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A Hybrid Controller with Chedoke-McMaster Stroke Assessment for Robot-Assisted Rehabilitation

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Abstract

Amongst the major challenges in post-stroke rehabilitation are the repetitiveness nature of rehabilitation procedure, and the accessibility of therapists for long-term treatment. In manual rehabilitation procedure, the patient is subjected to repetitive mechanical movement of the affected limb by the therapist. In one of the techniques called *active-assist exercise*, the subject moves his affected limb along a specified trajectory with the therapist guiding the motion. The therapist gives some assistance to the subject to complete the course if deemed necessary and the procedure repeats. The significant advantages of using robots in assisting rehabilitation are its efficiency and it is fatigue free. The robots however need to be developed to have the capability of human therapist in providing the rehabilitation more naturally. In this paper, the work focuses on developing a new framework for the robot controller system. In particular, a low-level controller, which is in the form of force controller based on impedance control theory is discussed. The controller is capable of governing the active-assist exercise through autonomous guidance during the therapeutic procedure based on the Chedoke-McMaster stroke assessment method.

Keywords: *Rehabilitation robot, Low-level Controller, Chedoke-McMaster Stroke Assessment.*

Nomenclature

x is the Cartesian coordinate of the robotic platform's end effector
x_d is the targeted coordinate of the system
f is the force exerted on the actuators
m is the mass of the robot
k_p' is the gain to control the robot stiffness
k_v' is the gain to control the robot's damping response
K is the kinetic Energy of the system

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$\tilde{x}$	plant symbols
$\tilde{S}$	control state
$\tilde{r}$	control symbol
i	index of discrete states
c and k	index of plant symbols and control symbols
n	time index that specifies the order of the symbols in the sequence
δ	The transition function from plant symbols to control state
$\emptyset$	output function of control symbol

1. Introduction

The ability of a person's reaching motion is important and crucial for many daily activities such as dressing, eating, and simply getting in and out of a chair so as to make them independent. Besides, the ability to reach enables support to increase one's safety and mobility [2]. Having stroke most likely reduces the ability to reach because of the death of the related brain cells that govern the activity. However, due to the plasticity of the brain structure, at least partial recovery is possible [3]. Generally, recovery can be greatly enhanced by rehabilitation therapy. Rehabilitation therapy after stroke is crucial to help the stroke patient regains as much use of his limbs as possible. In particular, intervention intensity and specificity have been shown to have a good effect on the recovery of the stroke patient [4]. Studies with constraint-induced therapy, whereby the patient's unaffected upper-extremity is constrained for long periods of time to force the person to use their affected upper extremity, suggest that there are benefits to drastically increase the patient's training intensity; in particular increasing the number of hours of repeated therapies seems to have a positive impact on the recovery process [4]. These studies reported that the increased usage of the affected limbs provide long term benefits even when implemented at the level considered as chronic phase (i.e. more than a year after occurrence of stroke) [4]. Short term studies using constraint induced therapy on sub-acute stroke patients also show promising results as reported in [5]. Thus, it would be to the best interest of the stroke patients to engage in the rehabilitation training that is intense, frequent and safe possible.

Naturally, stroke patients have to deal with mental and physical disabilities after the stroke. Stroke rehabilitation is the process by which the patients go through treatment in order to return to normal, independent life as much as possible. These patients mostly will go through both physical therapy and job-related therapy. Although these therapies have some overlapping areas of implementations, physical therapy focuses primarily on major motor functions such as posture and walking, whereas job-related therapy focuses on relearning activities of daily life such as eating, drinking, reading, writing etc. For some stroke patients, rehabilitation is an ongoing process to maintain and refine skills; and it can involve working with specialists for months or years after the stroke [8].

2. System description

2.1 Robotic Platform with Low-Level Controller

A robotic platform for robot assisted rehabilitation has been developed and is shown in Figure 1.1. The system has two degrees of freedom allowing the arm to be guided to follow planar trajectory longitudinally along the linear guide and rotates upon the z-axis of the platform. In this paper, the discussion is focusing on the system controller which consists of high and low level controllers.
The low level controller is of the form of PD controller and designed by utilizing the Lagrangian formalism as shown in the equation (1.1). The PD controller is used to control the motion of the robot-assisted rehabilitation system joints [1].

$$f = \frac{d}{dt}\left(\frac{\partial(K-V)}{\partial \dot{x}}\right) - \frac{\partial(K-V)}{\partial x} \tag{1.1}$$

While the PD controller can be used to control the robot linear motion, there are still disturbances in the robot dynamics that exists in the non-linear form. In order to solve this problem the controller can be designed to compensate the disturbance by modelling the approximation of the non-linear term. The type of controller developed is based on partition control shown in equation (1.2) and equation (1.3). Where the robot linear mass is controlled through the f' term.

$$f = m\left(-k_p'(x - x_d) - k_v'\dot{x}\right) = mf' \tag{1.2}$$

$$\left(-k_p'(x - x_d) - k_v'\dot{x}\right) = f' = \ddot{x} \tag{1.3}$$

Equation (1.2) can be expressed as equation (1.4), where $\hat{b}$ represents the nonlinear part of the system and is estimated from the dynamics of the robot centrifugal and Coriolis forces.

$$f = \alpha f' + \beta = m\ddot{x} + \hat{b}(x, \dot{x}) \tag{1.4}$$

where $\alpha = m$ (estimated mass, m)

$\beta = \hat{b}(x, \dot{x})$ (estimated b)

The equation shows that f' represents a linear system while β represents a non-linear system. If good estimation of $\hat{b}$ is achieved, the system's closed-loop error can be reduced by feed-forwarding the errors of the non-linearities into the closed-loop system. The control partitioning system is shown in equation (1.5);

$$m\ddot{x}_d + b(x_d, \dot{x}_d) - mf' - \hat{b}(x, \dot{x}) = 0 \tag{1.5}$$

and the actual closed loop of the system is given by equation (1.6)

$$\ddot{x}_d + k_v'\dot{x} + k_p'(x - x_d) = 0 \tag{1.6}$$

From equation (1.6), it can be seen that by utilizing the control partitioning approach, the nonlinear contribution towards the robot dynamic response can be controlled in a closed-loop system. However, in the robot-assisted rehabilitation applications, the goal will always change and it is important to track the robot desired trajectory frequently. In order to track the desired trajectory, a desired acceleration trajectory is added to the closed-loop control system but there will be a drift of error even if we apply the correct estimation. Hence, to compensate this error, a closed-loop system for the acceleration error is also created. The low-level controller for the system is now can be expressed as in equation (1.7)[1].

$$f' = \ddot{x}_d - k_v'\dot{x} - k_p'(x - x_d) \tag{1.7}$$

and the closed loop of the system is given by equation (1.8)

$$(\ddot{x}_d - \ddot{x}) + k_v'(\dot{x}_d - \dot{x}) + k_p'(x_d - x) = 0 \tag{1.8}$$

The overall closed-loop system can be depicted in Figure 2.

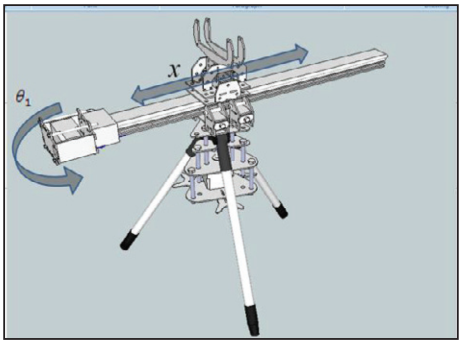


Figure 1: Robotic platform for Stroke Rehab

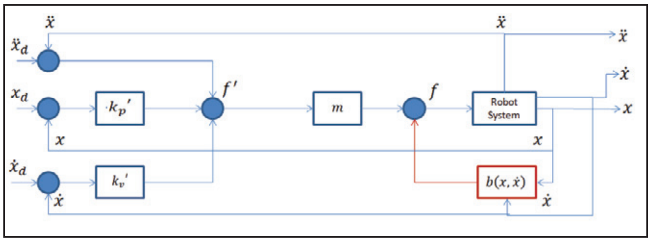


Figure 1: Overall system block diagram

In the next paragraph, we explain the high-level controller part of the hybrid controller system.

2.2 High-Level Controller

Many of the researches on robot-assisted rehabilitation focuses on low-level position control [9]. If a task is simple, (i.e., it does not involve various subtasks that need coordination) then providing a desired or reference task trajectory for the low-level device controller can be done without much difficulty. However, it will be quite difficult to specify a reference trajectory for low-level controllers for a complex task. In such cases, the reference trajectory of a specific subtask will likely depend on what happened in the previous subtask. The following subtask may be influenced by whether the previous subtask has been completed as desired or might have been disturbed by external disturbance or simply because different patients have different physical anatomy and characteristics. It is of course possible to define a low-level reference trajectory for each subtask of a complex task considering all possible scenarios and anticipating all possible events. However, such a scheme is inflexible, difficult to manage, and difficult to expand and adjust to new task requirements. It is more useful if a new structure can be developed where by the low-level reference trajectory online generation can be made as an automatic function of a separate high-level decision making process. In this way, a prearranged design approach can be utilized to generate the low-level reference trajectories for a complex task. For that, a supervisory control structure is proposed to accomplish the goal as follows:

i) To simplify a complex task into several simple subtasks,

ii) To generate low-level trajectory for each subtask

iii) To monitor the execution of each subtask to produce minimum jerk in the motion.

A hybrid supervisory control structure has been adopted in many control systems in industry, consumer electronics and medicine and the general structure is depicted in Figure. 3.

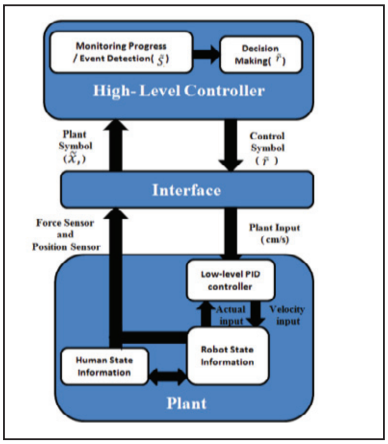


Figure 3: General structure of DES controller

The hybrid structure can be separated into two parts namely the "Plant" and the "Controller". The continuous part, identified as the "Plant" is typically an interface between the software and the rehabilitation robot. Meanwhile, the "Controller" includes a discrete decision process that is typically a discrete-event system (DES) described by a finite state automaton [9].

The high-level controller is in the form of discrete-event system (DES) deterministic finite automaton, which is specified by equation (1.9)

$$D = (\tilde{S}, \tilde{x}, \tilde{r}, \delta, \emptyset) \tag{1.9}$$

where $\tilde{x}$ represents *plant symbols*, which is generated from a set of events. $\tilde{S}$ is the control state of the system. The transition function $\delta: \tilde{S} \times \tilde{x} \to \tilde{S}$ explains the role of each element of the automaton to determine the next discrete state to be activated based on the current discrete state. In order to notify the low-level PD controller, the high level controller generates *control symbol*, $\tilde{r}$, using an output function $\emptyset: \tilde{S} \to \tilde{r}$.The action of the high-level controller is described in equations (1.10) and (1.11) respectively,

$$\tilde{S}_i[n] = \delta(\tilde{S}_i[n-1], \tilde{x}_k[n]) \tag{1.10}$$
$$\tilde{r}_c[n] = \emptyset(\tilde{S}_i[n]) \tag{1.11}$$

i represent the index of discrete states. *c* and *k* represent the index of *plant symbols* and *control symbols*, respectively. *n* is the time index that specifies the order of the symbols in the sequence.

In order to design the high-level controller for the rehabilitation tasks we define a set of discrete states, $\tilde{S}$. Each of the discrete state represents different velocities for particular trajectory in which the patient has to be assisted to follow as part of the rehabilitation therapy.

Once the discrete set, $\tilde{S}$ is determined, the next step is designing the events for the rehabilitation task. Generally the available sensory information from the robotic systems and the input from patient provide the core set of the events. The set of events are not unique and are decided based on the needs of the rehabilitation therapy.

3. Control methods

The objective of the research work is to access the stroke patient by using the CMA guideline followed by determining and executing proper rehabilitation task. The task is either to assist or resist the patient movement, considering the patient current progress and the safety of the task. In the task, the patient is required to follow a specific trajectory. Based on the preliminary information of the force exerted while following the trajectory, the stroke patient is categorized based on the CMA method. In the case where assistant is required for the stroke patient, a gradual increase in the velocity of the trajectory is programmed and controlled by low-level controller. Meanwhile, if the patient is able to apply positive force when following the trajectory, the velocity of the system is decreased by the high-level controller in order to generate relative resistive force that the patient could sustained.

Table 1: List of control states

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

In the following, we present the design of the plant and the control symbols of the system high-level controller based on Chedoke-McMaster Stroke Assessment (CMA). CMA is a procedure to assess the hemiparetic arm of the stroke patient. It defines seven stages of motor impairment as reported in[7]. All the above seven stages can be classified by identifying the three impairments that limit arm movement in chronic brain injury that are 1). increased tone 2). in coordination (characterized as lack of directional force control 3). agonist weakness. These assessment techniques could provide a means to diagnose a patient, as well as to monitor their treatment. The CMA provides the basis for the evaluation of movement impairment and the severity of the stroke patient. The seven categories of severity of stoke patient under the CMA are translated as the *Control States*, $\tilde{S}$ under the DES framework and shown in Table 1 The additional State 8 in table 1 represents the control state where the patient arm has reached the desired position in the rehabilitation trajectory. Each of the *control symbol, $\tilde{r}$)* generates a unique rehabilitation therapy mode that mends to cater different stages of stroke impairment (i.e. CMA). Table 2 lists all the *control symbol* for the system low level controller. Note that the control symbol $\tilde{r}_8$ is to provide negative velocity to bring the arm back to the original position. The *control symbol* induces the *plant input* that is the input to the low level PD controller for the rehabilitation task. The task is the action that the robot has to perform and they are listed in table 2. Table 3 lists the *plant symbol* that triggered the transaction between control states $\tilde{S}$. $\tilde{x}_8$ represents the state of the robot that has reached the desired position. *Plant symbols* are generated based on the information from position sensor (motor) and force sensor (exerted force by the patient) of the robot.

Throughout the robot rehabilitation therapy, this information is continuously monitored and the relation is shown in the finite automaton in Figure 4.

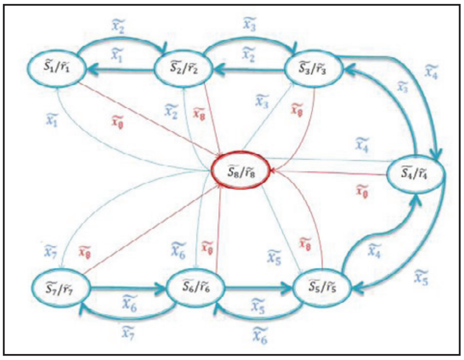


Figure 4: Finite automaton of robot assisted rehabilitation controller

Table 2: List of control symbols and definitions

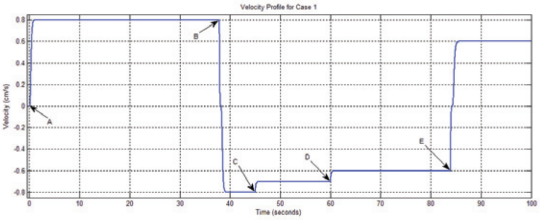
Control Symbol	Definition of actions
$\tilde{r}_1$	The client needs total assistance with maximum speed (0.8cm/s)
$\tilde{r}_2$	Maximal assistance with Speed maximum (0.7cm/s)
$\tilde{r}_3$	Moderate assistance (0.6cm/s)
$\tilde{r}_4$	Minimal assistance (0.5cm/s)
$\tilde{r}_5$	Clients needs supervision (0.4cm/s)
$\tilde{r}_6$	Client is modified independent but needs assistance from devices (0.3cm/s)
$\tilde{r}_7$	Client is timely and safely independent (0.2cm/s)
$\tilde{r}_8$	Negate flag value

Table 3: List of plant symbols and definitions

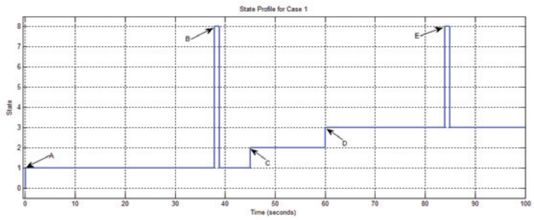
Plant Symbol	Impairment inventory generated from the force sensors
$\tilde{x}_1$	Flaccid paralysis : 0% of normal strength (N)
$\tilde{x}_2$	Spasticity is present and felt as a resistance to passive movement : 0%-10% of normal strength (N)
$\tilde{x}_3$	Marked spasticity but voluntary movement present 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 arm arrived at desired position (29cm) or origin (0cm)

4. Simulation results

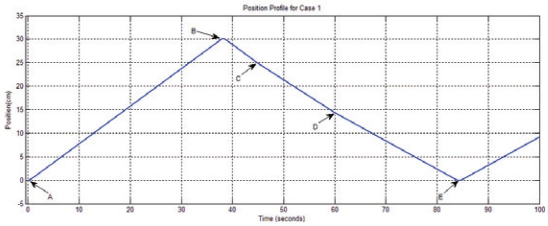
The performance of the proposed high-level control framework for robot assisted rehabilitation is analysed in the simulation studies in order to evaluate its efficacy. The simulation is done using Matlab/State flow software. In the simulation studies the subject is instructed to move his forearm to follow a straight trajectory to a desired position that is located 29cm away from the origin and return back to the starting position to complete a task. The subject is assumed to be at Stage 1 of CMA where he suffers flaccid paralysis and has 0% of normal person strength. The reading from the patient force sensor produces an event, $\tilde{x}_1$. This triggers *control state*, $\tilde{S}_1$. Then *control symbol*, $\tilde{r}_1$ is activated and desired velocity of 0.8cm/s is commanded via interface. The desired velocity is given as step input to low-level PD controller at point **A** as shown in Fig. 1.5(a). It can be observed that at any event of velocity change, the influence of the low-level PD controller damps the step input to achieve i). 1 second settling time and ii). zero percent overshoot. When event $\tilde{x}_8$ (subject's arm arrives at desired position(i.e.,29cm)) is reached, *control state*, $\tilde{S}_8$ is triggered and $\tilde{r}_8$ became activated to bring back the patient arm backs to its original position. $\tilde{r}_8$ is a special function that negates the flag value used to negate the desired velocity value. at point **B**. The subject’s forearm is now in a reverse motion going back to its original position. During the subject’s forearm reverse motion, the subject is able to exert force that produces an event, $\tilde{x}_2$. When event $\tilde{x}_2$ occurs, *control state*, $\tilde{S}_2$ is triggered to provide less assistance to the patient. At the same time, $\tilde{r}_2$ is activated and the low-level PD controller is given a negated desired velocity of -0.7cm/s at point **C** . Then again the subject exerts a force with higher value that triggers event $\tilde{x}_3$. Consequently, event $\tilde{x}_3$ produces *control state,* $\tilde{S}_3$ to provide moderate assistance to the patient. At the same time, $\tilde{r}_3$ is activated and the low-level PD controller receives and damps the desired velocity of -0.6cm/s at point **D**. When the subject arm reaches the initial position an event $\tilde{x}_8$ occurs. The event $\tilde{x}_8$ triggers *control state,* $\tilde{S}_8$ to negate the velocity value and $\tilde{r}_8$ is activated. The low-level PD controller is then is commanded with positive desired velocity of 0.6cm/s at point **E**. The subject’s arm now is reaching back to the goal position and the process of moving patient arm back and forth from origin position to the goal position is repeated until the subject chooses to stop. Figure 5(c) shows the position of the subject's forearm when every event is triggered. Fig. 1.5(b) shows the patient's CMA states.



(a)



(b)



(c)

Figure 5: a) velocity profile, b) state profile and c) position profile

5. Conclusion

In this paper, a high-level controller with Chedoke McMaster assessment used for robot-assisted rehabilitation is discussed and simulated. The proposed high-level controller could generate low-level reference trajectories automatically based on the condition of the subjects. These reference trajectories are damped and smoothen using the low-level PD controller to give more realistic inputs to the robotic platform. The proposed system also features the Chedoke-McMaster based stroke assessment that takes place during the process of rehabilitation therapy. The discrete event system (DES) provides a control framework, which is flexible, controllable, and easily extendable to new task requirements and more unanticipated situations. Future work in this area would involve testing of the proposed controller framework on a real robotic platform developed.

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