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# An interactive control architecture for interpersonal coordination in mirror game

Chao Zhai [a], Michael Z.Q. Chen [b,*], Francesco Alderisio [c], Alexei Yu. Uteshev [e], Mario di Bernardo [c,d]

[a] Institute of Catastrophe Risk Management, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore
[b] School of Automation, Nanjing University of Science and Technology, Nanjing, Jiangsu 210094, PR China
[c] Department of Engineering Mathematics, University of Bristol, Merchant Venturers' Building, Woodland Road, Bristol, BS8 1UB, United Kingdom
[d] Department of Electrical Engineering and Information Technology, University of Naples Federico II, 80125 Naples, Italy
[e] Faculty of Applied Mathematics, St. Petersburg State University, Universitetskij pr.35, Petrodvorets, 198504, St. Petersburg, Russia

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ABSTRACT

In this work, an interactive control architecture based on velocity segments is developed to generate the human-like trajectories in the mirror game, a simple yet effective paradigm for studying interpersonal coordination, and the existence of velocity segments possessing a prescribed signature is theoretically guaranteed. Then an online control algorithm for the architecture is proposed to produce joint improvised motion with a human player or another virtual player while exhibiting some desired kinematic characteristics. Finally, the transition from solo motions to joint improvised motions is illuminated, and the proposed control architecture is validated by matching the experimental data.

## 1. Introduction

People suffering from social deficits (i.e., schizophrenia or autism) find it hard to engage in social activities and interact with others, which inevitably brings sorrow to themselves and their relatives (Boraston, Blakemore, Chilvers, & Skuse, 2007; Couture, Penn, & Roberts, 2006). The theory of similarity in Social Psychology suggests that individuals prefer to cooperate with others sharing similar morphological and behavioral features, and that they tend to unconsciously coordinate their movements (Folkes, 1982; Schmidt & Fitzpatrick, 2014; Walton, Richardson, Langland-Hassan, & Chemero, 2015). It has been shown that motor processes caused by interpersonal coordination are closely related to mental connectedness, and that motor coordination between two people promisingly contributes to social attachment (Feniger-Schaal et al., 2016; Raffard et al., 2015; Wiltermuth & Heath, 2009).

The *mirror game* provides a simple paradigm to study social interactions and the onset of motor coordination among human beings, as it happens in improvisation theater, group dance and parade marching (Noy, Dekel, & Alon, 2011; Noy, Levit-Binun, & Golland, 2015). In order to enhance social interaction through motor coordination, it would be desirable to create a virtual player (VP) or computer avatar capable of playing the mirror game with a human subject (typically the patient) either by mimicking similar kinematic characteristics or producing dissimilar ones (Zhai, Alderisio, Tsaneva-Atanasova, & Di Bernardo, 2014a). Indeed, this would allow modulation of the kinematic similarity of the VP while maintaining a certain level of coordination with the human player (HP) so that the latter is unconsciously guided towards the direction of some desired movement features. Within this scope, the European Project "AlterEgo" was launched (http://www.euromov.eu/alterego/). The purpose of the project is to promote social interaction of patients suffering from mental impairments (e.g., autism and schizophrenia) through motor coordination. Essentially, it aims at developing a new rehabilitation method to enhance the social competence of patients with social deficits by using virtual reality and humanoid robots.

Human–robot interaction finds extensive applications in haptic interfaces (Liu & Zhang, 2014; Sharifi, Behzadipour, & Vossoughi, 2014), person recognition (Boucenna, Cohen, Meltzoff, Gaussier, & Chetouani, 2016) and human mental development (Boucenna, Anzalone, Tilmont, Cohen, & Chetouani, 2014). Specifically, Liu and Zhang (2014) investigates the control of human arm movement in the cooperative welding process with the robot. Boucenna et al. (2016) illustrates the emergence of person recognition through mutual imitation, whereas (Boucenna et al., 2014) evaluates the effects of human participants on

* Corresponding author.
*E-mail address:* mzqchen@outlook.com (M.Z.Q. Chen).

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the robot learning of social signature through an imitation game. It is demonstrated that the recognition of facial expressions and postures can be achieved via a sensory-motor architecture based on neural networks.

In this work, a customized human-like VP is created to socially interact with a HP in the mirror game. The main challenge is to develop a mathematical model capable of driving the VP or robot to joint-improvise with a HP in the mirror game, while guaranteeing an assigned *motor signature* as defined in Hart, Noy, Feniger-Schaal, Mayo, and Alon (2014) and Słowiński et al. (2016). The first step towards this goal is to design a control architecture able to generate *in-silico* trajectories reproducing the motor signature exhibited by a certain HP playing solo. In so doing, an architecture based on velocity segments is proposed (Hart et al., 2014). The second step is to provide such architecture with an online control algorithm allowing the VP to produce joint improvised motions and interact with a HP or another VP.

Much research effort has been spent on the design of control architectures for the virtual agent or robot (Dumas, de Guzman, Tognoli, & Kelso, 2014; Kelso, de Guzman, Reveley, & Tognoli, 2009; Mörtl, Lorenz, & Hirche, 2014; Zhai, Alderisio, Słowiński, Tsaneva-Atanasova, & Bernardo, 2016; Zhai, Alderisio, Tsaneva-Atanasova, & Di Bernardo, 2014b, 2015). To be specific, Zhai et al. (2016, 2015) develop a cognitive architecture of a VP in the mirror game by reconciling the movement tracking with individual motor signature in the framework of optimal control theory; Mörtl et al. (2014) investigates the generation of goal-directed movements for robotic agents via behavioral dynamics in repetitive joint action tasks; Dumas et al. (2014) introduces a paradigm called *human dynamic clamp*, which enables real-time interaction between a HP and a VP driven by the model of coordination dynamics; Zhai et al. (2014b) presents an adaptive control algorithm for the VP to track the human leader in the mirror game; Kelso et al. (2009) designs a coupled dynamical system for studying real time interaction between a HP and a computer avatar driven by the Haken–Kelso–Bunz (HKB) model (Haken, Kelso, & Bunz, 1985).

However, in the aforementioned works the time series of a HP obtained from solo trials have to be used in order to generate the joint motion of a customized VP (Zhai et al., 2016; Zhai, Alderisio, Słowiński, Tsaneva-Atanasova, & Bernardo, 2018; Zhai et al., 2014b, 2015), which limits its movement diversity due to the finite number of available pre-recorded trajectories. The proposed approach here overcomes this drawback by allowing the VP to autonomously exhibit any motor signature with specified kinematic features (characterizing the solo motion of a given HP) during the interaction with another agent. Here the main contributions of this work are listed below.

1. A novel perspective on modeling human movement and on the generation of movement trajectory of a customized VP in the mirror game is offered, which complements previous investigations (Zhai et al., 2016, 2018, 2014b, 2015). Specifically, this work is based on velocity segments characterizing the movement similarity, while previous work focused on probability density functions of velocity time series.
2. The control architecture proposed in this work is able to spontaneously generate solo movement trajectories of a given HP instead of using pre-recorded time series (Zhai et al., 2016, 2018, 2014b, 2015).
3. In previous investigations, a boundary value problem had to be solved at each time step in order to generate the motion of a customized VP, which results in high computation costs (Zhai et al., 2016, 2018, 2015). Here, the solution to a simple differential equation allows to produce the real-time motion trajectory of a VP with relatively low computation costs.

The outline of this paper is given as follows. Section 2 introduces the experimental paradigm of the mirror game, a quantitative marker of motor signatures, and their construction method. Section 3 focuses on the design of a control architecture for the VP. Specifically, an algorithm capable of generating solo motions with prescribed kinematic features is developed, followed by an online control algorithm allowing the VP to produce joint improvised motion with another agent. Experimental validations are carried out in Section 4 to validate the proposed approach. Finally, Section 5 makes a conclusion and discusses future directions.

**Fig. 1.** Mirror game set-up at the University of Montpellier (Zhai et al., 2016). Two horizontal strings are mounted perpendicularly at eye level and centrally between the two human participants. Two small balls are mounted on the parallel strings, respectively. Human participants are instructed to hold the handle beneath each ball and move it along the string back and forth. Cameras are installed around the participants to collect experimental data and record their movement trajectories. In solo trials, only one human participant is instructed to perform the motion. In joint trials, two human participants are seated opposite each other and interact while moving their respective ball.

## 2. Preliminaries

### 2.1. Mirror game

The mirror game is a simple yet effective paradigm to investigate the onset of social motor coordination between two players and describe their movement imitation at high temporal and spatial resolution (Dahan, Noy, Hart, Mayo, & Alon, 2016; Hart et al., 2014; Noy et al., 2011). Fig. 1 shows the experimental set-up of mirror game to collect the experimental data, which are used to validate the proposed numerical algorithms.

The mirror game can be played in three different experimental conditions (Słowiński et al., 2016):

1. Solo Condition: This is an individual trial. Participants perform the game on their own and try to create interesting motions.
2. Leader–Follower Condition: This is a collaborative round, whose purpose is for the participants to create synchronized motions. One player leads the game, while the other tries to follow the leader's movement.
3. Joint-Improvisation Condition: Two players are required to imitate each other, create synchronized and interesting motions and enjoy playing together, without any designation of leader and follower roles.

Human movements in solo condition reflect their intrinsic dynamics, i.e., their individual motor signature (Słowiński et al., 2016). On the other hand, participants reconcile their respective intrinsic dynamics with the communal goal (movement synchronization) in leader–follower or joint-improvisation condition. Here, the focus is on the mathematical modeling of human coordination in solo and joint improvisation (JI) condition, and light is shed on their interconnection.

### 2.2. Motor signature

In the mirror game, motor signatures refer to the unique, time-persistent, kinematic self-similarity characteristics of human hand movements in solo condition (Hart et al., 2014; Słowiński, Rooke,