool to present these essential parts of human dance motions [63].

Each task includes two components, which explain what to do and how to do the task, respectively [62], [63]. After human dance motions are observed by a robot, several task sequences are produced for representing these motions, and each task sequence corresponds to a body part of the robot. Each task in every sequence is processed to generate suitable joint angles of some body part of the robot. Finally, all the joint angles of robot's body parts are integrated into a whole dance motion to be transferred to the robot.

Due to the differences of physical function between upper body and leg, two different task models are used to handle upper body and leg motions, respectively. Nakaoka *et al.* proposed a leg task model by considering the effects of waist and feet in the procedure of imitating in [62], and Kudoh *et al.* [63] integrated the upper body and leg task model [62] as a whole to achieve the LFO for imitating human dance motions. By using the task models, the real robots can successfully perform Japanese folk dances they observed [62], [63] (see Fig. 7).

Based on the motion primitive model, a task model is more productive to imitate human dance motions because it can effectively extract the essential characteristics of human dance motions and map these to the robot. It overcomes the physical differences between a human and a biped humanoid robot. Moreover, to guarantee harmony of dance motions and balance

Fig. 7. HRP-2 imitates human dance motions by using task model [11].

of the robot body, the method of ZMP compensation and yaw compensation are used [62], [63]. More importantly, the task model is a general model to control the imitation of motion, which can be used in different kinds of robot morphology, only if the task (what to do) and the skill parameter (how to do) can be described properly.

There are some weaknesses in the task model. First, the task model has its own prerequisite in use. To imitate some motions on some body parts of a robot, the task model must be customized according to the characteristics of the motion and the body part. Unfortunately, the customized task model can only be suitable for special use. For example, the task model in [62] and [63] is suitable to imitate Japanese folk dances (such as Aizu-Bandaisan, Jongara-bushi, and Kabuki) that have the characteristics of keeping both feet on the floor and cannot imitate dances with other motions such as spin, turn, leap, or sitting on the floor. Second, the expressive ability of the task model is limited. The motions of human dance vary in number and degree of difficulty. Due to the difference in body structure between the human and robot, some human dance motions may exceed the physical limit of mechanical devices of the robot. These dance motions cannot be imitated by using the task model because its task and skill parameter cannot be described.

C. Synchronization for Music

In society, dance is usually accompanied by music. Music has many elements, including beat, rhythm, melody, timbre, dynamics, tempo, harmony, and mode. Thus, how to synchronize robotic dance motions to music is an interesting research topic in robotic dance.

1) Synchronization for Music Beat and Tempo: Music beat and tempo are two important means of musical expression and are connected tightly together. They complement each other for synchronization with robotic dance. Therefore, if a robotic dance is synchronized to one, it must be synchronized to the other. The key to synchronizing robotic dance motion to music beat and tempo lies in the solutions to two problems: how to accurately calculate the next predicted music beat and the next inter-beat-interval, and how to reasonably arrange robotic dance motion to start at the next predicted music beat and finish within the next inter-beat-interval.

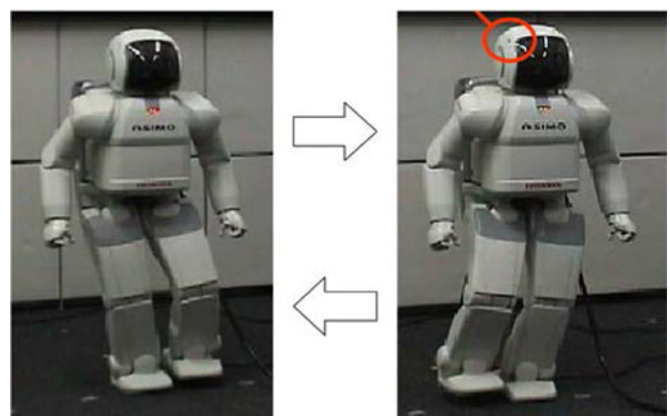


Fig. 8. Asimo dances while listening to music by its microphone [48].

Several approaches are developed to recognize music beats and to synchronize them. The Max/MSP environment is used to perceive music beats and enables Keepon to dance in synchrony with music beats [16] (see Section II-A3). The robotic steps were viewed as the basic dance actions in [48] and [49], and a feedback-control method was used to regulate the step intervals of the robot to keep its steps in time with musical beats [48] (see Fig. 8) that were predicted in a real-world environment by implementing a beat-tracking method based on [76]. By contrast, Murata *et al.* designed a new beat-tracking algorithm using spectro-temporal pattern matching and used a shorter window length to achieve robust estimation of music tempo. A noise cancellation method is introduced based on the semiblind independent component analysis [77] (semiblind ICA) so that a robot can perform its steps with the predicted music beats in a noisy environment [49].

After estimating music beats and predicting the next inter-beat-interval by IBT [78], Santiago *et al.* assigned and implemented a dance movement chosen from a predefined dance library for the next beat interval [50]. In [51], the beat positions from music signals are extracted in real time by using a beat identification algorithm [79], [80], and then some dance moves stored in a motion database were arranged for synchronizing the predicted beats of music. Seo *et al.* used fast Fourier transform to achieve the real-time beat extraction, and Labanotation [81] was used to create robotic dance motions. The dance motions of the robot were modified to accomplish the synchrony based on the detected music BPM [52]. In [53], a new beat-tracking method was proposed to acquire beat and tempo from music audio signals, and the timing of beats was used to synchronize robotic dance motions with it.

Unlike the above methods, Tholley *et al.* proposed a framework based on reinforcement learning [54] in which robots can respond rhythmically to music beats and learn how to dance. Inspired by the law of human dance with different music tempos, robotic motions are modified according to the change of music tempo and robotic joint limitation [55]–[57]. Xia *et al.* proposed a method to create robotic choreography based on the Markov chain model [58], which can synchronize the produced robotic dance to music beats and emotions (see Section II-D6).

Music beats, as a synchronous signal, guide the procedure of arranging robotic dance. Music tempos influence the speed of robotic dance motions. The robotic dance is in tune with music beats and the speed of the dance motion is changing with music tempo to make the robot dance in a harmonious manner. Moreover, robotic dance motions predefined in a motion database are extracted to form a sequence of dance motions; therefore, the dances created by these methods always maintain their characteristics. From the perspective of artificial intelligence, the above methods endow a robot with the ability to dance in synchrony with music beat and tempo, and to express more human-like behaviors.

However, music has many other important features, such as rhythm, melody, timbre, dynamics, harmony, and musical form, which have not been considered by the above methods. Moreover, although robotic dance created by these methods is innovative to a certain extent, these motions are predefined in their database. Repeated robot dance motions can become boring over time. It is difficult to implement real-time algorithms of music beat tracking; therefore, it may weaken the charm and effect of the produced robotic dance.

2) Synchronization for Music Rhythm: The original element of music is harmonious sound, and its essence is music rhythm. Rhythm not only organizes orderly music to run, vary, and develop, but also makes music notes to become long or short, strong or weak, so that music is graceful. Similar with music, dance has its own rhythm. Rhythm endows the proper movement characteristics of dance, which allows dance movements to be fused in continuous rhymes. After extracting the rhythms of music and robotic dance, respectively, we can synthesize and synchronize both of them in a matching manner. Then, the robot can dance with music harmoniously.

Based on this idea, Shiratori *et al.* presented a method of automatic synthesis of human motion and music, aiming to synchronize robotic dance motion to music rhythm [56], [64]. The method consists of three stages: motion feature analysis, music feature analysis, and motion synthesis based on both features. In the stage of motion and music feature analysis, each motion with the corresponding rhythm and intensity features is

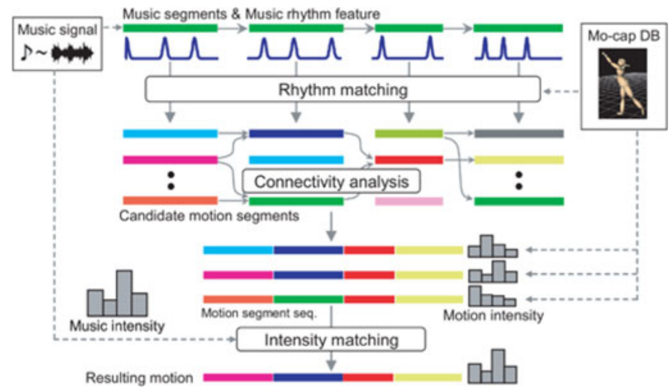


Fig. 9. Overview of motion synthesis algorithm in [64].

acquired from input dance motions, and music segments with the corresponding rhythm and intensity features are generated after analyzing the input music sequence. In the motion synthesis stage (see Fig. 9), a dance motion can be chosen according to the rhythm feature of each music segment, if the dance motion has similar rhythm feature as the current music segment.

The research can be expanded to the area of synchronizing robotic dance to music rhythm. Obviously, the features of music determine the result of dance choreography, which is a sequence of dance motions. The method can achieve effective dances generated by music and bring more adaptability and diversity. Because the basic dance motions are predefined, the dances produced can maintain the characteristics of the dance very well. If the method is applied on a humanoid robot, the robot will dance with music rhythm that is more lifelike and vivid, and will show more human-like behaviors.

However, the method has its own weaknesses. While music rhythm is used in synchronizing dance motion and music by matching both rhythms, many important music features are not used as matching objects. In addition, the set of alternative dance motions is static, and these basic dance motions always repeat in different dances. Finally, the method has been verified only on computer animation. Therefore, if it is expanded to the robot platform, many problems such as balancing control and motion adjustment must be considered.

D. Creation of Robotic Choreography

The creation and development of dances continuously improve human aesthetic consciousness. Human dance experts usually use their own familiar dance motions to create dance works. However, most robotic dances are realized by preprogrammed methods; as a result, people lose their interest in watching robotic dances as they may not be interested to interact with a robot with predictable motions.

1) Random Generation: The method of random generation is the simplest method to create robotic choreography. It needs a database of the dance motion units, where each represents a basic dance motion of the robot. These units are usually predefined according to a particular goal. After selecting several dance motion units by random algorithms, the method concatenates the units into a whole dance work. For instance, Shinozaki *et al.*

constructed a robot dance system to research dance entertainment using humanoid robots [65].

In general, the method can create robotic choreography and keep the characteristics of human dance because each dance motion in the dance unit database is predefined. By concatenating any number of dance units randomly, the method can create robotic dance works to a certain extent. Moreover, the method can make the robot create dance works autonomously. With an expansion mechanism of the dance unit database, new dance units will be created dynamically and stored in real time.

2) Mapping Rule: Environmental events (features) are always used as stimuli to enable a robot to express some behaviors, and the relationships between environmental features and robotic behaviors are usually realized based on mapping rules. In the robotic dance, these behaviors are assigned as the predefined dance motions of the robot. As environmental features change, an event sequence will be built dynamically. By matching the predefined rules, the event sequence is mapped to a sequence of robotic dance motions, which constitute a novel robotic dance work.

Generally, many factors can drive a robot to dance in its environment, such as colors, sounds, temperature, and human activity. Oliveira *et al.* designed a Lego NXT robot with two Lego-NXT kits, and constructed a framework in which the robot can perform its dance motions in response to the inputs of multimodule events [66]. These inputs are shaped by three rhythmic events (representing soft, medium, and strong musical note-onsets), different dance floor colors, and awareness of surrounding obstacles [66]. Based on the analysis of musical blocks in the environment, a music-driven approach was proposed for robotic choreography [67].

An environmental stimulus enables the robot to produce the conditioned behaviors. The rules build the mapping from the environmental stimulus to robotic dance motions and can be customized according to a specific goal. With changes in environmental stimuli, the robot must adapt continuously to the different rules to perform suitable dance motions. It performs innovative dances and exhibits a dynamic compromise between short-term synchronization and long-term autonomous behavior. Moreover, the dance works created by the mapping rules can maintain the characteristics of the dance as the dance motions used in the rules are predefined by humans.

Theoretically, various mapping rules could be created if all environmental factors are taken into account. The robot will then behave in more graceful manner according to the changes of environmental stimulus. Unfortunately, many important environmental factors have not been used to build rules by [66] and [67], such as speech signals and human activities. As a result, the produced robotic dances do not exhibit enough innovation. Furthermore, unless a user adds new dance motions by redefining or updating the rules, the same dance motions will repeat. Finally, the method has not considered interaction with humans.

3) Chaotic Dynamics: Chaos is not only the inherent property, but also the common phenomenon of a nonlinear system. Dance, as a nonlinear artistic form, expresses its grace by the variation of motions and formation. Thus, it is possible that robotic dance uses chaotic dynamics to annotate.

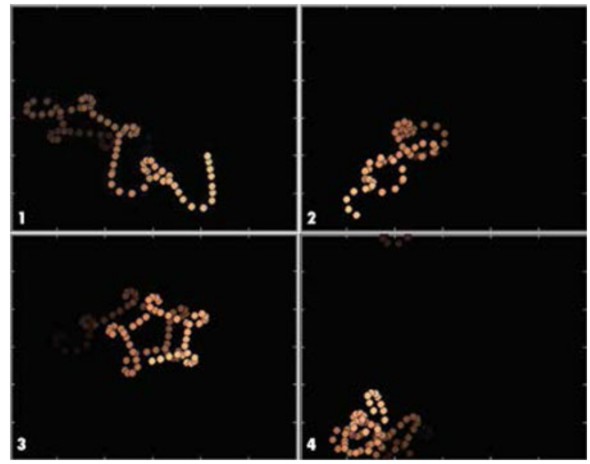


Fig. 10. Chaotic itinerant behavior generated by a MIURO robot [11].

Chaos dynamics has three features: fractals, the sensitivity of the initial value, and the singular attractor. By applying chaos dynamics into the robotic dance, we can achieve the compromise between innovation and consistency. The dependence on the initial conditions ensures that each variation of dance motion is different from the original motion, while the chaotic attractor is kept consistent between the two dance motions.

Aucouturier *et al.* proposed a method to make a vehicle-like robot to generate chaotic itinerant behavior of dance among low-dimensional local attractors by a network of FitzHugh-Nagumo neurons [68]. The beats in a musical signal are input as a pulse train to stimulate the network of FitzHugh-Nagumo neurons. After converting the output of the neural network by using a three-time-scale architecture, motor commands are generated to produce a dance trajectory in a 2-D plane in real time (see Fig. 10).

The resulting dances show various motion styles, some are periodic and tightly coupled to the rhythm of music, and others are more independent and can jump autonomously from one motion style to the next [68]. Although the neural network method can create robotic dances effectively, it has limitations. The method is used for a simple vehicle-like robot (MIURO) and is not suitable for a humanoid robot. In addition, the method only uses music beats as the input stimuli of the neural network, and not the other features such as music or environmental factors.

4) Interactive Reinforcement Learning: Interactive reinforcement learning (IRL) is an important method of machine learning and uses human subjective evaluations as the environmental reinforcement signals so that an intelligent system is stimulated to learn an optimal strategy to achieve the target. Robot choreography based on IRL is a new method to make robots learn to dance according to human preferences. The aesthetic feeling of robotic dance motions has no objective evaluation criterion; therefore, the method uses human subjective evaluations as the measurement of these motions, and it is suitable for robotic choreography.

Meng *et al.* constructed a system of robotic choreography based on IRL to constitute robotic dances according to human preferences [82]. Its system diagram is in Fig. 11. The Sarsa

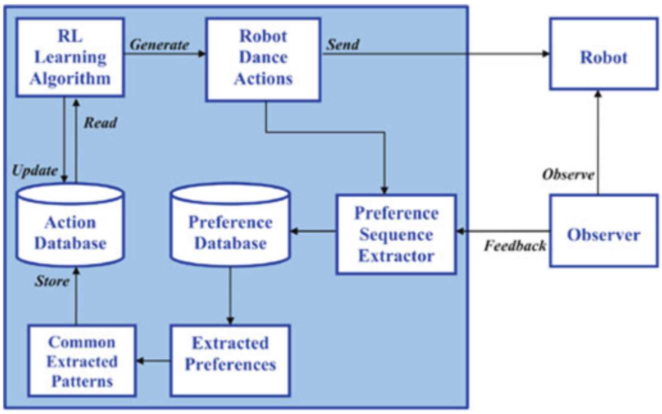


Fig. 11. System diagram [82].

Fig. 12. Individuals (dance motions) of a generation generated by IEC [14].

reinforcement learning algorithm updates the action database, in which each action has different accumulated rewards, and the Softmax action selection algorithm is used for choosing some dance actions to constitute dance works, and a robot is encouraged to choose the more highly rewarded dance actions than those with low rewards [82]. In the simulation experiments, all the preferred dance actions from the different participants are incorporated proportionally to constitute the robotic dances.

The method incorporates varying percentages of participants' preferences to select graceful motions and constitute a robotic dance, and the results show the innovation of dance in a certain extent. Furthermore, it makes the robot choose autonomously the preferred dance motions with the high rewards to constitute a robotic dance [82], which reflects that the method has a certain degree of intelligence. However, if there is one participant, the set of the preferred actions with high reinforcements will tend to converge to a steady set. The robotic dance works created by this method always use the repeated dance actions from the steady set and reduce the innovativeness of dance works. If there are many participants, who have different appreciation levels and preferences, it will make the graceful degree of dance works fluctuate among the different participants' evaluation criteria. In addition, the method follows subjective aesthetics of humans and does not maintain the characteristics of dances. Thus, the gracefulness of created robotic dance works depends directly on the appreciation levels of participants.

5) Evolutionary Computation: When evolutionary computation [69] is applied to the field of robotic dance, it can be divided into two types: traditional evolutionary computation (TEC) and interactive evolutionary computation (IEC). Through multiple iterations of generations within a population, TEC produces an excellent individual set and uses the fitness function to direct the evolution. IEC uses human subjective evaluations as the values of the fitness function. The dance motions of robots are regarded as individuals of the population in the area of robotic choreography. After the evolution of several generations, a set of graceful dance motions is generated, and a beautiful dance can be created by concatenating these motions in some way.

Based on TEC, Eaton proposed an approach to the synthesis of humanoid robot dance [83]. Its fitness function, which assesses the quality of dance movements, refers to "Performance Competence Evaluation Measure" [84] and is built based on the sum of all movement values over all joints and the time the robot remains standing [83]. The results show the fluid motions and the lifelike nature of dance. The whole procedure of evolution in TEC does not require human participation, which is intelligent in a certain extent. However, considering the subjective characteristic of dance's aesthetic appreciation, it is unclear whether the fitness function in TEC has the same ability as the human dance expert with respect to aesthetic evaluation.

Vircikova *et al.* introduced the interactive genetic algorithm as the concrete realization of IEC into robotic choreography [13]–[15]. They constructed a multirobot system to evolve the aesthetic dance motions for humanoid robot (see Fig. 12). The method can create robotic dances. Similar to IRL, IEC uses human subjective evaluation of esthetics to guide the evolutionary direction of robotic dance motions because the aesthetic feeling of robotic dance motions has no objective evaluation criterion. It is easy to create personalized robotic dance motions according to human preferences.

To obtain good results, many interactions are needed between a human and a robot, a burden to the human. In addition, how to maintain the characteristics of dance for new robotic dance motions is not considered. New motions may not meet human aesthetic criteria, which reduces the effectiveness of the method.

6) Markov Chain Model: A Markov chain is a discrete time stochastic process with the Markov property. Xia *et al.* first introduced the Markov chain model into the area of robotic choreography [58]. Robotic dance was viewed as a sequence of its dance motions, where each motion was regarded as a state of Markov chain, and the next motion was determined only by the previous motion and the current music emotion.

Considering the effects of music beats and emotions, Xia *et al.* focused on automating the procedure of robotic dance choreography driven by music without human interaction [58]. A general representation of robotic dance formalization can be used on different robots if these robots' joints are independent of each other and the joints can be activated simultaneously [58]. Moreover, the method not only makes robots automate dance choreography, but also makes robotic dance synchronize with music beats and emotions. Therefore, the produced robotic dance reflects better results and is more acceptable to human.

Because the next dance motion primitive is selected based on the transition probability and is determined by the previous motion and the current music emotion, the whole robotic dance is a sequence of unpredictable dance motions. Meanwhile, robotic dance choreography depends tightly on music; therefore, the results of robotic choreography will be different if the music changes. However, there are many important music factors excluded by the method, such as music rhythm and music intensity.

The method generates four schedules of motion primitives $\mathrm{S_c}$ ($\mathrm{S_{Head}}, \mathrm{S_{LArm}}, \mathrm{S_{RArm}}, \mathrm{S_{Legs}}$) according to four categories ($\mathrm{c} \in \{\mathrm{Head, LArm, RArm, Legs}\}$) and, then, executes these four schedules simultaneously to produce a whole body dance for robot. The method does not consider the grace and beauty of the combination of these primitive motions, which simultaneously emanate from the four schedules; consequently, the whole body dance motions may be uncoordinated. Therefore, the method does not maintain the characteristics of dance. Finally, it is difficult or impossible to build an accurate transition probability matrix in the method with many motion primitives, which may limit the application range of the method.

III. Discussion

Robotic dance is indeed an intelligent motor behavior composed of sophisticated perception, advanced thinking and learning, and autonomous decision making. It is an important means of exploring and developing various abilities of social robots. A taxonomy for robotic dance has identified four categories of robotic dance: cooperative human–robot dance, imitation of human dance motions, synchronization for music, and creation of robotic choreography. These categories have respectively endowed robots with various abilities:

1) execute tasks cooperatively with humans;
2) act some behaviors more like human;
3) coordinate with its embodied environments;
4) solve problem autonomously and independently.

The four categories of robotic dance and dancing robots are discussed followed by areas of future research.

A. Dancing Robots

A dancing robot is an essential platform of embodying robotic dance. However, the mechanical structure of the existing robots is not sophisticated enough to perform many complex human motions. Many biped humanoid robots (e.g., NAO, ASIMO, and QRIO) do not have a spine and waist, and all wheeled humanoid robots (e.g., Ms-DanceR, PBDR, and Lego-NXT) do not have legs. In addition, many differences exist in the body dynamics between humans and robots. Finally, due to the complexity of human dance motions (e.g., spin and jump), many human dances cannot be reproduced using a robotic platform. Thus, human-like dance by robots is limited by the existing physical structure of robots. Achievements of robotic dance will inform new dancing robots, and possibly other kinds of robots.

B. Cooperation

Cooperation is a way of joint action among individuals or groups to achieve the same objective. Cooperative human–robot dance regards the human and robot as cooperative objects, regards body-based communication as the medium, and regards mutual dance as the final cooperative behavior.

Research on creature-robot cooperation can be used for exploring and studying the creature's habits and behaviors. The cooperation among robots is more meaningful, and these robots can complete complicated tasks by cooperating with each other, such as in a football game. Robots exhibit actions after perceiving people's intention in the procedure of cooperation. Advances promote robotic intelligence and machine consciousness to a certain extent and enable robots to act more similarly to humans.

C. Imitation

Imitation is a type of learning and skills improvement by observing and mimicking other individual behaviors. The robotic ability of imitation provides a way of self-development and self-consciousness for robots, and may be vital for artificial intelligence and machine consciousness. Imitating human motions is still preliminary. It is unclear when to begin to imitate, how to imitate, and what should and should not be imitated. It is also unclear how task factors should be considered. In addition, a robot cannot learn human motions by observing directly with its "eyes" (cameras) as a human does.

From the viewpoint of group intelligence, while only one robot may have a new skill in a robot group, other robots could learn it by imitating the first robot's behaviors, and thereby acquire the new skill. Moreover, the initial robot, which has a new skill, may learn the new skill by imitating someone's behavior. Thus, the autonomous ability of robots will be improved, and the adaptability of robot groups will be strengthened.

D. Synchronization

Synchronization is a phenomenon of embodying consistency and standardization in time, by coordinating events in a system. The final target of synchronization for music is that robot dances with music harmoniously and consistently. Music has various elements that depict its own intrinsic properties, and the diversity of the concerned musical elements brings many possibilities to synchronize robotic dance to music. However, only musical beat, tempo, and rhythm are used so far. Although it is difficult to extract the other musical elements from music signals, the effects of synchronizing robotic dance to music may be improved if these musical elements are considered.

First, real-time algorithms of extracting the musical elements need to be designed, and the robotic dance motions should be arranged according to some specific musical elements' characteristics. For example, a robot varies its dance motions according to musical melody and changes its speed of motion according to musical dynamics. Additionally, music can serve as a crucial signal to synchronize motions, which come from different robots at some point, in a group dance of multiple robots. All robots should dance together consistently and harmoniously under the control of the same music, without preprogramming.

Music is also an important component to transform the above achievements to synchronize robotic behaviors. In the environment, there are many event sources (e.g., human activities and temperature), and each one has its own way of changing. The combinations of the event sources can be defined according to the needs of application, and robotic behaviors can be used for synchronizing the combinations. For example, when a robot walks in unfamiliar surroundings, once the robot perceives some obstacles that are in the way, it should bypass them and continue to walk forward. Noticeably, once a robot can vary actively its behaviors as the environment is changing, the robot has a high degree of intelligence and consciousness.

E. Creation

The creation of robotic choreography reflects that robots "behave" autonomously and intelligently, aiming at good robotic choreography that is created by robot itself. Good robotic choreography has three features: 1) preservation of the characteristics of human dance; 2) innovativeness of the dance; and 3) accordance with human aesthetics. However, none of the existing achievements meet the three features simultaneously because of 1) the contradiction between the preservation of dance's characteristics and innovativeness and 2) the absence of objective criteria on dance aesthetics.

Improvisation is an interesting way to create dance works, which is used usually by human dance experts. Improvisation refers to creating his/her works according to someone's sudden inspiration and some prompts from the environment. A robot could create its choreography autonomously with improvisation according to the perceived environment (e.g., a word spoken by someone; the weather). Improvisation may be a promising research direction of robotic choreography in the future. In the creation of robotic choreography, the autonomous ability of a robot is one of the most important qualities, which enables a robot to act its behaviors actively and adaptively in its embodied environment.

F. Areas for Future Research

Although robots can perform dances supported by models and methods, many open areas, to be addressed, exist:

1) To develop new dancing robots with improved physical structure and hardware so that each dancing robot has its own way of expressing its dance behaviors and can realize various dance movements.
2) To imitate more kinds of human dance motions. In society, different human dances have their own style and characteristic dance motions. Common models to adapt to more kinds of human dance may be necessary.
3) To enable a robot to synchronize its dance to various music types harmoniously as a human does. This may require that a robot use its dance motions to explain its understanding of a musical artistic conception.
4) To create good robotic choreography with three features: the preservation of the characteristics of human dance, innovativeness, and accordance with human aesthetics.
5) To realize group dance with multiple robots. There are many complicated problems that need to be solved in group dance, including collisions or interferences of multiple robots, synchronization among multiple interoperable robots' motions, and the transformation of dance compositions in a group dance.
6) To create a general expressive means of robotic dance. Up to now, the robotic dances cannot be easily transferred from one type of robot to another. Therefore, a general expressive means for robotic dance may be required.
7) To enable a robot to improvise and create corresponding choreography autonomously.

References

[1] J. Hanna, *To Dance is Human: A Theory of Nonverbal Communication*. Chicago, IL, USA: Univ. Chicago Press, 1987, pp. 1–327.

[2] Y. B. Lobo and A. Winsler, "The effects of a creative dance and movement program on the social competence of head start preschoolers," *Social Develop.*, vol. 15, no. 3, pp. 501–519, Aug. 2006.

[3] S. Brownlow and A. Dixon, "Perception of movement and dancer characteristics from point-light displays of dance," *Psychol. Rec.*, vol. 47, no. 3, pp. 411–421, 1997.

[4] M. Peick, "Dance as Communication : Messages sent and received through dance," *J. Undergraduate Res.*, vol. VIII, pp. 1–11, 2005.

[5] A. Lesté and J. Rust, "Effects of dance on anxiety," *Am. J. Dance Theory*, vol. 12, no. 1, pp. 19–25, Mar. 1990.

[6] M. Ritter and K. G. Low, "Effects of dance/movement therapy: A meta-analysis," *Arts Psychother.*, vol. 23, no. 3, pp. 249–260, Jan. 1996.

[7] Y.-J. Jeong, S.-C. Hong, M. S. Lee, M.-C. Park, Y.-K. Kim, and C.-M. Suh, "Dance movement therapy improves emotional responses and modulates neuro-hormones in adolescents with mild depression," *Int. J. Neurosci.*, vol. 115, no. 12, pp. 1711–1720, Dec. 2005.

[8] S. C. Koch, K. Morlinghaus, and T. Fuchs, "The joy dance: Specific effects of a single dance intervention on psychiatric patients with depression," *Arts Psychother.*, vol. 34, no. 4, pp. 340–349, Jan. 2007.

[9] M. S. Ada, K. Suda, and M. Ishii, "Expression of emotions in dance: relation between arm movement characteristics and emotion," *Perceptual Motor Skills*, vol. 97, no. 3, pp. 697–708, Dec. 2003.

[10] N. Dael, M. Mortillaro, and K. R. Scherer, "Emotion expression in body action and posture," *Emotion*, vol. 12, no. 5, pp. 1085–1101, Oct. 2012.

[11] J. J. Aucouturier, "Cheek to chip: Dancing robots and AI's future," *Intell. Syst.*, vol. 23, no. 2, pp. 74–84, Mar. 2008.

[12] J. Or, "Towards the development of emotional dancing humanoid robots," *Int. J. Soc. Robot.*, vol. 1, no. 4, pp. 367–382, Oct. 2009.

[13] M. Vircikova and P. Sincak, "Dance choreography design of humanoid robots using interactive evolutionary computation," in *Proc. 3rd Workshop Young Researchers Human-Friendly Robot.*, 2010.

[14] M. Vircikova, Z. Fedor, and P. Sincak, "Design of verbal and non-verbal human-robot interactive system," in *Proc. 11th IEEE-RAS Int. Conf. Humanoid Robots*, 2011, pp. 87–92.

[15] M. Virčíková and P. Sinčák, "Artificial intelligence in humanoid systems," Ph.D. dissertation, Dept. Cybern. Artif. Intell., FEI TU Kosice, Kosice, Slovak Republic, 2010.

[16] M. P. Michalowski, "Rhythmic human-robot social interaction," Ph.D. dissertation, Robot. Inst., Carnegie Mellon Univ., Pittsburgh, PA, USA, 2010.

[17] H. Kozima, M. P. Michalowski, and C. Nakagawa, "Keepon," *Int. J. Soc. Robot.*, vol. 1, no. 1, pp. 3–18, Nov. 2009.

[18] T. Landgraf, M. Oertel, A. Kirbach, R. Menzel, and R. Rojas, "Imitation of the honeybee dance communication system by means of a biomimetic robot," in *Biomimetic and Biohybrid Systems*, vol. 7375. Barcelona, Spain: Springer, 2012, pp. 132–143.

[19] T. Landgraf, "RoboBee: A Biomimetic Honeybee Robot for the analysis of the dance," Ph.D. dissertation, Dept. FachbereichfürMathematik und Informatik, FreieUniversität, Berlin, Germany, 2013.

[20] A. Beck, L. Cañamero, A. Hiolle, L. Damiano, P. Cosi, F. Tesser, and G. Sommavilla, "Interpretation of emotional body language displayed by a humanoid robot: A case study with children," *Int. J. Soc. Robot.*, vol. 5, no. 3, pp. 325–334, Jun. 2013.

[21] D. McColl and G. Nejat, "Recognizing emotional body language displayed by a human-like social robot," *Int. J. Soc. Robot.*, vol. 6, no. 2, pp. 261–280, Jan. 2014.

[22] B. Robins, K. Dautenhahn, R. TeBoekhorst, and A. Billard, "Robotic assistants in therapy and education of children with autism: Can a small humanoid robot help encourage social interaction skills?," *Universal Access Inf. Soc.*, vol. 4, no. 2, pp. 105–120, Jul. 2005.

[23] A. Duquette, F. Michaud, and H. Mercier, "Exploring the use of a mobile robot as an imitation agent with children with low-functioning autism," *Auton. Robots*, vol. 24, no. 2, pp. 147–157, Oct. 2008.

[24] G. Bird, J. Leighton, C. Press, and C. Heyes, "Intact automatic imitation of human and robot actions in autism spectrum disorders," *Proc. Biol. Sci.*, vol. 274, no. 1628, pp. 3027–3031, Dec. 2007.

[25] H. Kozima and C. Nakagawa, "Interactive robots as facilitators of children's social development," in *Mobile Robots: Towards New Applications*. Rijeka, Croatia: Intech, 2006, pp. 269–286.

[26] H. Kozima, C. Nakagawa, Y. Yasuda, and D. Kosugi, "A toy-like robot in the playroom for children with developmental disorder," in *Proc. Int. Conf. Develop. Learning*, 2004, pp. 188–189.

[27] H. Lehmann, I. Iacono, B. Robins, P. Marti, and K. Dautenhahn, "'Make it move': Playing cause and effect games with a robot companion for children with cognitive disabilities," in *Proc. 29th Annu. Eur. Conf. Cognitive Ergonomics*, 2011, pp. 105–112.

[28] B. Robins, K. Dautenhahn, E. Ferrari, G. Kronreif, B. Prazak-Aram, P. Marti, I. Iacono, G. J. Gelderblom, T. Bernd, F. Caprino, and E. Laudanna, "Scenarios of robot-assisted play for children with cognitive and physical disabilities," *Interact. Stud.*, vol. 13, no. 2, pp. 189–234, 2012.

[29] M. Fujita, K. Sabe, Y. Kuroki, and T. Ishida, "SDR-4X II : A small humanoid as an entertainer in home environment," in *Robotics Research*. Siena, Italy: Springer, 2005, pp. 355–364.

[30] E. Kac, "Foundation and development of robotic art," *Art J.*, vol. 56, no. 3, pp. 60–67, 1997.

[31] S. Yoshida, D. Sakamoto, Y. Sugiura, M. Inami, and T. Igarashi, "RoboJockey: Robotic dance entertainment for all," in *Proc. SIGGRAPH Asia 2012 Emerging Technol.*, 2012, pp. 1–2.

[32] A. Nakazawa, S. Nakaoka, K. Ikeuchi, and K. Yokoi, "Imitating human dance motions through motion structure analysis," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2002, vol. 3, pp. 2539–2544.

[33] S. Nakaoka, A. Nakazawa, K. Yokoi, and K. Ikeuchi, "Leg motion primitives for a humanoid robot to imitate human dances," *J. Three Dimensional Images*, vol. 18, no. 1, pp. 73–78, 2004.

[34] K. Kosuge and Y. Hirata, "Human-robot interaction," in *Proc. IEEE Int. Conf. Robot. Biomimetics*, 2004, pp. 8–11.

[35] K. Kosuge, T. Hayashi, Y. Hirata, and R. Tobiyama, "Dance partner robot—MsDanceR," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2003, vol. 3, pp. 3459–3464.

[36] K. Kosuge, T. Takeda, Y. Hirata, M. Endo, M. Nomura, K. Sakai, M. Koizumi, and T. Oconogi, "Partner ballroom dance robot —PBDR," *SICE J. Control. Meas. Syst. Integr.*, vol. 1, no. 1, pp. 74–80, 2008.

[37] T. Takeda, Y. Hirata, and K. Kosuge, "HMM-based Error recovery of dance step selection for dance partner robot," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2007, pp. 1768–1773.

[38] Y. Hirata, T. Hayashi, T. Takeda, K. Kosuge, and Z. Wang, "Step estimation method for dance partner robot 'MS DanceR' using neural network," in *Proc. IEEE Int. Conf. Robot. Biomimetics*, 2005, pp. 523–528.

[39] T. Takeda, Y. Hirata, Z. Wang, and K. Kosuge, "HMM-based error detection of dance step selection for dance partner robot—MS DanceR," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2006, pp. 5631–5636.

[40] T. Takeda, Y. Hirata, and K. Kosuge, "Dance partner robot cooperative motion generation with adjustable length of dance step stride based on physical interaction," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2007, pp. 3258–3263.

[41] T. Takeda, Y. Hirata, and K. Kosuge, "Dance step estimation method based on HMM for dance partner robot," *IEEE Trans. Ind. Electron.*, vol. 54, no. 2, pp. 699–706, Apr. 2007.

[42] F. Tanaka and H. Suzuki, "Dance interaction with QRIO: A case study for non-boring interaction by using an entrainment ensemble model," in *Proc. 13th IEEE Int. Workshop Robot Human Interactive Commun.*, 2004, pp. 419–424.

[43] F. Tanaka, B. Fortenberry, K. Aisaka, and J. R. Movellan, "Developing dance interaction between QRIO and toddlers in a classroom environment: Plans for the first steps," in *Proc. IEEE Int. Workshop Robot Human Interactive Commun.*, 2005, pp. 223–228.

[44] F. Tanaka, J. R. Movellan, B. Fortenberry, and K. Aisaka, "Daily HRI evaluation at a classroom environment: Reports from dance interaction experiments," in *Proc. 1st ACM SIGCHI/SIGART Conf. Human-robot Interaction*, 2006, pp. 3–9.

[45] J. Bryden, D. Hogg, S. Popat, and M. Wallis, "Building artificial personalities: Expressive communication channels based on an interlingua for a human-robot dance," in *Proc. 11th Int. Conf. Simulation Synthesis Living Syst.*, 2008, pp. 80–87.

[46] M. Wallis, S. Popat, J. McKinney, J. Bryden, and D. C. Hogg, "Embodied conversations: performance and the design of a robotic dancing partner," *Design Stud.*, vol. 31, no. 2, pp. 99–117, Mar. 2010.

[47] M. Wallis, S. Popat, A. Bayliss, J. McKinney, J. Bryden, D. Hogg, M. Godden, and R. Walker, "SpiderCrab and the emergent object: designing for the twenty-first century," in *Proc. Conf. Designing User eXperiences*, 2007, vol. 44, pp. 2–17.

[48] K. Yoshii, K. Nakadai, T. Torii, Y. Hasegawa, H. Tsujino, K. Komatani, T. Ogata, and H. G. Okuno, "A biped robot that keeps steps in time with musical beats while listening to music with its own ears," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2007, pp. 1743–1750.

[49] K. Murata, K. Nakadai, K. Yoshii, R. Takeda, T. Torii, H. G. Okuno, Y. Hasegawa, and H. Tsujino, "A robot uses its own microphone to synchronize its steps to musical beats while scatting and singing," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2008, pp. 2459–2464.

[50] C. B. Santiago, J. L. Oliveira, L. P. Reis, and A. Sousa, "Autonomous robot dancing synchronized to musical rhythmic stimuli," in *Proc. 6th Iberian Conf. Inf. Syst. Technol.*, 2011, pp. 1–6.

[51] D. Grunberg, R. Ellenberg, I. H. Kim, J. H. Oh, P. Y. Oh, and Y. E. Kim, "Development of an autonomous dancing robot," *Int. J. Hybrid Inf. Technol.*, vol. 3, no. 2, pp. 33–44, 2010.

[52] J. Seo, J. Yang, J. Kim, and D. Kwon, "Autonomous humanoid robot dance generation system based on real-time music input," in *Proc. 22nd IEEE Int. Symp. Robot Human Interactive Commun.*, 2013, pp. 204–209.

[53] N. Nakahara, K. Miyazaki, H. Sakamoto, T. X. Fujisawa, N. Nagata, and R. Nakatsu, "Dance motion control of a humanoid robot based on real-time tempo tracking from musical audio signals," in *Proc. 8th Int. Conf. Entertainment Comput.*, 2009, pp. 36–47.

[54] I. S. Tholley, Q. Meng, and P. W. H. Chung, "Towards a learning framework for dancing robots," in *Proc. IEEE Int. Conf. Control Autom.*, 2009, pp. 1581–1586.

[55] T. Shiratori, S. Kudoh, S. Nakaoka, and K. Ikeuchi, "Temporal scaling of upper body motion for Sound feedback system of a dancing humanoid robot," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2007, pp. 3251–3257.

[56] T. Shiratori and K. Ikeuchi, "Synthesis of dance performance based on analyses of human motion and music," *Inf. Media Technol.*, vol. 3, no. 4, pp. 834–847, 2008.

[57] T. Okamoto, T. Shiratori, S. Kudoh, and K. Ikeuchi, "Temporal scaling of leg motion for music feedback system of a dancing humanoid robot," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2010, pp. 2256–2263.

[58] G. Xia, J. Tay, R. Dannenberg, and M. Veloso, "Autonomous robot dancing driven by beats and emotions of music," in *Proc. 11th Int. Conf. Auton. Agents Multiagent Syst.*, 2012, pp. 205–212.

[59] T. Shiratori, A. Nakazawa, and K. Ikeuchi, "Rhythmic motion analysis using motion capture and musical information," in *Proc. IEEE Int. Conf. Multi-Sensor Fusion Integration Intell. Syst.*, 2003, pp. 89–94.

[60] T. Shiratori, A. Nakazawa, and K. Ikeuchi, "Detecting dance motion structure through music analysis," in *Proc. 6th IEEE Int. Conf. Autom. Face Gesture Recog.*, 2004, pp. 857–862.

[61] S. Nakaoka, A. Nakazawa, K. Yokoi, H. Hirukawa, and K. Ikeuchi, "Generating whole body motions for a biped humanoid robot from captured human dances," in *Proc. IEEE Int. Conf. Robot. Autom.*, 2003, vol. 3, pp. 3905–3910.

[62] S. Nakaoka, A. Nakazawa, F. Kanehiro, K. Kaneko, M. Morisawa, H. Hirukawa, and K. Ikeuchi, "Learning from observation paradigm: Leg task models for enabling a biped humanoid robot to imitate human dances," *Int. J. Robot. Res.*, vol. 26, no. 8, pp. 829–844, Aug. 2007.

[63] S. Kudoh, T. Shiratori, S. Nakaoka, A. Nakazawa, F. Kanehiro, and K. Ikeuchi, "Entertainment robot : Learning from observation paradigm for humanoid robot dancing," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. Workshop: Art Robots*, 2008.

[64] T. Shiratori, A. Nakazawa, and K. Ikeuchi, “Dancing-to-music character animation,” *Comput. Graph. Forum*, vol. 25, no. 3, pp. 449–458, Sep. 2006.

[65] K. Shinozaki, A. Iwatani, and R. Nakatsu, “Construction and evaluation of a robot dance system,” in *New Frontiers for Entertainment Computing*, vol. 279. Milano, Italy: Springer, 2008, pp. 83–94.

[66] J. L. Oliveira, L. P. Reis, and B. M. Faria, “An empiric evaluation of a real-time robot dancing framework based on multi-modal events,” *TELKOMNIKA Indones. J. Electr. Eng.*, vol. 10, no. 8, pp. 1917–1928, Dec. 2012.

[67] S. F. de Sousa Junior and M. F. M. Campos, “Shall we dance? A music-driven approach for mobile robots choreography,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2011, pp. 1974–1979.

[68] J. Aucouturier, Y. Ogai, and T. Ikegami, “Making a robot dance to music using chaotic itinerancy in a network of FitzHugh-Nagumo neurons,” in *Proc. 14th Int. Conf. Neural Inf. Process.*, 2008, pp. 647–656.

[69] Y. Suga, Y. Ikuma, D. Nagao, S. Sugano, and T. Ogata, “Interactive evolution of human-robot communication in real world,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2005, pp. 1438–1443.

[70] Y. Hirata, Y. Koike, Z. Liu, and K. Kosuge, “Development of omni-directional mobile base with servo brakes for passive dance partner robot,” in *Proc. IEEE Int. Conf. Robot. Biomimetics*, 2009, pp. 676–681.

[71] H. Wang and K. Kosuge, “Understanding and reproducing waltz dancers’ body dynamics in physical human-robot interaction,” in *Proc. IEEE Int. Conf. Robot. Autom.*, 2012, vol. 1, pp. 3134–3140.

[72] H. Wang and K. Kosuge, “Control of a robot dancer for enhancing haptic human-robot interaction in waltz,” *IEEE Trans. Haptics*, vol. 5, no. 3, pp. 264–273, Jan. 2012.

[73] D. Zicarelli, “An extensible real-time signal processing environment for max,” in *Proc. Int. Comput. Music Conf. Int. Comput. Music Assoc.*, Ann Arbor, MI, USA, 1998, pp. 463–466.

[74] K. Ikeuchi and T. Suehiro, “Toward an assembly plan from observation. I. Task recognition with polyhedral objects,” *IEEE Trans. Robot. Autom.*, vol. 10, no. 3, pp. 368–385, Jun. 1994.

[75] Y. Kuniyoshi, M. Inaba, and H. Inoue, “Learning by watching: Extracting reusable task knowledge from visual observation of human performance,” *IEEE Trans. Robot. Autom.*, vol. 10, no. 6, pp. 799–822, Dec. 1994.

[76] M. Goto, “An audio-based real-time beat tracking system for music with or without drum-sounds,” *J. New Music Res.*, vol. 30, no. 2, pp. 159–171, Jun. 2001.

[77] R. Takeda, K. Nakadai, K. Komatani, T. Ogata, and H. G. Okuno, “Exploiting known sound source signals to improve ICA-based robot audition in speech separation and recognition,” in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, 2007, pp. 1757–1762.

[78] J. L. Oliveira, F. Gouyon, L. G. Martins, and L. P. Reis, “IBT: A real-time tempo and beat tracking system,” in *Proc. Int. Conf. Music Inf. Retrieval*, 2010, pp. 291–296.

[79] E. D. Scheirer, “Tempo and beat analysis of acoustic musical signals,” *J. Acoust. Soc. Am.*, vol. 103, no. 1, pp. 588–601, Jan. 1998.

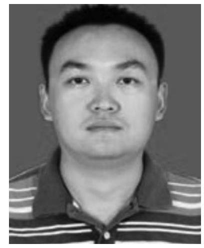
[80] A. P. Klapuri, A. J. Eronen, and J. T. Astola, “Analysis of the meter of acoustic musical signals,” *IEEE Trans. Audio, Speech Lang. Process.*, vol. 14, no. 1, pp. 342–355, Jan. 2006.

[81] A. H. Guest, *Labanotation: The System of Analyzing and Recording Movement*. Oxford, U.K.: Psychology Press, 2005.

[82] Q. Meng, I. Tholley, and P. W. H. Chung, “Robots learn to dance through interaction with humans,” *Neural Comput. Appl.*, vol. 24, no. 1, pp. 117–124, Nov. 2014.

[83] M. Eaton, “An approach to the synthesis of humanoid robot dance using non-interactive evolutionary techniques,” in *Proc. IEEE Int. Conf. Syst., Man, Cybern.*, 2013, pp. 3305–3309.

[84] D. Krasnow and S. J. Chatfield, “Development of the ‘performance competence evaluation measure’ assessing qualitative aspects of dance performance,” *J. Dance Med. Sci.*, vol. 13, no. 4, pp. 101–107, 2009.



Hua Peng received the M.S. degree from Hunan Normal University, Changsha, China, in 2008. He is currently working toward the Ph.D. degree with the Cognitive Science Department, Xiamen University, Xiamen, China.

He is also a Lecturer with the College of Information Science and Engineering, Jishou University, Jishou, China. His research interests include machine intelligence and robotic technology.

Changle Zhou received the Ph.D. degree from Beijing University, Beijing, China, in 1990.

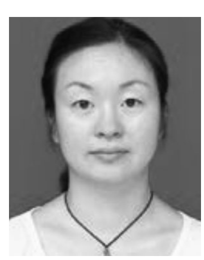
He is currently a Professor with the Cognitive Science Department, Xiamen University, Xiamen, China. His research interests include computational linguistics, brain theory, and computational musicology with an emphasis on computational models for metaphor, awareness and creativity, and intelligent techniques for traditional Chinese medicine information processing.

Huosheng Hu received the M.Sc. degree from Central South University, Changsha, China, and the Ph.D. degree from Oxford University, Oxford, U.K.

He is currently a Professor with the School of Computer Science and Electronic Engineering, University of Essex, Colchester, U.K. His research interests include behavior-based robotics, human–robot interaction, embedded systems, mechatronics, learning algorithms, and networked service robots.

Fei Chao received the B.Sc. degree in mechanical engineering from the Fuzhou University, Fuzhou, China, and the M.Sc. degree (with distinction) in computer science from the University of Wales, Cardiff, U.K., in 2004 and 2005, respectively, and the Ph.D. degree in robotics from the Aberystwyth University, Aberystwyth, U.K., in 2009.

He is currently an Assistant Professor with the Cognitive Science Department, Xiamen University, Xiamen, China. His research interests include developmental robotics, machine learning, and optimization algorithms.



Jing Li received the M.S. degree from Yunnan University, Kunming, China.

She is currently a Professor with the College of Musicology and Dancing, Jishou University, Jishou, China. Her research activity is focused on Chinese national dances.