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WaltzBots: Understanding interpersonal coordination mechanism underlying ballroom dance

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1 Introduction

In ballroom dancing, where individuals dance around the dance hall, spontaneous coordination between dancers is extremely important [1]. While the elegant performance in ballroom dance results from many rehearsals, dancers need to adapt to uncertain factors such as the collision avoidance from other pairs and the ballroom's condition in real time [1]. It is expected that understanding the coordination mechanism underlying ballroom dance can facilitate the development of autonomous robots that can spontaneously coordinate with robots or humans through physical interaction with them in real time under real-world constraints.

In previous studies, Kosuge et al. developed a partner ballroom dance robot (PBDR) system that can dance with humans. In this system, a robot estimates a leader (a human)'s intention based on sensory information with the help of force and torque sensors and realizes a feasible step [2]. Furthermore, the robot system has been extended to a teaching robot system that helps humans learn ballroom dance steps, where the robot plays a leader and the human plays a follower [3]. In this robotic system, physical interaction plays essential roles in human–robot coordination as a leader–follower system. Although the lead-and-follow relationship is an important aspect of coordination in ballroom dance, the co-creative mechanism in ballroom dance, in which dancers affect each other, is still unclear.

Therefore, this study aims to understand the co-creative coordination mechanism in an improvisational aspect of ballroom dance. To this end, we employ a synthetic approach, textcolorblackan understanding-by-building approach and establish a ballroom dance robot "pair" system. More specifically, we developed a decentralized robot-pair system (Fig. 1) that can dance waltz, a basic ballroom dance style, via a simple decentralized control system. We demonstrate that the developed system spontaneously generates waltz-like coordination patterns (e.g., rotational and translational coordination with quick and slow side steps).

2 Model

We focus on the improvisational aspect of ballroom dance to understand the interpersonal coordination mechanism underlying waltz. When dancers make a pair for the first time, dance sequences are generated through interactions between dancers. In this study, we attempted to develop a ballroom dance pair that can realize interpersonal waltz-like dance. Here, waltz-like coordination should meet the following requirements: 1) The pair exhibits periodic coordination that changes between quick and slow sections. 2) The pair exhibits both rotational and translational motions. 3) The pair adaptively switches between rotational and translational motions. This study proposes a simple decentralized coordination mechanism for a ballroom dance robot pair to realize these coordination patterns.

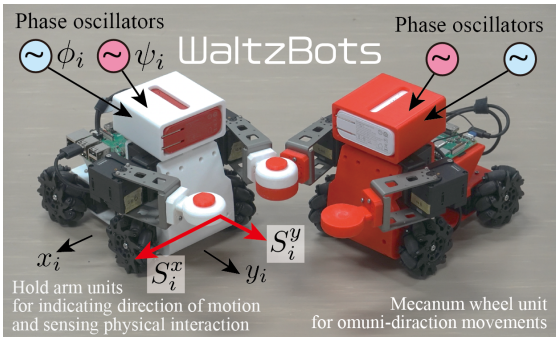

Figure 1: Developed ballroom dance robots: WaltBots.

The proposed robot pair consists of two homogeneous dance robots. Each robot has two arms to hold the other robots and has mechanical wheels to move around on the ground. With respect to the basic motion, each robot moves to the left or right based on two phase oscillators. The target robot's velocity along the left–right direction $\bar{x}_i$ is described as follows:

$$\dot{\bar{x}}_i = V\cos\psi_i(1+\sin\phi_i), \tag{1}$$

where V is the amplitude of the robot's periodical velocity; ψ_i is a phase oscillator that determines the robot's direction of motion, and ϕ_i is a phase oscillator to determine the velocity of the robot. When $\cos\psi_i > 0$, the robot moves to the right. In contrast, the robot moves to the left when $\cos\psi_i < 0$. To move in quick and slow step times as in Waltz, the robot repeats movements and stops periodically: it moves when $\sin\phi_i$ is around $\pi/2$ and stops when $\sin\phi_i$ is around $3\pi/2$.

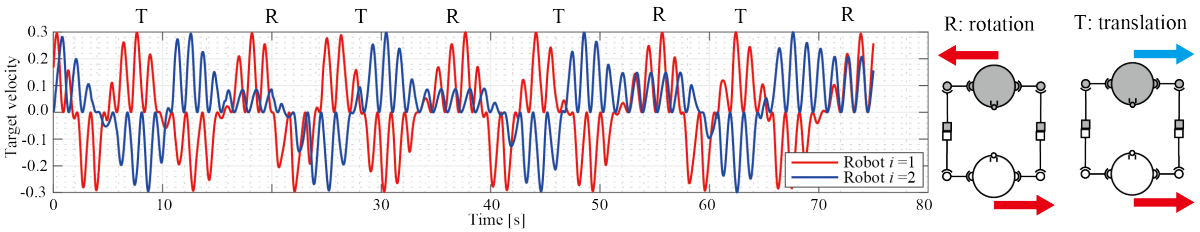

Figure 2: Emergence of waltz-like coordination patterns through the simple decentralized control mechanism.

For inter-robot rhythm control, we designed a simple, decentralized manner that exploits the physical interaction between robots.

$$\dot{\phi}_i = \omega - \sigma S_i^y \cos\phi_i, \tag{2}$$

where ω is the intrinsic angular velocity for the rhythm of the ith robot's motion ($i = 1,2$); σ is a positive constant value for feedback gain, and S_i^y represents the force along the fore-aft direction that the ith robot perceives through the arms. This sensory feedback mechanism is designed based on the different inter-robot physical interactions between rotational and translational motion, in which the robots pull each other along the fore-aft direction (e.g., $S_i^y > 0$). In contrast, the robots push each other along the fore-aft direction (e.g., $S_i^y < 0$) in translational motion to avoid the movement of each robot in a different direction. When the robot perceives the pulling force along the fore-aft direction ($S_i^y > 0$), the local sensory feedback term is modulated so that the phase of the oscillator ϕ_i is close to $3\pi/2$ to generate the robot pair's rotation with quick and slow motions.

We designed a simple directional coordination mechanism for flexible switching between the rotational and translational motions of the robot pair. We suppose that the robot is pulled to the right by the the other robot and determine whether the pulled robot moves to the right? We assume that the reasonable direction of the robot ' s motion depends on the context of the robot pair's motion, whether rotational or translational. We designed a context-dependent direction coordination mechanism as follows:

$$\dot{\psi}_i = \omega_{\rm dir} + \sigma_{\rm dir} \tanh(S_i^y) S_i^x \cos\psi_i, \tag{3}$$

where $\omega_{\rm dir}$ is the intrinsic angular velocity in the direction of the robot's motion; $\sigma_{\rm dir}$ is a positive constant value for feedback gain, and S_i^x represents the external force along the left–right direction that the robot perceives through the arms. A positive value of S_i^x indicates that the robot is pulled to the right. When the robot is pulled toward the right ($S_i^x > 0$) during rotational motion ($S_i^y > 0$), the sensory feedback term modulates the direction of the robot's motion toward the left (e.g., the opposite direction of the pulling force) to enhance the rotational motion of the robot pair. In contrast, during translational motion ($S_i^y < 0$), the feedback term modulates the direction of the robot's motion in the same direction as that of the pulling force.

3 Waltz-like coordination via decentralized mechanism

To evaluate the proposed model, we conducted experiments. For the experimental setup, both robots implement the same control mechanism and control parameters. There were no explicit roles for the leader and follower; thus, we employed a symmetrical robot system. The control parameters were heuristically set as $\omega = 5.0$, $\sigma = 0.45$, $\omega_{\rm dir} = 1.0$, and $\sigma_{\rm dir} = 0.005$. At the beginning of the experiments, the robots had an initial phase difference $\Delta\phi = \phi_2 - \phi_1$ of π in rhythm control.

Through physical interaction, the robots modulate the phase for rhythm ϕ_i to synchronize the timing of the sidestep motions with each other. Consequently, both quick and slow motions emerged cyclically (Fig. 2). Furthermore, the robots change the direction of motion depending on the sensory information. The robot pair spontaneously switches rotational and translational motions under coordination with quick and slow movements, such as the movements in walking (Movie of experiments:`https://drive.google.com/file/d/1G7_YORDuQhJveHinVQk-S4dGx4oPgCXC/view?usp=sharing`). In these coordinations, the resultant slipping wheels on the floor seem to play a substantial role for the robots during rotational motion.

4 Conclusion and future work

This study developed a simple decentralized ballroom dance robot pair to understand the essential coordination mechanism underlying ballroom dance. The robot generates waltz-like coordination patterns via physical interactions between robots and a simple decentralized coordination mechanism.

In a further study, we will evaluate the relationship between coordination patterns and dynamics of the coupled–oscillator systems and discuss linkages to human behaviors in ballroom dance.

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