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Electroencephalography(EEG)-Based Instinctive Brain-Control of a Quadruped Locomotion Robot

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***Abstract*—Artificial intelligence and bionic control have been applied in electroencephalography (EEG)-based robot system, to execute complex brain-control task. Nevertheless, due to technical limitations of the EEG decoding, the brain-computer interface (BCI) protocol is often complex, and the mapping between the EEG signal and the practical instructions lack of logic associated, which restrict the user's actual use. This paper presents a strategy that can be used to control a quadruped locomotion robot by user's instinctive action, based on five kinds of movement related neurophysiological signal. In actual use, the user drives or imagines the limbs/wrists action to generate EEG signal to adjust the real movement of the robot according to his/her own motor reflex of the robot locomotion. This method is easy for real use, as the user generates the brain-control signal through the instinctive reaction. By adopting the behavioral control of learning and evolution based on the proposed strategy, complex movement task may be realized by instinctive brain-control.**

***Keywords*: Neurorobotics, human-robot interaction, brain-computer interface, instinctive control, quadruped robot**

I. INTRODUCTION

The ultimate goal of human-robot interaction and cooperation is that the robot can make a reasonable response directly to the user's intent. Brain-computer interface technology is based on the direct access to the information of physical activity in the thought processes of the human brain, providing an effective neuro-pathway connecting thinking and machine intelligence. This has become an important development direction in the field of human-computer interaction. The EEG based BCIs, characterized by the advantages such as non-invasive signal detection and easy for use, have been extensively researched and it has great potential of practical applications.

However, although much progress has been achieved for non-invasive BCIs, the available brain signals that can be used as control signals at a time are still limited. As development of robust signal features may take a long time, and signal decoding accuracies are far from enough for practical use, current research focuses on enhancing EEG signal decoding accuracy and decoding rate. Yet, there is no guide for researchers to follow.

Due to its great potential in medical rehabilitation, military, education and scientific research, in recent years, academia has set the applications of brain controlled robots as the research goal, carried out explorations on study of the use of machine intelligence to make up for the inadequacy of BCI technology. Related research, for example, the revealed research on brain-controlled robot soldiers in the budget of DARPA 2013, has continuously been funded by the health department, military, and the government.

Areas of brain-controlled robot and applications of BCIs [1]-[12], biomimetic behavior control [13]-[19], and biomimetic movement [20]-[24] are growing hand in hand. In 2D cursor control studies by Wolpaw [1], Pfurtscheller [2], BCI translates the brain signal into cursor's movements, which enables simple applications of BCIs. These applications are straightforward brain-computer interactions, where the computer executes the control commands according to the simple BCI protocol to finish tasks. With the enhancement of the complexity of the objectives and tasks, complex biomimetic robot systems have gradually emerged in the worldwide laboratories, and the biomimetic behavior control theory has been introduced (as shown in Fig. 1). These systems compensate the constraints in BCI technologies with robot intelligence. Birbaumer [5], Rebsamen [6] designed powered wheelchair with path planning (Deliberative behavior control), achieved brain controlled wheelchair navigation in the quasi-static environment. Iturrate [7], Millán [8], Röfer [9] designed the powered wheelchair with both autonomous navigation and reflection obstacle avoidance (Reflective behavior control)，which enabled brain controlled wheelchair navigation in a dynamic environment. Shenoy [11], Deng [12] designed a brain controlled biped robot system, further achieved the motion control of biomimetic system, where the generation of the actions were independently completed by the robot. In such system, EEG was mapped to a pre-set high-level task, such as go forward or carry a box, through carefully designed BCI protocol. These applications are characterized by the advanced "brain-intelligent robot system", instead of the "brain-computer system". These systems made complex deliberative decisions based on human experience, and they generate specific actions by robots with certain autonomous control.

The innate behavior control of the robot, including reflex control and instinctive control (Usually presents reflective behavior sequence), helps the robot to achieve the involuntary movement. Acquired behavior control of the robot, including deliberative control and social control, enables the robot more

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advanced intelligence and the ability of achieving voluntary movement. Currently, brain controlled robot systems for complex tasks mostly have already got a certain innate behavioral control and acquired behavioral control. However, the assigned tasks need complex BCI protocols to map the number-limited and delayed EEG signals to the scheduled task instructions lacking of logic association. During task execution, users actively or passively generate EEG signals according to both logical thinking to BCI feedbacks and requirements of EEG decoding technology. This challenges the users' quick reaction ability, attention level, and physical strength, which may limit the practical applications of brain controlled robots.

Compared with neuro-robot relying on neuro-interface in achieving direct instinctive control of artificial limbs, brain controlled robot is not competitive in terms of naturality and convenience, but it has great advantages, i.e., signal availability and ease of use.

Therefore, the focus of this study is to achieve EEG instinctive control of basic movements of biomimetic robots, through learning from the instinct and reflection characteristics of neural robot control, rather than through complex BCI protocols. This study uses the quadruped bionic robot as the specific object, and discusses how to directly control basic movements of the robot using EEG signals, and provides a detailed approach.

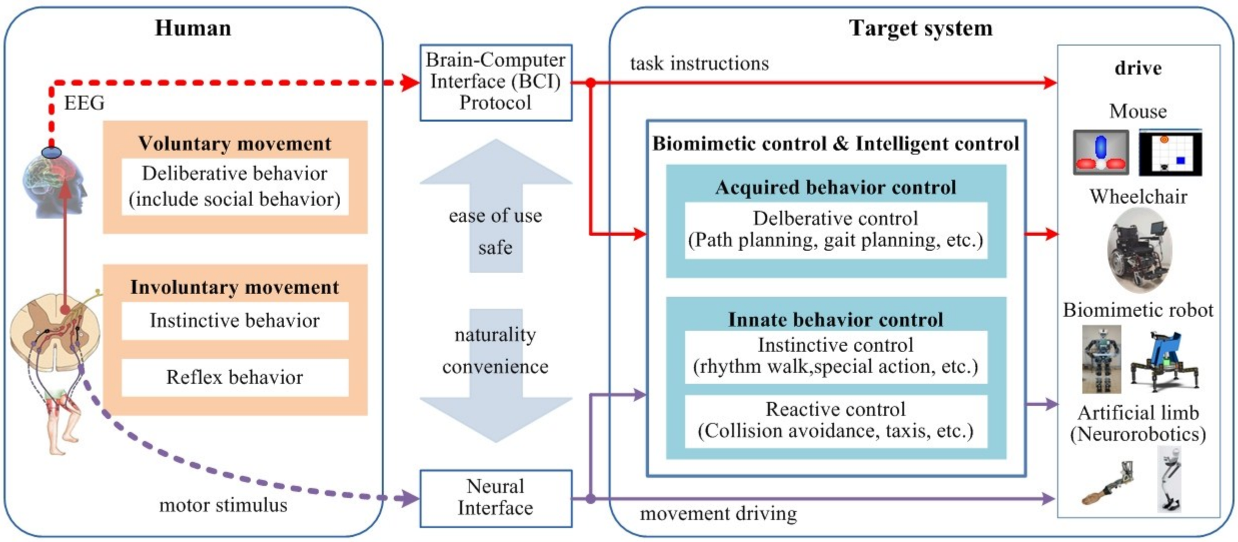

Figure 1. Technology development of brain controlled robots.

II. Control Method

A. Architecture

The higher animals in the nature with near-perfect exercise capacity and environmental adaptability are always the best reference of the robot intelligent control. H. Dickinson [13] believed that control of animal movement is quick mechanical reflection, together with the feedback and feedforward of the perception. At the same time that each unit of the animal body achieves their local action, they constituted the overall motor behavior of the animal. Nishikawa [14] and Biewener [15] further elaborated how the animal's nervous system, perceptual system and musculoskeletal system maintain the coordination process in motion. Rhythm control method of foot movement has been extensively studied and achieved excellent results [17]-[21].Through a combination of the central pattern generators (CPG) and perception of reflection, effective simulation could be done to biomimetic gait and gait transition of the quadruped movement.

Therefore, in the architecture of this study, robotic behavior control system includes CPG for instinctive rhythm walk and sensory stimuli for reflective balance control, as shown in Fig. 2. The corresponding EEG signal during human motor process interacts with the robot through natural mapping protocol of movement intention, to achieve the natural brain control of the quadruped robot.

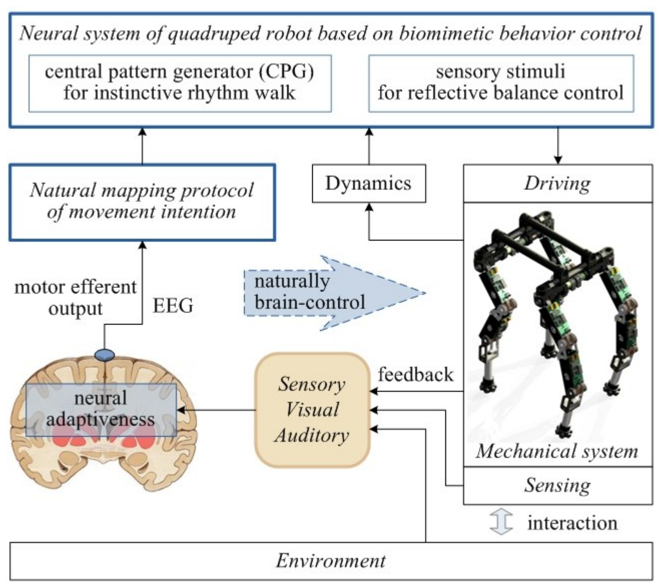

Figure 2. Architecture of instinctive brain-control of quadruped robot.

Robot neural control systems and robot dynamics model constitutes the first stage coupling in order for the robot to quickly adapt to the dynamic environment. Control mechanisms of the human brain and robot systems constitute the second stage coupling through the BCI, further enhance environmental adaptability and task execution ability through the human inherent action experience and thinking skills.

B. EEG Signal

In this study, five types of EEG signals which have relatively high spatiotemporal resolutions [25] are adopted for BCI, i.e. *Idle (no-control)*, *Lno (left hand movement in the first timed period)*, *Rno (right hand movement in the first timed period)*, *Lyes (left hand movement in the first and second timed periods)* and *Ryes (right hand movement in the first and second timed periods)*. All the signals are expected to be obtained through performing corresponding imagination of hand movement tasks. The details can be found in [25]. We apply signal processing and machine learning to distinguish the patterns from each other.

Recognition of each signal can be used as one control command, or combined with others to achieve more complex control, depending on control mode. In real case, subject decides what command to make. In fact, the proposed strategy can be applied to other types of EEG signals or non-EEG physiological signals, in which case the strategy design can be adjusted according to how the signals are generated and to the convenience of the user.

C. Protocol

The nerve rhythm control system of the robot is shown in Fig. 3, using similar approach as [16]. The rhythms of robot limbs are generated by the respective CGP models, which directly drives the movement of the hips. Shoulder and elbow's movement trajectories are generated by the transformation of hip movement trajectory under the same phase. Foot and ground contact force is used for feedback in the CPG model. Roll angle and pitch angle of robot body is used to correct the direct force feedback to render the robot better degree of adaptability to the varied terrain.

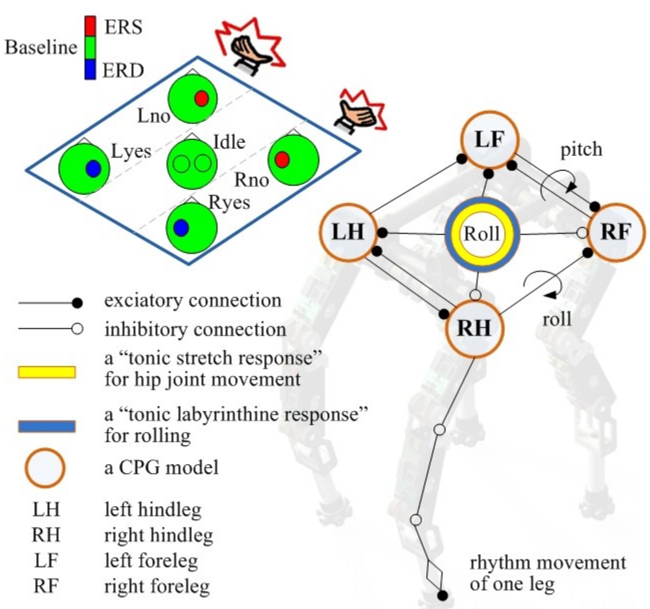

Figure 3. Rhythm control system of the quadruped robot.

Any effective EEG signal from the BCI is designed to be associated with the specific effect of the motor nervous system. For example, the sustained hand's movement (*Lyes*, *Ryes*) corresponds to the increased capacity of limb extensor of the robot system. Cessation of hand's movement (*Lno*, *Rno*) corresponds to the increased capacity of limb flexor. In this setting, natural brain control protocol of the quadruped movement is shown in Table I. Two consecutive EEG signal corresponds to the body movements of logically consistent action. For example, through the different movement duration of left hand and right hand (e. g., *Lyes→Rno*), flexion and extension coefficient at both ends of limb in the robot virtual nervous system is changed, so as to enhance the response of the neural network roll deflection capacity. This is essentially different from the robot first level of feedback "tonic labyrinthine response" for rolling; the latter only makes the appropriate changes in the roll angle through the robot neural network while the former applies the inherent action experience to the robot neural network. By this approach, we achieved brain control protocol similar to the direct neural control.

TABLE I. PROTOCOL OF BRAIN-CONTROLLED QUADRUPED MOVEMENT

1st→2nd response	Nervous system	Robot movement
Lno→Ryes/ Ryes→Lno	Left-legs flexed; Right-legs extended.	Roll right
Lyes→Rno/ Rno→Lyes	Left-legs extended; Right-legs flexed.	Roll left
Lno→Rno/ Rno→Lno	Fore-legs flexed (Hind-legs extended).	Pitch down
Lyes→Ryes/ Ryes→Lyes	Fore-legs extended (Hind-legs flexed).	Pitch up
Lyes→Lyes/ Rno→Rno	The activity of left foreleg is increased; The activity of right foreleg is decreased.	Turn right
Lno→Lno/ Ryes→Ryes	The activity of left foreleg is decreased; The activity of right foreleg is increased.	Turn left
Lno→Lyes/ Rno→Ryes	The activities of all legs are increased.	Speed up
Lyes→Lno/ Ryes→Rno	The activities of all legs are decreased.	Slow down
Idle (e. g. Lyes→Idle)	Keep	Keep

III. DISCUSSION

An instance of *roll right* is shown in Fig. 4. When the robot walks on inclined terrain from level terrain, the CPG network plays a role in adapting to terrain changes firstly. The specific effects are to stretch the legs under higher support force and to shorten the legs under lower support force, which will adjust the body posture from tilted to horizontal and maintain balance. CPG network partially inhibited the effects of varied terrain, but it is difficult to achieve the best adaptation and may cause foot slipping and instability, which requires the further adjustment by the user. As shown in Fig. 4, the user instinctively seeks to enhance the stretch ability of the right limbs and the flexible ability of the left limbs, by observing the robot's actual movement. In the time window T1 and T2 of the first decision-making period, the user keeps his right hand movement to generate *Ryes* signal. And in the second decision-making period, he keeps his left hand movement in T1 and stop to relax in T2 to generate *Lno* signal. View from specific control process, the user instinctively seeks to enhance the stretch ability of the robot's right limbs, so he sustained the movement of the right hand of himself's, as done in first decision-making period. And the user instinctively seeks to reduce the stretch ability of the robot's left limbs, so he changes his left hand from moving to relax, as described in second decision-making period. Through two consecutive brain control instruction *Ryes* and *Lno*, the flexion and extension ability of limbs in the neural network is changed to adjust the body posture and movement gait of the robot. This method makes the robot movement more consistent with the inherent walking experience of the user.

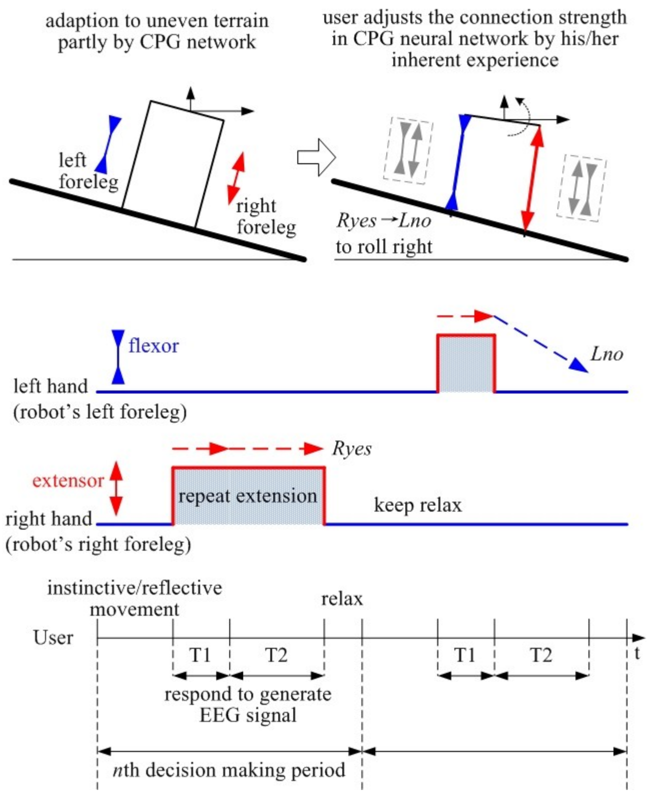

Figure 4. Roll right by the user's inherent experience in movement.

Similar to roll control method, hands slow down/speed up action weakens/strengthens the extensor of forelimb in the robot neural network, and strengthens/weakens the extensor of the hind legs, which adjusts the pitch motion of the robot. Continuous one hand movement (e.g. *Lyes→Lyes*) accelerates the limb motor activity, and increases the swings, in order to adjust the steering movement of the robot. Actions from low to high frequency of single-hand (e.g. *Lno→Lyes*) enhance the movement of all limbs activity, thereby adjusts the velocity of the robot, and generates the gait to the corresponding speed. If one of the continuous EEG signal is *Idle*, then nothing changes in the robot control system, and the current motion stage continues; during this period users can keep relaxed. In addition, *Idle* signal is used in the fault-tolerance, which means if the user finds unexpected decoding through visual feedback, he can cancel that command through using an *Idle* signal. Due to the relatively high decoding accuracy of *Idle* signal, the operation of the fault-tolerance and keeping relax are highly reliable.

In the brain control process, users mainly rely on visual feedback to obtain information. The human-robot interface of the brain control system is shown in Fig. 5. The system information is obtained through a real physical sensor to reproduce the posture and state of motion of the robot in the human-robot interface. EEG changes in the ability of limb flexion and extension of the nervous system is marked by color. Black limb indicates limb flexor and extensor factor uses default value, the red limb indicates extensor factor increased, and the blue limb indicates flexor factor is improved.

In the simulation test, the user adjusts the expectations of the robot movement according to the instinct of its own motor nerve, imagines its own hand's movement to generate EEG signals to adjust robot's movement. At the same time, the adjustment of robot limb flexion and extension capacity is provided to the user through visual feedback, and the user can visually observe the effect of robot limb flexion and extension adjustments that are consistent with their own action.

In tilted walking simulation, the user adjusted the limit cycle of rhythm quadruped walking by proposed method, and the expected roll motion was achieved. Furthermore, performance of the limit cycle is improved, the new rhythm trajectory changed away from the boundaries of basin of attraction walking to maintain the stable rhythm gait, as shown in Fig. 6.

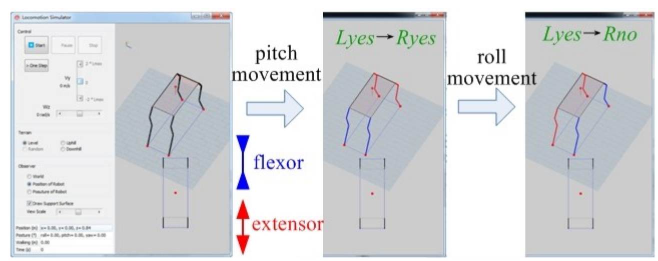

Figure 5. Visual feedback of instinctive locomotion control.

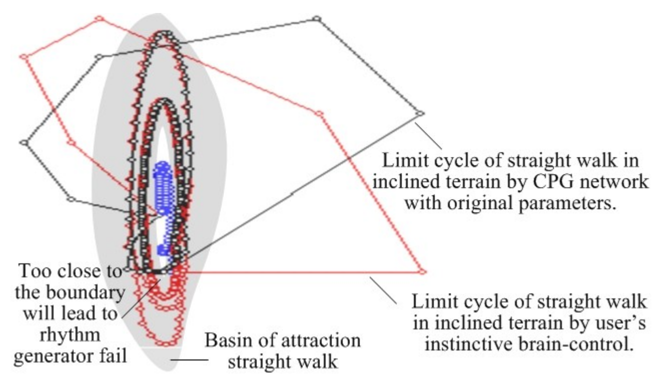

Figure 6. Phase space of a roll motion by instinctive brain-control.

IV. CONCLUSION

This manuscript describes the development process of the brain-controlled robot in detail. Artificial intelligence and bionic control is growing to be applied in electroencephalography (EEG)-based robot system, to realize complex brain-control task. Nevertheless, due to technical limitations of the EEG decoding, the brain-computer interface (BCI) protocol is often complex, and the mapping between the EEG signal and the practical instructions lack of logic associated, which restrict the user's actual use. This paper presents the strategy that can be used to control the quadruped locomotion robot by user's instinctive action, based on five kinds of movement related neurophysiological signal. In actual use, the user according to his/her own motor reflex of the robot locomotion, drives or imagines the corresponding limbs action to generate EEG signal to adjust the real movement of the robot. This method is easy to actually use, as the user generates the brain-control signal through the instinctive reaction. By adopting the behavioral control of learning and evolution based on the proposed strategy, complex movement task may be realized by instinctive brain-control.

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