Central pattern generator–based coupling control method for synchronously controlling the two-degrees-of-freedom robot

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Abstract

Synchronous control is a fundamental and significant problem for controlling a multi-joint robot. In this article, by applying two coupled Rayleigh oscillators as the referred central pattern generator models for the two joints of a two-degrees-of-freedom robot, the central pattern generator–based coupling control method is proposed for controlling the two-degrees-of-freedom robot’s joints. On these bases, the co-simulation model of the two-degrees-of-freedom robot with the proposed central pattern generator–based coupling control method is established via ADAMS and MATLAB/Simulink, and the performance of the central pattern generator–based coupling control method on synchronizing two motions of two-degrees-of-freedom robot’s joints is numerically simulated. Furthermore, the experimental setup of a two-degrees-of-freedom robot is established based on the real-time simulations system via the proposed central pattern generator–based coupling control method. And experiments are carried out on the established setup. Simulations and experimental results show that the phase of the controlled two-degrees-of-freedom robot’s joints is mutual locked to other, and their motion pattern can be adjusted through the coupling parameter in the central pattern generator–based coupling control method. In conclusion, the proposed central pattern generator–based coupling control method can control the two-degrees-of-freedom robot’s joints to produce the coordinated motions and adjust the rhythmic pattern of the two-degrees-of-freedom robot.

Keywords

Two-degrees-of-freedom robot, central pattern generator, Rayleigh oscillator, synchronous control
Introduction

In the last decades, two-degrees-of-freedom robots (TDFRs) are widely applied for imitating the motions of the natural creatures with multi-joints whose rhythmic motions depend on the synchronized locomotion of their joints. Therefore, to imitate coordinated swinging or walking of the multi-joints natural creatures, each joint of the TDFRs needs to be movement synchronized with other coupled joints. Consequently, the synchronized control is a fundamental problem in the research of the bionics, which is worth focusing on.

Currently, the widely applied control methods for multi-joint robots include sliding mode control, fuzzy control, crossing-coupling control and contour error coupled control, and central pattern generator (CPG) control. Kamal et al. controlled TDFR’s two joints to follow the two desired trajectories by applying the sliding mode control method. Combining proportional–integral–derivative (PID) control and fuzzy control, Mohan et al. controlled a TDFR to achieve the pre-appointed motions. Zhang et al. applied the crossing-coupling method to improve the synchronous errors of the sliding mode control method for a multi-motor system. Applying the crossing-coupling method to pre-compensate the contour error for the fuzzy PID control method, Liu et al. and Lee et al. reduced the tracking error and contour error for a three-axis machine tool. According to the neural biology of the rhythmic movement, Nandi et al. proposed the swing control method to the lower limb prosthesis based on the Rayleigh oscillator–based CPG model. Torrealba et al. proposed a method for controlling the knee prosthesis to cooperate with the sound knee. Fang et al. proposed a new approach for the control of metameric robot locomotion via the phase coordination of a CPG model. Fu et al. designed a nonlinear oscillator with the asymmetrical time ratio and discussed the synchronous of two coupled oscillators. de Pina Filho et al. established a CPG model for a three degree-of-freedom (DOF) robot via the Rayleigh oscillators and discussed its synchronous. Yu et al. proposed a motion planner via the van de Pol oscillators to generate the desired motions for a hexapod robot. Then, they applied a joint-space tracking controller to force the joints of the hexapod robot to track these desired motions. By employing two coupled MLMP (multi-layered multi-pattern)-CPG models (proposed by Nassour in 2014), Atoofi et al. generated the synchronous motions of the shoulder joint and the elbow joint of a NAO robot to complete the drawing task.

Sliding mode control methods and fuzzy control methods both control each joint of the multi-joint robots to follow the specific referred trajectories, so they have the worse abilities on the synchronous controlling. Although crossing-coupling control and contour error coupled control methods have better abilities on the synchronous controlling, they are bad at adjusting locomotion patterns of robots. CPG control methods, which apply the CPG models to generate the referred trajectories and apply extra trajectory tracking control laws to track these generated referred trajectories, are complicated because of their utilized extra tracking control laws.

To overcome the drawbacks of these mentioned control methods and to synchronously control TDFR’s two joints, utilizing two coupled Rayleigh oscillators with the mutual locked phases as the referred models of the two joints, the CPG-based coupling control (CPGCC) method is proposed. On these bases, the co-simulation model of the TDFR with the proposed CPGCC method is established via ADAMS and MATLAB/
Simulink, and the performance of the CPGCC method on synchronizing two motions of TDFR’s joints is numerically simulated. Furthermore, the experimental setup of a TDFR is established based on the real-time simulation system via the proposed CPGCC method. And experiments are carried out on the established setup.

**Dynamical modeling of the TDFR**

Conventionally, a TDFR can be simplified as a two-linkage mechanism with two rigid bodies and two joints, which is attached on a base as shown in Figure 1. Observing Figure 1, the linkage AB with its mass center of $p_1$ is connected with the base through the rotating hinge A, and the linkage BC with its mass center of $p_2$ in connected with the linkage AB through the rotating hinge B. According to the Lagrange kinetic equation, the dynamic model of the TDFR, as shown in Figure 1, can be expressed as

\[
\begin{align*}
\tau_1 &= M_{11}\ddot{\theta}_1 + M_{12}\ddot{\theta}_2 + C_1 \\
\tau_2 &= M_{21}\ddot{\theta}_1 + M_{22}\ddot{\theta}_2 + C_2
\end{align*}
\]

where $\tau_1$ and $\tau_2$ are the torques applied to the hinges A and B, respectively; $\theta_1$ is the angle of the linkages AB relative to the direction of $x$ and $\theta_2$ is the angle of the linkages BC relative to the linkage AB; $M_{11}$, $M_{12}$, $M_{21}$, and $M_{22}$ are the components of the inertia matrix; and $C_1$ and $C_2$ are the Coriolis/centripetal forces of the linkages AB and BC, respectively. According to the Lagrange kinetic equation, $M_{11}$, $M_{12}$, $M_{21}$, $M_{22}$, and $C_2$, are given by

\[
\begin{align*}
M_{11} &= \frac{1}{3}m_2l_c^2 + \frac{1}{3}m_1l_1^2 + m_2l_1l_c2\cos\theta_2 \\
M_{12} &= M_{21} = \frac{1}{3}m_2l_c^2 + m_2l_1l_c2\cos\theta_2 \\
M_{22} &= \frac{1}{3}m_2l_c^2 \\
C_1 &= -\frac{1}{2}m_2l_1l_c2\sin\theta_2\dot{\theta}_1^2 - m_2l_1l_c2\sin\theta_2\dot{\theta}_1\dot{\theta}_2 \\
C_2 &= \frac{1}{2}m_2l_1l_c2\sin\theta_2\dot{\theta}_1^2
\end{align*}
\]

where $l_1$ and $l_2$ are the length of the linkages AB and BC, respectively; $l_c$ is the distance from the hinge A to $p_1$; $l_c$ is the distance from the hinge B to $p_2$; $m_1$ and $m_2$ are the masses of the linkages AB and BC, respectively.
According to equation (1), the state space models $\Sigma_1$ and $\Sigma_2$ of the TDFR’s two linkages are given as

\[
\begin{align*}
\dot{x}_1 &= x_2 \\
\dot{x}_2 &= M_{11}^{-1}(-M_{12}\ddot{\theta}_2 - C_1 + \tau_1)
\end{align*}
\] (2)

and

\[
\begin{align*}
\dot{x}_3 &= x_4 \\
\dot{x}_4 &= M_{22}^{-1}(-M_{21}\ddot{\theta}_1 - C_2 + \tau_2)
\end{align*}
\] (3)

where $(x_1, x_2)^T = (\theta_1, \dot{\theta}_1)^T$ and $(x_3, x_4)^T = (\theta_2, \dot{\theta}_2)^T$ are the state vectors of the models $\Sigma_1$ and $\Sigma_2$, respectively.

To generate the synchronous motions of the linkages AB and BC, the models $\Sigma_1$ and $\Sigma_2$ need to have the same frequencies and the locked phases.

**Control method for the TDFR**

In this section, via the coupling terms, two Rayleigh oscillators are coupled with the same frequencies and locked phases for imitating the motions of the TDFR’s two joints. In addition, using these coupled Rayleigh oscillators as the referred models, the CPGCC method is proposed to synchronously control the TDFR’s two joints.
Principle of the coupled Rayleigh oscillators

The Rayleigh oscillator, which is a second-order nonlinear dynamic system with a limit cycle, is expressed as

\[
\ddot{y} + d \left( h - \dot{y}^2 \right) \dot{y} + k^2 y = 0
\]  

(4)

where \( y \) is the output of the oscillator and \( d, h, \) and \( k \) are the parameters of the oscillator.

For convenience, the Rayleigh oscillator given by equation (4) can be rewritten as a state space model expressed as

\[
\begin{cases}
\dot{z}_1 = z_2 \\
\dot{z}_2 = -d \left( h - z_2^2 \right) z_2 - k^2 z_1
\end{cases}
\]  

(5)

where \((z_1, z_2)^T = (y, \dot{y})^T\) is the state vector of this state space model.

Adding the coupling terms \( c(y_2 - \dot{y}_1) \) into the two Rayleigh oscillators given by equation (4), we have

\[
\ddot{y}_i + d_i \left( h_i - \dot{y}_i^2 \right) \dot{y}_i + k_i^2 y_i + c_i \left( y_j - \dot{y}_j \right) = 0 \quad (i, j = 1, 2)
\]  

(6)

where \( y_i \) is the output of the two oscillators and \( d_i, h_i, \) and \( k_i \) are the parameters of the oscillators.

According to the works published in de Pina Filho et al., the two Rayleigh oscillators with the coupling terms given by equation (6) are coupled to each other with the same frequencies and locked phases.

CPG model–based control method for the TDFR

The proposed CPGCC method applies the limit cycle of the Rayleigh oscillator to restrain interference and applies the locked phases of the coupled Rayleigh oscillators to synchronize the motions of TDFR’s two joints.

Figure 2 shows the control block diagram of the proposed CPGCC method. As shown in Figure 2, each joint of the TDFR is controlled by one control loop which includes the linearizer, the Rayleigh oscillator, and inverse DC model. The two coupled Rayleigh oscillators are used to generate the periodically oscillated deviations \( \theta_{d1} \) and \( \theta_{d2} \) of the two joints. Two torque compute modules are used to calculate the oscillating torques \( u_{c1} \) and \( u_{c2} \) according to the deviations. The linearizers calculate the nonlinear torques \( u_{n1} \) and \( u_{n2} \) for compensating the nonlinear terms in the dynamical model of the TDFR given by equation (2). The inverse DC models are used to calculate the desired driving current voltages \( v_1 \) and \( v_2 \) according to the joint torques.
Defining the swing angle deviations of the joints relative to the zero position as

$$\theta_d = \theta - \theta_z$$ and $$\theta_d = \theta - \theta_z$$

(7)

where $$\theta_z$$ and $$\theta_z$$ are the zero position angles of the joints of the TDFR.

When the torques $$\tau_1$$ and $$\tau_2$$ shown in Figure 2 are given by

$$\begin{cases} 
\tau_1 = u_{c1} + u_{n1} \\
\tau_2 = u_{c2} + u_{n2} 
\end{cases}$$

(8)

where

$$u_{c1} = M_1 \left( -d_1 \left( h_1 - \dot{\theta}_d \right) \ddot{\theta}_d - k_1 \dot{\theta}_d^2 - c_1 \left( \dot{\theta}_d - \dot{\theta}_d \right) \right)$$

$$u_{n1} = M_1 \ddot{\theta}_d + C_1$$

$$u_{c2} = M_2 \left( -d_2 \left( h_2 - \dot{\theta}_d \right) \ddot{\theta}_d - k_2 \dot{\theta}_d^2 - c_2 \left( \dot{\theta}_d - \dot{\theta}_d \right) \right)$$

$$u_{n2} = M_2 \ddot{\theta}_d + C_2$$

Figure 2. Control block diagram of the TDFR with the proposed CPGCC method.
The dynamical error models of the joints of the TDFR can be expressed as

\[
\begin{align*}
\ddot{\theta}_{d1} + d_1 \left( h_1 - \dot{\theta}_{d1}^2 \right) \dot{\theta}_{d1} + k_1^2 \theta_{d1} + c_1 \left( \dot{\theta}_{d1} - \dot{\theta}_{d2} \right) &= 0 \\
\ddot{\theta}_{d2} + d_2 \left( h_2 - \dot{\theta}_{d2}^2 \right) \dot{\theta}_{d1} + k_2^2 \theta_{d2} + c_2 \left( \dot{\theta}_{d2} - \dot{\theta}_{d1} \right) &= 0
\end{align*}
\]  

(9)

Substituting equations (7)–(9), we have

\[
\begin{align*}
\ddot{\theta}_1 + d_1 \left( h_1 - \dot{\theta}_1^2 \right) \dot{\theta}_1 + k_1^2 \theta_1 + c_1 \left( \dot{\theta}_1 - \dot{\theta}_2 \right) &= 0 \\
\ddot{\theta}_2 + d_2 \left( h_2 - \dot{\theta}_2^2 \right) \dot{\theta}_1 + k_2^2 \theta_2 + c_2 \left( \dot{\theta}_2 - \dot{\theta}_1 \right) &= 0
\end{align*}
\]  

(10)

Observing equations (6) and (10), the dynamical error models of the TDFR shown in Figure 2 are two coupled Rayleigh oscillators. In conclusion, it is obvious that the movements of the joints of the TDFR with the torques given by equation (8) are coupled to each other similar to two coupled Rayleigh oscillators.

**Numerical simulations and analyses**

In this section, the TDFR with the proposed CPGCC method is simulated, and the synchronization of the two joints controlled by the proposed method is analyzed.

**Simulation model**

Figure 3 shows the simulation model of the CPGCC method established in Simulink. In Figure 3, the symbols theta1 and theta2 represent the swing angles \( \theta_1 \) and \( \theta_2 \) of linkages AB and BC as shown in Figure 1, the symbols theta_d1 and theta_d2 represent the deviations between the swing angles and the zero positions given by equation (7), and the symbols torque1 and torque2 are the torques applied on the two joints. Modules tor1 and tor2 are used to calculate the desired torques \( \tau_1 \) and \( \tau_2 \) according to equation (8), respectively. The module TDFR is the rigid model of the TDFR, whose structure is shown in Figure 1, given by ADAMS. The structural parameters of the TDFR are listed in Table 1, and the controlling coefficients in equation (8) are listed in Table 2. During the simulation, the zero positions \( \theta_{z1} \) and \( \theta_{z2} \) are 0.

**Simulation results and analyzing**

**Behaviors of the Rayleigh oscillators.** Figures 4–6 show the simulated results of two coupled Rayleigh oscillators given by equation (6) with parameters listed in Table 2. The behaviors of two separate Rayleigh oscillators with the different initial conditions \((0.05, 0)\) and \((-0.05, 0)\) are shown in Figure 4. Observing Figure 4, the different initial conditions result in the different phases of the two oscillators. Moreover, the phase difference between the two oscillators would be held in the oscillating process. By contrast, when the two Rayleigh oscillators with the different initial conditions \((0.05, 0)\) and \((-0.05, 0)\)
Figure 3. Simulation model of the TFDR with the CPGCC method.

Table 1. Structural parameters of the TDFR.

| Parameter                                      | Symbol | Value  |
|-----------------------------------------------|--------|--------|
| Mass of linkage AB                           | \( m_1 \) | 2.7 kg |
| Mass of linkage BC                           | \( m_2 \) | 14.2 kg |
| Length from hinge A to the center of linkage AB | \( l_{c1} \) | 0.2 m |
| Length of linkage AB                         | \( l \) | 0.4 m |
| Length from hinge B to the center of linkage BC | \( l_{c2} \) | 0.362 m |

TDFR: two-degrees-of-freedom robot.

Table 2. Parameters of coupled Rayleigh oscillators.

| Parameter                      | Symbol | Value                     |
|--------------------------------|--------|---------------------------|
| Damper coefficients           | \( d_1, d_2 \) | 1 s/(m rad^3)            |
| Stiffness coefficients        | \( k_1, k_2 \) | 10/(m rad s^2)^{0.5}    |
| Amplification coefficients    | \( h_1, h_2 \) | 40(rad/s)^2              |
| Coupling coefficient          | \( c_1, c_2 \) | 2/(m s rad)              |

are coupled with the coupling coefficients listed in Table 2, their behaviors are shown in Figure 5. As shown in Figure 5, although the different initial conditions result in the different phase, the phase difference would be eliminated at 7 s due to the coupled terms given by equation (6). When two Rayleigh oscillators with the same initial conditions are coupled with coupling coefficients \( c_1 \) and \( c_2 \) of 2/(m s rad) and \(-2/(m s rad)\), their behaviors are shown in Figure 6. Observing Figure 6, although the two oscillators have the same initial conditions, a confirmed phase difference is presented at 7 s and maintained
in the whole oscillating process. As shown in Figures 4–6, it is clear that the two coupled Rayleigh oscillators have the same dynamical behaviors, despite having different initial conditions. In conclusion, two Rayleigh oscillators’ behaviors can be synchronized by the coupled terms given by equation (6).
When the damping coefficients of the Rayleigh oscillators are equal to 1, Figures 7 and 8 show the simulated phase planes and time histories of the Rayleigh oscillators with various amplification coefficients and stiffness coefficients listed in Table 2.

**Figure 6.** Simulated time histories of two Rayleigh oscillators with the same initial conditions (0.05, 0) and (0.05, 0) coupled with coupling coefficients $c_1$ and $c_2$ of $2/(\text{m s rad})$ and $-2/(\text{m s rad})$, respectively.

**Figure 7.** Simulated phase planes of Rayleigh oscillators with amplification coefficient $h$ of 1, 4, and 9.

When the damping coefficients of the Rayleigh oscillators are equal to 1, Figures 7 and 8 show the simulated phase planes and time histories of the Rayleigh oscillators with various amplification coefficients and stiffness coefficients listed in Table 2,
Observing Figure 7, the amplifications of the Rayleigh oscillators increase from 1 to 13 with the amplification coefficient $h$ increase from 1 to 16. Observing Figure 8, the frequencies of the Rayleigh oscillators increase with the stiffness coefficient $k$ increase from 1 to 3.

**Performances of the CPGCC method.** Figures 9 and 10 show the simulated time histories of the rotations of TDFR’s two joints ($\theta_1$ and $\theta_2$) controlled with the proposed CPGCC method. Observing Figure 9, when the TDFR’s joints are controlled with coupling coefficients $c_1$ and $c_2$ of $2/(m \cdot s \cdot rad)$ and $2/(m \cdot s \cdot rad)$, respectively, the rotations of the hinges A and B have the same phases during the oscillating process. By contrast, when the TDFR’s joints are controlled with coupling coefficients $c_1$ and $c_2$ of $2/(m \cdot s \cdot rad)$ and $-2/(m \cdot s \cdot rad)$, respectively, their simulated time histories of rotations are shown in Figure 10. As shown in Figure 10, the rotations of the hinges A and B hold a confirmed phase difference during the oscillating process. The results shown in Figures 9 and 10 indicate that the proposed CPGCC method is able to control the TDFR’s joints to synchronously rotate.

**Experiment and results**

**Experimental setup**

Figure 11 shows the experimental setup of a TDFR established on a real-time simulation system (myRio, National Instrument). Observing Figure 11, the experimental setup of a TDFR comprises the TDFR, a driver, and a real-time simulation system. The real-time simulation system is used as the controllers via the proposed CPGCC methods, as well as to process the feedback sensing signals. Two joints of the TDFR are driven by two
Figure 9. Simulated time histories of the angles of TDFR’s two joints controlled with the proposed CPGCC method with coupling coefficients $c_1$ and $c_2$ of $2/(m \cdot s \cdot rad)$ and $2/(m \cdot s \cdot rad)$, respectively.

Figure 10. Simulated time histories of the angles of TDFR’s two joints controlled with the proposed CPGCC method with coupling coefficients $c_1$ and $c_2$ of $2/(m \cdot s \cdot rad)$ and $-2/(m \cdot s \cdot rad)$, respectively.

to servo motors, respectively. The driver is used to provide the desired driving voltage according to the controlled signals from the controllers.
Figure 11. Experimental setup of a TDFR based on the real-time simulation system.

Figure 12. Experimental time histories of the angles of TDFR’s two joints controlled with the proposed CPGCC method with coupling coefficients $c_1$ and $c_2$ of $2/(m\cdot s\cdot rad)$ and $2/(m\cdot s\cdot rad)$, respectively.

Results

Figure 12 shows the time histories of the angles of TDFR’s two joints controlled by the proposed CPGCC method with coupling coefficients $c_1$ and $c_2$ of $2/(m\cdot s\cdot rad)$ and $2/(m\cdot s\cdot rad)$, respectively. Observing Figure 12, it is obvious that the two angles have different phases during the six beginning cycles. However, their phases are synchronized after the sixth cycle. On the contrast, when the coupling coefficients $c_1$ and $c_2$ are equal to $2/(m\cdot s\cdot rad)$ and $-2/(m\cdot s\cdot rad)$, respectively, the time histories of the angles of TDFR’s two joints are shown in Figure 13. Figure 13 shows the two angles which have no phase difference separated to each other after the third cycle and maintain a phase difference of
approximately half cycle. The experimental results demonstrated that the proposed CPGCC method can synchronously control the multi-objects with the coupling phases.

**Conclusion**

To synchronously control TDFR’s two joints, by utilizing two coupled Rayleigh oscillators with the mutual locked phases as the referred models of the two joints, the CPGCC method is proposed. On these bases, the co-simulation model of the proposed CPGCC method is established via ADAMS and MATLAB/Simulink, and the performance of the CPGCC method on synchronizing motions of TDFR’s two joints is numerically simulated. Furthermore, the experimental setup of a TDFR is established based on the real-time simulation system via the proposed CPGCC method. And experiments are carried out on the established experimental setup. The simulated results of the Rayleigh oscillators show that Rayleigh oscillators can be coupled by adding coupling terms, and the phase difference can be changed according to coupling coefficients. The simulated and experimental results of the CPGCC method show that phases of the controlled TDFR’s joints are mutually locked to others, and their motion pattern can be adjusted through the coupling terms in the CPGCC method. In conclusion, the proposed CPGCC method can be used to synchronously control the TDFR’s joints and adjust the rhythmic pattern of the TDFR. Different from the conventional methods which apply the coupled Rayleigh oscillators for generating the reference trajectories and applying additional PD controllers for tracking these trajectories, the coupled Rayleigh oscillators in this article are used as the controllers via their convergences. Therefore, this article illustrates the feasibility.
of designing the coupling controllers without using the additional tracking controller, which is useful for the multi-joint robot.

**Declaration of conflicting interests**

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