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A Novel Cognitive Architecture for a Human-like Virtual Player in the Mirror Game

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Abstract—The so called mirror game, which in its simplest formulation involves two people mirroring each other’s movement, provides a paradigm to study social interaction. However, a customized virtual player can replace either of the two human participants and hopefully help with the rehabilitation of patients suffering from social disorders by regulating its kinematics. In this paper we investigate the coordination movement between an avatar (virtual player) and a human player in the mentioned game. A novel cognitive architecture is proposed to drive the motion of the virtual player so that it generates a “human-like” trajectory for a human player. In order to achieve this objective, the Haken-Kelso-Bunz (HKB) equation is adopted to describe the social motor coordination between the virtual and the human player. In addition, both an adaptive algorithm for the coupling parameters in the HKB equation and a feedback controller are developed in order to guarantee human features for the virtual player in its kinematics. Finally, extensive experiments are conducted to validate the approach described above.

I. INTRODUCTION

Synergetic movements of two or more people mirroring each other frequently occur in our daily life such as dance, choir singing and movement therapy. Undoubtedly, it is of great importance to reveal the effect of mirroring movements among people on human physiological and mental functions. The mirror game provides a simple, yet effective experimental platform to investigate the onset of social motor coordination between two players [1]. In its simplest formulation, two players are asked to create synchronized movements which can be played in two different experimental conditions: Leader-Follower condition, in which one player (leader) is required to lead the game and the other one attempts to track his/her trajectory, and Joint Improvisation condition, in which both players are required to imitate each other and create synchronized and interesting movements without a designated leader.

It has been suggested that social motor coordination is linked to the feeling of mental connectedness between individuals. Also, movement synchrony promotes the attributed rapport, which is due to both perceptual similarity and psychological attribution [2]. For these reasons, the possibility of using the mirror game as a tool to develop innovative rehabilitation strategies for patients suffering from social disorders has been recently suggested [3], [4], [5], [6]. (See also the work done under the project ‘AlterEgo’ funded by the European Union at [7].)

In order to do so, it would be desirable to create a customized virtual player (for instance a robot or a computer generated avatar) able to interact with the patient so that its kinematical and morphological properties can be designed in order to match those of the patient as accurately as possible. Then, a key challenge is to develop a cognitive architecture able to drive such a virtual player.

In this paper we tackle this challenge and discuss the derivation of a novel cognitive architecture (as opposed to the one introduced in [1]) for the virtual player to play the mirror game with a human being while preserving the features of human motor coordination described in the literature [1], [8], [9], [10], [11], [12], [13], [14]. As a starting point, we use the Haken-Kelso-Bunz (HKB) model introduced in [10] to describe bimanual coordination in humans. The main idea is to develop a nonlinear feedback control strategy for the HKB model able to tame its dynamics so as to provide the trajectory of the end-effector of the avatar playing the mirror game with a human being. In this paper two experimental models are proposed so that the avatar can act as a follower or a leader when performing the game, respectively called follower model and leader model. When the avatar acts as a follower, the feedback control strategy makes sure that the closed-loop HKB model faithfully tracks the trajectory of the human player which is being sensed in real-time. When the avatar acts as a leader instead, pre-recorded time series of human end-effector movement are used to generate a “human-like” trajectory for the avatar to lead the game.

After presenting the architecture of the resulting cognitive interface, both a numerical and an experimental validation of the interface are presented. The experiments are carried out on an experimental set-up developed at the University of Bristol and show the effectiveness of the proposed strategy. Compared with the relevant work on human-machine interaction [15], [16], our cognitive architecture is able to reconcile motor coordination and trajectory tracking in the follower model via adaptation and feedback mechanisms. Moreover, the two experimental models are unified so that the leader model can be converted into the follower one by tuning some parameters.

The rest of this paper is organized as follows. In Section II, the mirror game and experimental conditions will be discussed. A cognitive architecture for the virtual player is presented in Section III. In addition, experimental results are given in Section IV. Finally, in Section V we draw a conclusion on the current work and discuss the potential directions for future
research.

II. MIRROR GAME

The mirror game was originally used as an experimental paradigm to study joint improvised actions between two human participants in several activities as for example improvisation theatre, sport, or dance [1]. As already pointed out, in this paper we formulate the mirror game as a control problem in order to investigate the coordination movement between a human player and a virtual player along two line segments in two different experimental conditions. Specifically, we consider the following set-up: two balls are mounted on two respective parallel lines (strings). Both the virtual player and the human player are required to move the ball back and forth along the strings and try to synchronize their movements. The position of the ball moved by the human player is detected by a position sensor and it is then sent to the cognitive architecture that generates the position and the velocity of the ball driven by the virtual player as an output (see Fig. 1).

When the virtual player is designated as a follower, the aim is to design a follower model such that the ball driven by the avatar can track the motion of that guided by the human player as accurately as possible while showing features typical of human motion (in terms of reaction time, typical velocity and acceleration profiles). When the virtual player is designated as a leader, the aim is for the architecture to spontaneously generate the motion of the ball driven by the virtual player while taking into account the movement of the human player. Indeed, in the latter case, if the human player lags far behind, the virtual player needs to get back to the follower in order to guide and encourage him/her to play the game.

III. COGNITIVE ARCHITECTURE

The interactive cognitive architecture of the virtual player is mainly composed of four parts: a reference model, a model of motor coordination between the players, a parameter adaptation mechanism and a feedback control input (see Fig. 2). The reference model serves to predict the movement of the human player (in the follower configuration) or to provide self-generated signals (in the leader configuration). The model of motor coordination between the two players is described by the HKB equation as follows [10]

\[
\dot{x} + (\alpha x^2 + \beta \dot{x} - \gamma)\dot{x} + \omega^2 x = [a + b(x - r_v)^2](\dot{x} - r_v)
\]

where \(x\) denotes the output position of the virtual player, \(r_v\) and \(r_v\) represent the position and velocity (reference signals) of the human player, respectively. Parameters \(\alpha, \beta\) and \(\gamma\) characterize the damping of movement for the virtual player, while \(\omega\) is related to the movement frequency. In addition, \(a\) and \(b\) denote the coupling strength between the two players. Normally, a pair of coupled HKB equations serves to account for experimental observations on intrapersonal and interpersonal coordination, such as phase transition, and each HKB equation describes the dynamical coordination of an end effector.

A. Follower Model

We start off by designing the follower model for the avatar to play the mirror game. In this scenario, the human player is the leader while the virtual player acts as a follower and as a consequence tries to synchronize its movement with the human participant. The follower model is composed of an algorithm to estimate the velocity of the human player from the sensed position, the HKB equation to model coordination, an adaptation law and a feedback controller (see Fig. 3). Thanks to the detected position and the estimated velocity of the human player, the adaptation law updates the coupling parameters in the HKB equation, whilst the feedback controller rectifies the output trajectory in real time so that the virtual player is able to track the human player. The mathematical description of the follower model is given by:

\[
\ddot{x} + (\alpha \dot{x}^2 + \beta \dot{x} - \gamma)\dot{x} + \omega^2 x = u(r_p, \dot{r}_v)
\]

where \(x\) denotes the output position of the virtual player, and the expression of the feedback controller is given by

\[
u(r_p, \dot{r}_v) = [a(t) + b(t)(x - r_p)^2](\dot{x} - \dot{r}_v) - C_p e^{-\varepsilon(x - \dot{r}_v)}(x - r_p)
\]

Here, \(r_p\) and \(\dot{r}_v\) represent position and estimated velocity of the human player, respectively. The constant \(C_p\) refers to the gain of the position feedback, while the constant \(\varepsilon\) captures the effect of the velocity error between the virtual player and the human player on the feedback gain. The adaptation law for the coupling parameters is designed as follows:

\[
\dot{a} = -\frac{1}{a}[(x - r_p)(\dot{x} - \dot{r}_v) + (x - r_p)^2]
\]
The velocity of the human player is estimated by

$$\dot{r}_v(t) = \frac{r_p(kT) - r_p((k-1)T)}{T}, \quad t \in [kT,(k+1)T)$$

where $k \in \mathbb{Z}^+$, and $T$ denotes the sampling period of the position sensor.

Remark 3.1: Note that the feedback controller consists of two terms. The first term corresponds to the coupling term in the classical HKB equation while the second term is designed to eliminate the constant mismatch in position when the reference velocity is close to zero. When the velocity error between the human player and the virtual player is relatively small, the second part will play the major role in regulating the output of the follower model. Otherwise, motor coordination is taken into account to generate the trajectory of the virtual player.

Remark 3.2: If we choose the following potential function

$$V = \frac{1}{2}(x - r_p)^2 + (\dot{x} - \dot{r}_v)^2 + a^2 + b^2$$

the time derivative of $V$ along the dynamics of the follower model with the proposed adaptation law satisfies

$$\dot{V} = -(x - r_p)^2 \leq 0,$$

which guarantees the stability of the follower model in each sampling period. However, this does not imply that the model is stable in the whole time domain. For further details on the stability analysis of this model see [17].

B. Leader Model

Next, we design the leader model for the avatar to play the mirror game. In contrast to the follower model, the virtual player acts as a leader and guides the human player in the mirror game. As a leader, the virtual player is supposed to generate its trajectory spontaneously. To this end, pre-recorded time series from human players are used as reference inputs, while the adaptation law and the feedback controller are the same as the ones employed in the follower model in order to make sure that the output of the HKB equation is able to track the reference trajectory. An additional term is added to make sure that the output of the controlled HKB equation is also influenced by the movement of the human player in real-time (see Fig. 4).

Specifically, the leader model can be given as follows:

$$\dot{x} + (\alpha \dot{x}^2 + \beta \dot{x}^2 - \gamma)\dot{x} + \omega^2 x = \lambda u(z,\dot{z}) + (1 - \lambda)C_h(r_p - x)$$

where $x$ and $r_p$ denote the output positions of the virtual player and the human player, respectively. The term $u(z,\dot{z})$ is selected as an adaptive feedback control signal described by:

$$u(z,\dot{z}) = [a(t) + b(t)(x - z)^2]([\dot{x} - \dot{z}] - C_p e^{-\delta(x - z)^2}(x - z)$$

where $z$ represents the pre-recorded position time series. The term $\lambda$ is set as $\lambda = e^{-\delta(x - r_p)^2}$ with $\delta$ being a constant selected empirically. In this way, if the position of the human player $r_p$ gets far away from that of the avatar $x$, then $\lambda \rightarrow 0$ and the control term responsible for tracking the pre-recorded time series is switched off. The state feedback control term $C_h(r_p - x)$ then dominates and leads the avatar to get closer to the position of the human player.

Remark 3.3: When $\delta = 0$, the leader model turns into a follower model in which the pre-recorded time series $z$ represents the leading trajectory. The virtual player disregards the movements of the human player and focuses on just tracking the pre-recorded time series without taking notice of what the human player is actually doing in real-time.

IV. Experiments

In this section a series of experiments are conducted to validate both the follower model and the leader model proposed for the virtual player, and the human-like features of the avatar motion.

A leap motion controller [18] is used to detect the position of the human hand during the mirror game which is then fed to a computer running our cognitive interface. Both a leap motion controller and a computer are placed on a table with the height of about 70 cm. The human player is asked to move his/her finger horizontally over the leap motion controller with a vertical distance of around 50 cm. This guarantees the maximum horizontal detection range for the leap motion controller, which is equal to about 60 cm. The position of the human hand is represented by a green solid ball on the computer screen, while a blue solid ball corresponds to the
position of the virtual player (see Fig. 5). The movement range of both players is mapped into the unit interval $[0, 1]$, and the algorithms are implemented in Matlab (Version R2012b).

Before human participants play the mirror game with the avatar in the follower model, they are told to act as leaders and let the virtual player track them for a 60s round. The parameters of HKB equation, adaptation law and feedback controller are set heuristically as follows: $\alpha = 1$, $\beta = 2$, $\gamma = -1$, $\omega = 0.1$, $C_p = 40$, $a(0) = b(0) = -10$ and $\varepsilon = 0.25$. From Fig. 6 and Fig. 7, we can see that with this parameter choice the virtual follower exhibits a desirable tracking performance. When the human player accelerates abruptly (green curve in Fig. 7 (a)), it takes about 300ms for the virtual player (blue curve in Fig. 7 (a)) to give a response. This can be achieved by introducing a time delay into the feedback controller for the follower model, and it turns out to be necessary to get the avatar to exhibit reaction times similar to those observed in humans [19]. In addition, the probability density function of the relative phase between the motion of the human player and that of the virtual player are also consistent with experimental results obtained when two human beings are asked to play the mirror game (see Fig. 7 (b)).

In another set of experiments, the virtual avatar is run by the cognitive architecture in the leader configuration and human participants are asked to act as followers and track the virtual player as accurately as possible during a 60s round. The parameters of the HKB equation, adaptation law and feedback controller are set heuristically as follows: $\alpha = 1$, $\beta = 2$, $\gamma = -1$, $\omega = 0.8$, $C_p = C_b = 40$, $a(0) = b(0) = -10$ and $\varepsilon = \delta = 5$. Fig. 8 shows the time evolution of the position with two different values of $\delta$. When $\delta = 0$, there is no coupling with the human player, meaning that the virtual player is focused on just tracking the pre-recorded time series. When $\delta = 5$, the trajectory of the virtual player does not match the pre-recorded time series as well as before since it is influenced by what the human player is doing. However, it is easy to see that the virtual player is able to track the pre-recorded time series quite well when the human player is close enough to the avatar itself. From Fig. 9, we can also notice that the profile of the probability density function of the relative phase between leader and follower is similar to the one in the follower model, and that the variance of the relative phase is quite small, which indicates that the coordination between human player and virtual player is stable.

Finally, in order to validate the features of the avatar motion, we run a preliminary evaluation of whether our algorithm imparts a “human-like” behaviour to the avatar by inviting 5 volunteers (acting as followers) to play the mirror game without telling them whether the leader was another human being or a virtual player. Specifically, the human players were shown the computer screen and given control of one of the balls displayed on the monitor (see Fig. 10). Each volunteer played the mirror game for 10 rounds (5 times following a human player and 5 times following the avatar, sequenced in a random order), each one 30s long. After each game, the volunteer was asked to guess whether the leader they had been following was a human player or the computer. We found that they identified the leader as a human being with a percentage worth 64%, which indicates a good performance of the artificial leader model in terms of its human-like behavior.

V. CONCLUSION

We presented the development and testing of an interactive cognitive architecture to drive the motion of the end-effector of a virtual avatar playing the mirror game with a human player. In order to investigate the human-machine interaction, two different configurations of the cognitive architecture were investigated, the former where the virtual player acts as a leader and the latter where it acts as a follower. An HKB equation combined with a nonlinear feedback controller was used to enable the virtual player to generate a trajectory with the desired features while either following or leading
the human player. We also discussed preliminary experimental results showing that the models perform as expected and can be tuned so as to make the motion of the virtual player share features typically observed in humans, such as similar reaction time and relative phase probability density functions. Future work will address the pressing open problem of better defining the features that can quantitatively characterize the motion of a human player so that they can be better reproduced by an improved version of our cognitive interface.

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