SYNOPSIS OF THE THESIS ENTITLED

Brain-Computer Interface for Position Control of a Robot Arm for Rehabilitative Applications

Submitted by

Arnab Rakshit

Brain-Computer Interface (BCI) refers to direct interfacing of a human/animal brain with a computer to acquire, understand and decode the brain states by the computer. BCI aims at achieving 2 fundamental motivations. First, it provides a non-muscular channel of communication between the brain and the computer to understand brain functioning. Second, it offers one modality to control the brain states/activity by suitably chosen stimuli. BCI has gained immense popularity over the last 2 decades for its widespread applications and versatility in neural rehabilitation (of patients suffering from neuro-motor disorders), mind-controlled external interface for gaming, auto-prompting cognitive failures in driving, brain-response-based collaborative decision-making for defense and other related applications, and many others. One of the common problems in neural rehabilitation by BCI means is concerned with position control of the end-effecter associated with a robot arm. This has interesting and useful applications in the design of artificial prosthetic limbs for neuro-motor disabled patients.

The thesis deals with the design and development of new control strategies for BCI-based position control of prosthetic robotic limbs, to rehabilitate a person with provision for controlling its motion in desired direction and orientation. The study undertaken in the thesis begins with single-link position control. Once a link of the robotic arm is correctly positioned with high positional accuracy, the BCI system is expected to generate a control command for the next selected link. The process of link selection of the robot arm thus is continued by the subject's own choice with the available signalling support by the BCI system, until the target position of the end-effecter is reached.

Controlling motor movement (planning an execution) in the desired manner is an important issue for motion control of a BCI-based robotic arm. For example, turning a robotic link by the desired angle requires (mentally imagined) motor switch to activate an electromechanical motor for turning for a given duration at constant speed (until the targeted position of the link is reached), and deactivate the motor for a pause (no turning). Naturally, such motion corresponds to an on-off control strategy in traditional control theory. Such kind of on-off control is needed for position control of individual links. When a number of links are to be turned in the desired order, the task becomes relatively complex. Hence, the link selection is to be carried out first by utilizing one evoked potential, called Steady-state visual evoked potential (SSVEP). After the link is selected, the position of the link is displaced by the desired angle by controlled duration motor activation followed by no motor-activation.

The motivation of the present research is to generate control commands for motion of the individual links in a desired manner, so as to position the end-effecter at the targeted position. One well-known control

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strategy that needs special mention in the present context is concerned with Motor Imagery based motor activation and Error-Related Potential (ErrP) based motor deactivation to position a link in the target position. The strategy is easy from the implementation point of view but results in large steady-state error in the position of the end-effecter. Additionally, the said scheme allows only fixed-order link selection because of the limitation of BCI-based communication between the subject and the controller. The thesis aims at handling the above problems by 3 distinctive approaches, presented in Chapters 2-4. In addition, the cognitive load of the subject in the BCI-based position control schemes usually is high. The thesis proposes one solution to reduce the cognitive load of the subject, by utilizing brain signals acquired to understand subject's intension, and generating control and actuation commands by additional automation to perform autonomous reaching and grasping of the target object. The additional automation has provisions for self-sensing, local control and actuation.

The thesis includes 5 Chapters. Chapter 1 provides a thorough review of the existing strategies for position control by brain-computer interface means. It begins with an introduction to Brain-Computer interfaces (BCI), and reviews the scope of closed-loop position control in the context of brain-inspired rehabilitative robotics. Traditional electroencephalography (EEG)-based brain signals used in the existing BCI interface are outlined next. The discussion spans over 4 important brain signals, including Event-Related De-synchronization followed by Event-Related Synchronization (ERD-ERS), Error-Related Potential (ErrP), P300, and Steady-State Visual Evoked Potential (SSVEP). The importance of the above signals in BCI-based position control of a robot arm in 2D and 3D workspaces are explained in brief. Although BCI earned great success in both laboratory and clinical environments, traditional BCI-based control even today lacks a formal and precise nomenclature and taxonomy. The chapter makes an early attempt to classify the existing BCI- based control strategies into 4 major heads: i) purely open loop control, ii) closed-loop with visual feedback, iii) closed-loop with encoded feedback, iv) Auxiliary control-based closed-loop system. All these four types of control strategies have their relative merits and demerits.

However, the last strategy is more important than the rest for its inherent advantages of relieving the cognitive load of the subject participating in the BCI loop. The auxiliary controller in addition offers high precision control, which usually is difficult to achieve by human agents. A brief overview of the architectural details of the fourth scheme stated above is given next in the chapter. The architecture of scheme 4 includes a Neural Interface and an Auxiliary Controller in cascade with the human brain in the loop. The modules involved in building the neural interface are discussed next. The functional architecture of the auxiliary control strategy is reviewed with reference to P-I-D control, vision based shared control and model predictive control. The state-of-the-art research on BCI-based control schemes are reviewed in detail in the later part of the Chapter. The chapter ends with a discussion on the scope of the thesis.

Chapter 2, 3, and 4 are original contributions of the present thesis, demonstrating new approaches to controller design for BCI-based rehabilitative applications with an aim to reduce steady-state positional error, settling time and also attempting to improve the relative stability of the proposed control systems by judiciously choosing the parameters of the controller. Chapter 2 is concerned with an important issue of velocity modulation of the individual links of a robot arm, each time the link crosses the desired target position. The velocity modulation includes speed reversal with a gradual declination in the amplitude of speed, each time the link or the end-effecter crosses the target position. The velocity modulation is advantageous in the sense that it has a tighter control over the position of the end-effecter. In the present

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implementation , given in Chapter 2, two control loops are utilized, where the outer loop takes care of position control and the inner loop attempts to control the speed of the end-effecter. The 2-loop cascade control naturally has improved performance in time-response, such as settling time and positional overshoot. Besides handling steady-state error, the additional merit of the proposed control strategy includes the design of a brain-actuated controller that produces a control command based on the occurrence of a P300 signal liberated by the subject in response to the zero crossings of the positional error signal. A stability analysis undertaken using root contour plots demonstrates that the proposed brain-actuated control system is stable for wider variations of controller parameters. An analysis of relative stability is undertaken to determine the optimal settings of the controller parameters that jointly improve settling time and DC gain. The analysis of stability further envisages that the choice of the initial speed of the end- effecter is of primary concern to limit the stability of the overall system. A large initial speed may result in instability as it may allow sustained oscillations for prolonged durations, whereas a small initial choice of velocity improves peak-overshoot at the cost of additional settling time. The choice of the initial velocity thus is an important concern for the proposed brain-actuated control system. The experimental evidence reveals that the system achieves an average success rate of 92.1% in a position control task, which is significantly higher than the other state-of-the-art approaches. The settling time of the system also came down 9.92s along with the significant reduction of peak-overshoot and positional steady-state error.

The above chapter also provides a thorough comparison of the controller performance with other hybrid-BCI-based position control schemes. However, it is found that the proposed control strategy outperforms the other approaches in terms of four performance metrics i.e. success rate, steady-state error, peak-overshoot and settling time.

Chapter 3 examines the problem of controller design by means of fuzzy logic. The work has importance over the preceding work presented in Chapter 2 with reference to the extraction of more information about the assessment of positional overshoot/undershoot by the BCI system itself to offer better freedom to the controller to improve positional accuracy in steady-state. It is important to note that the ErrP signal released by the experimental subject during the test phase of the control system just refers to the information that the subject just has experienced a zero-error crossing in the positional offset, but it hardly indicates the magnitude of positional error due to the movement of the end-effecter. The proposed fuzzy control policy can take decision about speed setting of the end-effecter or the links based on 2 parameters: magnitude and sign of errors. It is therefore important to mention here how we calibrate the magnitude of positional error. The magnitude of error can be approximately assessed by checking whether the end-effecter or the desired link crosses some user-defined landmark positions, spaced apart by small fragments of distance around the target position. Fixing landmarks undoubtedly creates additional complexity, but helps the BCI system to determine the approximate magnitude and sign of error. A fuzzy-rule-based system has been designed to set the speed of the selected link or the end-effecter in the desired direction based on the sign and magnitude of error. The control scheme was verified with the participation of twelve volunteers. An analysis of the proposed fuzzy controller reveals that the peak overshoot, settling time, and steady-state error decreased significantly with respect to the same of state-of-the-art algorithms.

In the above two works, the user is solely responsible for creating the complex trajectory of the robot arm using mental commands to reach and grasp any desired object. Such manual complex trajectory creation imposes high cognitive load on the human subjects, especially for the grasping task which requires

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highly precise position control to align the end-effecter with the desired object for proper grasping. Besides, the above two works employ a control scheme that controls a single link of the robot at a time, i.e., instead of controlling the end-effecter motion directly, the subject controlled the individual links.

The work presented in Chapter 4 eliminates the above drawbacks by employing a vision-based novel shared controller that enables the robot autonomously reach and grasp the desired object with minimal brain commands. The subject in the present scheme is relieved from planning a complex trajectory for the robot link to align it with the desired object. A 3D vision camera is mounted on the moving robot arm to capture the live feed of the surrounding environment while the participating subject observes the feedback of the camera on a digital monitor. The proposed system employs an image processing algorithm to automatically localizes the objects present within the field of view (FOV) of the camera and to blink the centroid of the objects on the monitor. The subject performs two simple tasks to virtually select the desired object present in the surrounding environment. First, he/she performs the motor imagery to rotate the camera in 3D space (rotating the 1st and 5th joint of the robot) to bring the desired object into its Field of view. Once the object is visible in the monitor, he/she needs to focus on the target object and he is expected to release P300 at the instant the target object flashes. The control logic is designed in such a way that whenever a P300 is received, the system registers the location of the object and actuates the end-effecter of the robot to reach the target location using inverse kinematics.

Next, a CNN-based novel robotic grasp detection network named Overlapping Object Grasp Net (OOGNet) is employed to precisely grasp the target object by a parallel plate gripper mounted at the end of the robot arm. The proposed Overlapping Object Grasping Network (OOGNet) generates a grasp rectangle, bounding box, and object class for each object in the image, thus associating each predicted grasp with its object. A custom loss function is proposed for simultaneous object and grasp detection to affiliate each estimated grasp with its corresponding object. The grasp rectangle is converted to the gripper configuration consisting of five parameters (center coordinate of the grasping rectangle, the height of the parallel plates of the gripper, the distance between the two parallel plates of the gripper, and the orientation of the grasping rectangle) for accurate grasping of the object. The network is also capable of grasping the desired object even if the object is partially overlapped by other objects.

As the entire reaching and grasping phase of the robot is made autonomous in the present thesis, the proposed scheme relieves the subject from complex manual trajectory planning, which reduces the overall cognitive load of the participating subject. The scheme also requires very little subject involvement in achieving a task (such as object pick and place) compared to existing state-of-the-art BCI schemes. Such minimal involvement of the human subject reduces the error arising from BCI decoding performance, hence increasing the overall task achievement accuracy. In addition, the system achieves a zero-steady state error within a negligible settling time. The control scheme was verified with the voluntary participation of 10 subjects. The task completion accuracy of 93.4% is achieved on average using the proposed control strategy. Most importantly the positional steady-state error came down to a negligible magnitude while the peak overshoot became almost zero.

The proposed grasping network was also tested separately in the presence of both a single object and multiple objects. In the single-object layout, the system was able to correctly grasp the object with

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97.8% accuracy while in the multi-object layout, the network achieved 96.4% accuracy to precisely grasp any object.

The chapter also provides a comparison of the cognitive workload developed in the subjects while operating a robot using their mental commands following three distinct BCI strategies (including the proposed strategy). NASA-TLX questionnaire survey developed by NASA Ames Research Center is used to assess the workload of the subjects. The workload assessment in this study employs a comprehensive rating system comprising six distinct dimensions: Mental Demands, Physical Demands, Temporal Demands, Performance, Effort, and Frustration. Participants are asked to assign ratings to each sub-scale based on their assigned tasks. Once the rating process is done, they participate in pair-wise comparisons to determine the most influential sub-scale. The overall score of the test is calculated by assigning weights to the sub-scales based on the frequency of selection during the comparison task. The result shows that the proposed task imposes the least cognitive load on the participating subjects compared to the other manual trajectory planning-based state-of-the-art BCI robot manipulation techniques.

Chapter 5 provides a self-review of the thesis and also examines the scope of possible extension of the thesis in both theory and practice.

Arnab Rakshit
Arnab Rakshit
Department of Electronics & Tele-communication Engineering.
Jadavpur University
Kolkata-700032, India

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