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Adaptive high-level control for robot-assisted rehabilitation: A Discrete Event System approach

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Abstract
This research introduces a two-degree-of-freedom rehabilitation robotic platform to enhance Constraint-Induced Movement Therapy (CIMT) for post-stroke upper limb rehabilitation. Unlike conventional CIMT, that depends on therapist intervention, the proposed system integrates a control framework balancing assistance and autonomy to improve patient engagement and recovery efficiency. The main contribution is a hybrid control architecture combining a low-level impedance controller with a high-level discrete event system (DES) controller. This dual-layer control enables real-time adaptation to a patient's motor impairment stage, offering dynamic and personalized rehabilitation. The high-level controller, structured around the Chedoke-McMaster Assessment (CMA), facilitates intelligent transitions between rehabilitation states, ensuring robotic assistance matches recovery progress. The design emphasizes simplicity, portability, and user-friendliness, employing a lightweight, cable-driven mechanism that produces smooth and natural movements, closely replicating manual therapy. Experiments with healthy subjects simulating impaired conditions demonstrated the system's ability to adjust assistance levels and movement velocities according to motor function stages. The results confirm the feasibility of an adaptive, patient-centric control framework that enhances motor engagement and supports progressive rehabilitation. Future work will focus on clinical validation with stroke patients, expanding movement directions, and long-term evaluation of therapeutic outcomes in real-world settings. Overall, this study offers a scalable, data-driven approach bridging robotic automation and therapist-guided rehabilitation, opening new possibilities for improving neuroplasticity and motor recovery after stroke.

Keywords:
Chedoke-McMaster;
Discrete Event System Approach;
Rehabilitation Robot;

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INTRODUCTION

Robot-assisted rehabilitation has emerged as a promising approach to enhance and quantify Constraint-Induced Movement Therapy (CIMT) for individuals with upper limb impairment following a stroke [1]. By limiting movement of the unaffected limb, CIMT, an evidence-based rehabilitation technique, encourages patients to use their impaired limb, thereby promoting neuroplasticity and the recovery of motor function [2].

Despite its efficacy, traditional CIMT is labor-intensive and only available to a limited number of patients due to its heavy reliance on therapist intervention. By lowering the workload of therapists while preserving high-intensity, repetitive, and task-specific training—all of which are essential for motor recovery—robotic systems offer a revolutionary solution in this regard [3][4]. Additionally, these systems provide quantifiable performance monitoring, which allows for real-time therapy modifications in response to patient progress [5][6]. Furthermore, by automating certain patient care tasks, robotic-assisted rehabilitation can maximize resource allocation and free up therapists to concentrate on more intricate interventions [7].

To improve stroke rehabilitation, several robotic CIMT platforms have been created. Using a master-slave control principle, the six-DOF Mirror Image Movement Enable (MIME) system applies forces to the injured limb to aid in rehabilitation [8]. To encourage sustained participation and adherence to rehabilitation exercises, other robotic systems use socially assistive robots and gamification [9]. Furthermore, some robotic devices actively assess movement impairments and compensate for deficits during therapy, acting as both therapeutic assistants and diagnostic tools [10]. Additionally, by fusing exoskeleton and end-effector designs, hybrid rehabilitation robots use adaptive control techniques to customize interventions according to the needs of each patient [11][31]. The CURER exoskeleton, which uses a lightweight, cable-driven design for upper-limb rehabilitation, and the xArm-5 robotic manipulator, which combines Industrial Internet of Things (IIoT) capabilities for remote therapy and augmented reality-assisted rehabilitation [12][13].

Even with these developments, there is still a significant gap in simulating the organic, minimally interventionist guidance of human therapists. The use of subtle fingertip guidance by therapists in manual rehabilitation promotes neuroplasticity and motor relearning by enabling patients to initiate movement with little external force [14][15]. Achieving this delicate balance between autonomy and assistance in robotic systems is difficult, though, and calls for sophisticated control strategies that can adjust to the unique motor impairments of each patient [16].

This study addresses these issues by presenting a new two-degree-of-freedom rehabilitation robotic platform that is intended to improve upper-limb therapy while maintaining ease of use, portability, and flexibility. The system's lightweight, cable-driven mechanism closely resembles therapist-guided rehabilitation, and it was inspired by the ARM Guide robot. This work's main innovation is its hybrid control framework, which combines a high-level discrete event system (DES)-based controller built around the Chedoke-McMaster Assessment (CMA) with a low-level impedance controller to guarantee fluid, natural motion execution. This configuration is rarely seen in portable rehabilitation robots. This architecture enables dynamic, stage-specific support that adheres to clinical assessment guidelines. Additionally, the system receives real-time feedback on patient engagement from the force sensors embedded in the end-effector, which allows it to adjust the therapy's intensity based on user effort. These features work together to provide a scalable, data-driven, patient-centered rehabilitation solution that links therapist-guided intervention and robotic automation. This paper presents the complete design, control architecture, and experimental validation of the proposed system. Preliminary tests using healthy subjects that simulate motor impairments suggest that the platform could offer adaptive, personalized rehabilitation that intelligently adjusts to patient needs.

METHOD

Rehabilitation Robot Design and Kinematic Analysis

The workspace requirements of Constraint-Induced Movement Therapy (CIMT) guided the rehabilitation robot's design and kinematic analysis, which concentrated on the normal range of motion required for this type of therapy. Primary movements of forward-backward movement, as illustrated in Figures 1. The workspace was carefully mapped to ensure the robot could assist the patient within the necessary range of motion, ensuring that all therapeutic movements are well within the robot's capabilities. The design of the rehabilitation robot was developed based on the workspace requirements of Constraint-Induced Movement Therapy (CIMT), ensuring that the system could facilitate movements essential for upper-limb recovery. The primary motion involved in CIMT, which consists of forward and backward arm movements, was carefully mapped to align with the natural range of motion observed in stroke patients, as illustrated in Figure 1. This approach ensures that the robotic system can effectively assist patients by providing movement within the necessary therapeutic range. By reinforcing task-specific and repetitive training, which are key principles in neurorehabilitation, the system promotes motor recovery through controlled and adaptive rehabilitation exercises [18][19].

The rehabilitation robot, depicted in Figure 2, consists of several key components designed to enhance rehabilitation therapy. The mechanical structure was developed using Google SketchUp for 3D modeling, while fabrication was carried out using a water jet cutter to ensure high precision and efficient assembly. The system comprises four major subsystems. The first subsystem features a rotational axis actuator responsible for the yaw motion of the robot, enabling smooth side-to-side movement of the patient's arm through a brushless DC motor that provides controlled rotation [20]. The second subsystem consists of a linear guide and a locking mechanism, which facilitates forward and backward movement of the robot's end-effector while maintaining stability through an active locking feature when required. The third subsystem includes a linear guide actuator powered by a brushless DC motor (AXH-450), which ensures precise linear motion that replicates natural rehabilitation movements [21]. The fourth subsystem consists of the gripper-based end-effector, which serves as the primary interface between the patient and the robotic system. The gripper is embedded with four force sensors, strategically placed to measure forces exerted in two axes: left-right and front-back. These sensors provide real-time monitoring of patient engagement, allowing for dynamic adjustments to therapy intensity based on individual performance [22][23]. The integration of these subsystems allows the robot to effectively assist in rehabilitation exercises while simultaneously tracking patient progress, ensuring that therapy remains data-driven and adaptive to individual needs.

Figure 1. Forward and backward arm movement workspace for rehabilitation

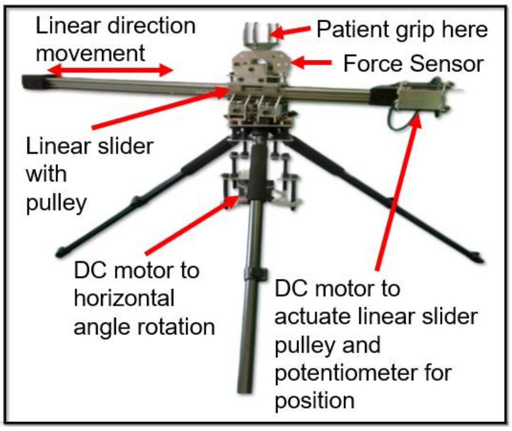

Figure 2. Prototype of robot-assisted rehabilitation system

Chedoke-McMaster based High Level Controller

The robot-assisted rehabilitation system is the control architecture of the rehabilitation robot is structured around the Chedoke-McMaster Assessment (CMA), a widely used clinical tool for evaluating motor impairment in stroke patients. The high-level controller operates as a supervisory system that dynamically adjusts rehabilitation therapy based on the patient's motor function stage. In parallel, a low-level controller regulates the impedance of the robot to ensure smooth and natural movement execution [24].

To facilitate real-time transitions between rehabilitation states, the high-level controller employs a Discrete Event System (DES). This framework categorizes patient recovery states and ensures that therapy adjustments are personalized based on individual impairments. The general structure of the DES controller is illustrated in Figure 3. The rehabilitation process begins when the patient initiates movement using their affected arm while holding onto the robotic gripper. The force sensors embedded in the gripper continuously measure the forces exerted by the patient, mapping them to their corresponding CMA-defined recovery stages. When the system detects weak force output, the velocity of movement is gradually increased to provide active assistance. Conversely, if the patient exhibits sufficient force output, the system applies resistive forces to encourage independent movement, thus promoting active engagement in the rehabilitation process [25].

The CMA-based control model is translated into control states under the DES framework, as summarized in Table 1. An additional state, labeled as State 8, represents the condition in which the patient's arm has reached the desired rehabilitation position.

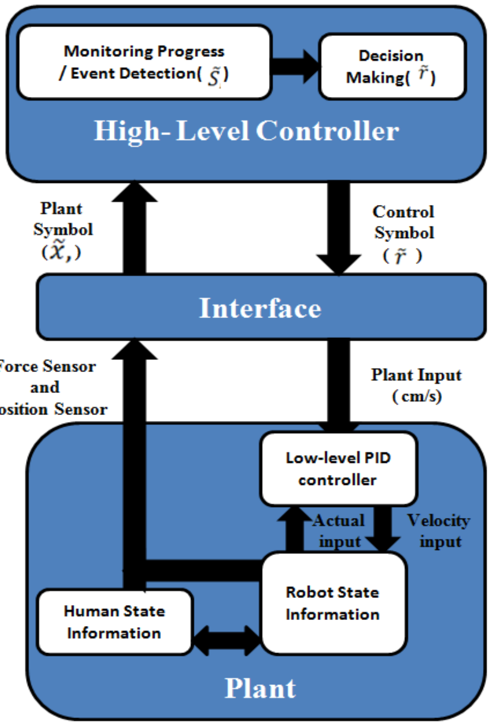

Figure 3. General structure of the DES controller

Each control state is assigned a unique control symbol that dictates the corresponding rehabilitation therapy mode. The list of control actions is provided in Table 2, while Table 3 presents the plant symbols used for transitioning between control states. The transitions within the DES controller are triggered by real-time sensor feedback obtained primarily from force and position sensors. The finite automaton illustrating these transitions is shown in Figure 4. The plant symbols generated from the sensor inputs determine the patient's functional state and guide their progression through different rehabilitation stages. This structured approach enables adaptive trajectory modifications based on the forces exerted by the patient, allowing velocity scaling for progressive assistance while integrating real-time feedback to dynamically adjust therapy intensity.

Table 1: List of control states

Control State	CMA Stage or Patient condition
State 1($\tilde{\varsigma}_1$)	CMA Stage 1
State 2 ($\tilde{\varsigma}_2$)	CMA Stage 2
State 3($\tilde{\varsigma}_3$)	CMA Stage 3
State 4($\tilde{\varsigma}_4$)	CMA Stage 4
State 5($\tilde{\varsigma}_5$)	CMA Stage 5
State 6($\tilde{\varsigma}_6$)	CMA Stage 6
State 7($\tilde{\varsigma}_7$)	CMA Stage 7
State 8($\tilde{\varsigma}_8$)	Patient arm has reached the desired position or initial position

Table 2: List of action symbols and definitions

Control Symbol	Definition of actions
$\tilde{r}_1$	The client needs total assistance with maximum speed (3.5cm/s)
$\tilde{r}_2$	Maximal assistance with Speed maximum (3.2cm/s)
$\tilde{r}_3$	Moderate assistance (3.0cm/s)
$\tilde{r}_4$	Minimal assistance (2.7cm/s)
$\tilde{r}_5$	Clients needs supervision (2.5cm/s)
$\tilde{r}_6$	Client is modified independent but needs assistance from devices (2.3cm/s)
$\tilde{r}_7$	Client is timely and safely independent (2.0cm/s)
$\tilde{r}_8$	Negate flag value

Table 3: List of plant symbols and definitions

Plant Symbol	Impairment inventory generated from the force sensors
$\tilde{x}_1$	Flaccid paralysis: 0% of normal strength (N)
$\tilde{x}_2$	Spasticity is present and felt as a resistance to passive movement: 0%-10% of normal strength (N)
$\tilde{x}_3$	Marked spasticity but voluntary movement present within synergistic patterns: 10%-50% of normal strength (N)
$\tilde{x}_4$	Spasticity decreases: 50%-80% of normal strength (N)
$\tilde{x}_5$	Spasticity wanes but is evident with rapid movement at the extremes of range:80%-90%% of normal strength(N)
$\tilde{x}_6$	Coordination and patterns of movement are near normal: 90%-100% of normal strength (N)
$\tilde{x}_7$	Normal movement: 90%-100% of normal strength(N)
$\tilde{x}_8$	Patient's arm arrived at the desired position (29cm) or origin (0cm)

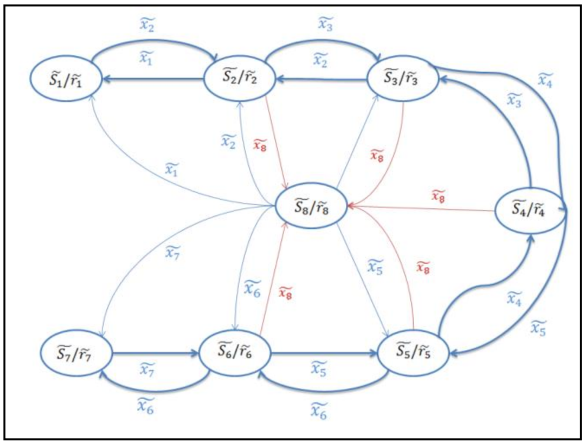

Figure 4. Finite automaton of robot assisted rehabilitation controller

The experimental setup, illustrated in Figure 5, consists of a supervisory controller implemented on a host PC, as shown in Figure 6, interfacing with the robotic platform through a microcontroller-based communication system. The MATLAB Stateflow toolbox in Simulink is used to develop both the high-level DES-based controller and the low-level impedance controller, ensuring real-time communication between the PC and the robotic system, as shown in Figure 7.

The Atmel microcontroller plays a vital role in signal processing by converting analog inputs from the sensors into digital data, which is transmitted via UART through a USB connection to the host PC. Additionally, the microcontroller receives digital commands from Simulink, which are converted back into analog signals to control the brushless DC motor driver that actuates the robotic platform. The system includes two brushless DC motors with built-in velocity control, which ensures precise and repeatable movements during rehabilitation. A multi-turn potentiometer is used as a position sensor to monitor the robotic arm's gripper position, ensuring accurate execution of therapeutic trajectories. Furthermore, the system is equipped with four Flexi-Force sensors capable of measuring forces within a 0-100N range, allowing real-time monitoring of patient effort and dynamic adjustments to therapy intensity based on force constraints.

The experimental setup facilitates continuous monitoring of rehabilitation progress, with the robotic system adapting in real-time to the patient's motor recovery state. The integration of force feedback, trajectory control, and real-time sensor data enables a highly responsive rehabilitation system that ensures therapy remains personalized, effective, and adaptable. The block representation of the experimental setup is shown in Figure 5, while the detailed Simulink block diagram of the control implementation is provided in Figure 6.

Figure 5. Experimental setup

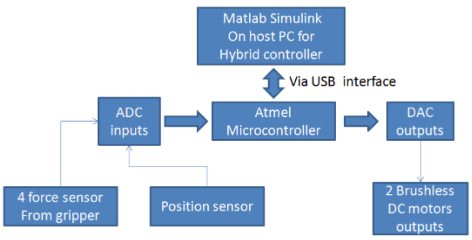

Figure 6. Block representation of experimental setup

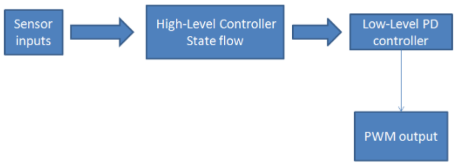

Figure 7. The simulink block diagram

The integration of these hardware and software components ensures that the rehabilitation system operates efficiently, allowing for precise control of the robotic movements while simultaneously providing real-time feedback to the therapist and patient.

RESULTS AND DISCUSSION

The supervisory hybrid real-time control system was evaluated for its effectiveness in state transitions and patient state assessment, with experiments conducted on a healthy subject. The subject simulated stroke patient impairment at Chedoke-McMaster (CMA) impairment level 2, during which the supervisory hybrid control automatically selected maximal assistance as the appropriate therapy for this condition. The subject's right hand was placed on the robotic gripper, and the system dynamically adjusted the therapy based on force sensor input data, demonstrating the system's responsiveness to varying levels of simulated impairment. These results confirm the system's ability to adapt rehabilitation assistance in real time, based on force feedback, thereby offering a personalized therapeutic experience. For deployment in clinical settings, structured therapist training and compatibility with current rehabilitation protocols will be necessary to ensure effective and safe integration into existing healthcare environments.

States triggered by force sensors' inputs on the high-level DES control

The high-level control system responded to the force sensor inputs by triggering appropriate states corresponding to the patient's condition. As the subject mimicked the impaired state, the system engaged in maximal assistance, adjusting the velocity and movement to match the impaired motor functions [26]. Force inputs at specific points in the rehabilitation cycle, as depicted in Figure 8, showed key transitions between stages. For instance, when the force input reached 0 N at point A, corresponding to CMA stage 4, low velocity was applied to prevent overwhelming the subject while promoting gradual control improvement [27]. At points B and C, force inputs fluctuated between -20 N and -60 N and returned to 0 N, respectively, marking the onset of spasticity and the need for controlled movement.

Plant input produced by all the states' high-level controllers

The system's ability to adapt to spasticity, especially in stages 2 and 6, demonstrated its capacity to facilitate rehabilitation. As the force input increased to between 40 N and 60 N at point D, stage 6 was triggered, where coordination improved, and a moderate velocity was introduced to challenge the patient while ensuring correct movement patterns. This adaptive response highlights the system's effectiveness in delivering tailored rehabilitation that progresses with the patient's recovery [28]. Furthermore, the dynamic interaction between the supervisory control states and the plant inputs, as shown in Figure 9, illustrated how the system's transitions fostered patient engagement, independence, and motor skill development. Throughout therapy, the system alternated between forward and backward motions to ensure coordination and active participation, consistent with established findings linking brain signals to motor movements [32]. In order to maintain patient safety, the system offered maximum assistance at a lower velocity when patients showed limited voluntary movement. In order to encourage independence and strengthen motor learning, the system increased velocity as the patient's motor function improved [29].

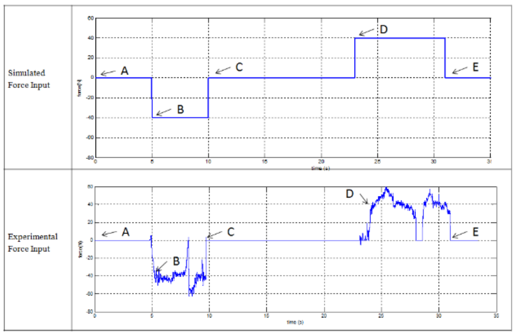

Figure 8. Force input for the system

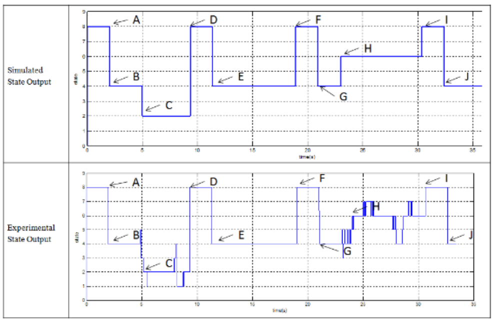

Figure 9. High-Level Control Triggers the State

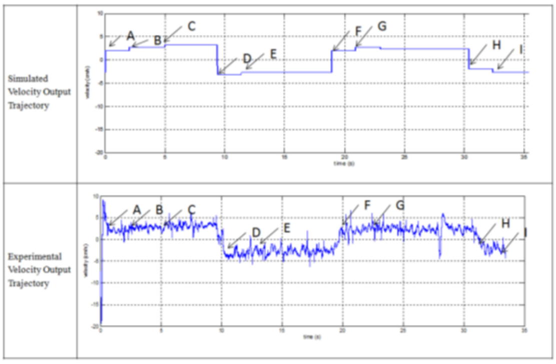

Figure 10. Velocity Output

Velocity produced by all the plant inputs

The way the supervisory control states adjust the system's velocity output and customize the rehabilitation process to the patient's requirements is further illustrated in Figure 10. To represent the patient's degree of impairment, the different velocities, such as 3 cm/s for minimal assistance and 2 cm/s for maximal assistance were carefully selected. The velocity increased to encourage additional engagement and rehabilitation progress as the patient's abilities improved. This adaptive control strategy aligns with studies emphasizing the significance of assistance levels and velocity in maximizing stroke recovery [30].

CONCLUSION

This study demonstrates that the integration of a high-level supervisory control framework with precise plant inputs in a robot-assisted rehabilitation system can significantly enhance patient engagement and improve recovery outcomes. A key novelty of this system lies in the discrete event system (DES)-based high-level controller structured around the Chedoke-McMaster Assessment (CMA), which represents a novel approach in the context of portable rehabilitation platforms. This architecture enables structured, stage-specific adaptation of therapy based on patient motor impairment, supported by real-time force feedback that dynamically adjusts movement velocity and assistance level. In addition, the lightweight, cable-driven mechanical design closely mimics therapist-guided movements while maintaining portability and ease of use. Experimental validation with healthy subjects simulating impaired conditions confirmed the system's ability to deliver adaptive, personalized rehabilitation. While the findings establish feasibility, clinical validation involving stroke patients remains a critical next step. Moreover, the current system is limited to forward-backward planar motion suited for Constraint-Induced Movement Therapy (CIMT); future work will focus on expanding the range of motion, conducting long-term evaluations, and improving clinical applicability. For deployment in clinical settings, structured therapist training and compatibility with existing rehabilitation protocols will be necessary to ensure effective integration and broader adoption.

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