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A framework for simultaneous training and therapy in multilateral tele-rehabilitation

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ABSTRACT

The problem of designing a framework for simultaneous training and therapy in multilateral tele-rehabilitation systems is considered in this paper. The usage of robotic devices in the automation of rehabilitation procedure helps overcoming the limitation in conventional physiotherapy methods by decreasing duration of process and training sessions. The problem arises by increasing the number of robots interacting together in the tele-rehabilitation process. These robots are called “operators”. In this paper, a new approach is proposed to overcome such issues. The self-intelligence between the numbers of agents working together in the multi-agent system is the key item which is used to achieve the cooperative tele-rehabilitation system. Three scenarios are proposed for implementing practical tele-rehabilitation process to satisfy the aim of simultaneous therapy and training. A simulation was launched to verify the performance of the multi-agent network; additionally, experimental study was done on the AUTWRIST robot which was designed and implemented by the authors. The simulation results approved the superiority of the proposed method in the presence of a trainee, a patient, and a therapist all together.

1. Introduction

Two main reasons for neurological lesions are stroke and spinal cord injuries. In the US alone, total cost of stroke is 34.3 billion dollars in 2008 and has been estimated to be 69.1 billion dollars in 2016 [1]. Based on experiment results, frequent movement repetition challenges conventional physiotherapeutic strategies for the motor rehabilitation of the centrally paretic forearm in the way that early initiation of active movements has a better result than spasticity reduction in patients’ recovery. This means that task-oriented repetitive movements have a direct positive effect on improvement of muscle strength and movement in patients with neurological injuries. Robotics and automation technology have the ability to assist and enhance rehabilitation by acquiring high repetition number of movements [2]. Regarding the manually-assisted training criteria, physiotherapy actions has several limitations. This method is labor intensive which means that training sessions are often shorter than required to obtain proper therapeutic outcome. Also, manually-assisted training is not a repeatable method and does not measure performance and progress of patient. The consistency of training is related to therapist experience and performance.

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In contrast to conventional methods, by the implementation of robotic devices rehabilitation procedure can be automated which increases device training sessions and duration of process [3]. With virtual reality implementation the therapy can be a functional and highly motivating context and therefore better result can be achieved by therapy [4].

Generally there are two types of rehabilitation devices, end-effector based robots and exoskeletons. Exoskeletons have similarity to human anatomy and could be actuated by limited methods while end-effector robots could be in any configuration. There are some upper-extremity rehabilitation type of exoskeleton robots such as MAHI, Rupert and CADEN-7 and some of are end-effector type such as MIT-MANUS and MIME. These robots were previously described and investigated in [5] by the authors.

On the other hand, a multi-agent system (MAS) is composed of some agents which are able to communicate with their neighborhoods for computational and decision-making tasks. The agents can share their information using the network interfaces to reach a goal together. The goal might be consensus, synchronization, or surveillance. One of the most fundamental objectives in multi-agent systems is the consensus. The consensus problem considers the agreement of agents over a special issue in spite of limitations in the network.

In the proposed structure, each operator acts as an agent in the MAS. Each agent considers some assumptions according to its perception of the environment. Cooperation and interaction with the neighbors cause the initial assumption to be changed until all of the agents reach to a unique value [6]. Indeed, all agents have to communicate with their neighbors to agree upon an issue and due to this agreement, the agents can have teamwork. This is a challenging problem owing to the restricted connections in the network.

In this report, the cooperative teleoperation problem is assumed as a leader-follower problem in multi-agent systems. It is proved in [7] that the bilateral teleoperation problem can be regarded as a consensus problem. In [8], acceleration consensus structure is considered for motion control in multilateral teleoperation. Unlike the mentioned approaches, the leader-follower structure in multi-agent systems is utilized in this paper; thus, the consensus value, the value upon which the agents agree, depends on the weighted average of the state variables of just the leaders. Since our main objective is simultaneous training and therapy, the leader-follower structure is more suitable than the other multi-agent structures. In fact, by using the leader-follower structure, we can determine one or more of the agents as the leaders such that the other agents should synchronize themselves with the specified leaders. Besides, the proposed structure is very flexible and we can propose several strategies based on this structure according to the skill level of the trainees and the improvement of patient. This issue is illustrated in detail in Section 4. In brief, the most important contributions of this paper are as follows. First, proposing a multi-agent based framework for multilateral teleoperation. Second, utilization of the proposed framework in simultaneous training and therapy in tele-rehabilitation systems.

The rest of this paper is organized as follows. In Section 2, the proposed multi-agent based approach for cooperative teleoperation problem is illustrated. Utilization of this approach in tele-rehabilitation system is described in Section 3. In Section 4, the necessary strategies for the interaction between the therapist, patient, and the trainee are explained. Mathematical formulation of this problem is presented in Section 5. Section 6 represents the simulation results. Finally, conclusions and future works are expressed in Section 7.

2. Preliminaries

In this section a brief preliminarily knowledge about the terms used in the proposed structure is described. The first subsection is about the multi-agent systems, while the second one describes about the teleoperation terms and equations.

2.1. Multi-agent systems

Graph theory is a helpful utility to investigate multi-agent systems. An undirected graph $\mathcal{G}$ on vertex set $\mathcal{V} = 1, 2, \ldots, n$ contains $\mathcal{V}$ and a set of unordered pairs $\mathcal{E} = \{(i, j) : i, j \in \mathcal{V}\}$, which are called $\mathcal{G}$'s edges. The two vertices are called adjacent, if there is an edge between two vertices. A graph is simple if it has no repeated edges or self-loops. If we can find a path between any two vertices of a graph $\mathcal{G}$, then $\mathcal{G}$ is connected, otherwise we call this graph disconnected. A subgraph $\mathcal{X}$ of $\mathcal{G}$ is an induced subgraph if two vertices of $\mathcal{V}(\mathcal{X})$ are adjacent in $\mathcal{X}$, if and only if they are adjacent in $\mathcal{G}$. An induced subgraph $\mathcal{X}$ of $\mathcal{G}$ that is maximal, subject to being connected, is called a component of $\mathcal{G}$.

Here a system consisting of n agents and one or more leaders is considered. Therefore, the state of agent i is denoted by x_i for $i = 1, \ldots, n$. Regarding the n agents as the vertices in $\mathcal{V}$, the relationships between n agents can be in a convenient manner described by a simple and undirected graph $\mathcal{G}$, which is defined. Thus, (i, j) defines one of the graph's edges in case agents i and j are neighbors. So, $\mathcal{N}_i(t)$ denotes the set of labels of those agents which are neighbors of agent i $(i = 1, \ldots, n)$ at time t. The weighted adjacency matrix of $\mathcal{G}$ is denoted by $A = [a_{ij}] \in \mathcal{R}^{n\times n}$ where $a_{ij} = 0$. Related degree matrix $\mathcal{D} = diag\{d_1, d_2, \ldots, d_n\} \in \mathcal{R}^{n\times n}$ is a diagonal matrix, where diagonal elements $d_i = \sum_{j=1}^{n} a_{ij}$ for $i = 1, \ldots, n$. Then the Laplacian of the weighted graph is defined as $L \triangleq \mathcal{D} - A$. In this article, a graph $\bar{\mathcal{G}}$ associated leader is mainly concerned. In fact, $\bar{\mathcal{G}}$ contains n agents (related to graph $\mathcal{G}$) and the leader. The term "the graph, $\bar{\mathcal{G}}$, of this system is connected", means that at least one agent in each component of $\mathcal{G}$ is connected to the leader.