Control Engineering Practice 17 (2009) 368–381

Contents lists available at ScienceDirect

Control Engineering Practice

journal homepage: www.elsevier.com/locate/conengprac

Iterative learning control of FES applied to the upper extremity for rehabilitation

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ARTICLE INFO

Article history:
Received 1 August 2007
Accepted 29 August 2008
Available online 21 October 2008

Keywords:
Iterative learning control
Functional electrical stimulation
Robotics
Tracking control
Muscle models

ABSTRACT

Iterative learning control schemes are used to apply functional electrical stimulation to the triceps of unimpaired subjects in order to perform trajectory tracking tasks. The subjects supply no voluntary effort and a robotic workstation is used to constrain their movement, impose known dynamics at the point of interaction with the robot, and provide assistive torque about the shoulder. Results from 18 subjects are presented and show that a high level of performance can be achieved using the proposed method. In addition to illustrating how stimulation and robotics can be successfully combined in order to perform reaching tasks, the results provide justification for the system to be subsequently used by stroke patients for rehabilitation.

1. Introduction

Strokes affect between 174 and 216 people per 100,000 population in the UK each year (Mant, Wade, & Winner, 2004). Since around two-thirds of patients in England survive their stroke, there are more than 900,000 people who have had a stroke living in England of which 50% will be left disabled and dependent (Hudson, Scharaschkin, Wilkins, & Taylor, 2005). Half of all acute stroke patients starting rehabilitation will have a marked impairment of function in one arm of whom only about 14% will regain useful sensory-motor function (Royal College of Physicians, 1989). The stroke patient is unable to practice arm movement because of impaired motor control and the delay in recovery may lead to a decreased likelihood of recovery occurring at all (Castro-Alamancos, Garcia-Segura, & Borrell, 1992).

Functional electrical stimulation (FES) can provide the experience of moving for the patient, and consequently may limit the problem of inability to practice movement because of impaired motor control. It has been used successfully to improve recovery of upper limb motor control (Burridge & Ladouceur, 2001) and recent studies have shown that when stimulation is associated with a voluntary attempt to move the limb, improvement is enhanced (Burridge & Ladouceur, 2001). A hypothesis has been proposed to explain this enhanced recovery observed when stimulation is applied to correspond with a subject's intended movement (Rushton, 2003), which suggests that the degree of functional recovery is closely related to the accuracy with which the stimulation assists the subject's completion of a repeated task.

In this paper, the task will be to repeatedly track a trajectory which is predefined so that the subject's voluntary intention is exactly known. This then allows FES controllers to precisely assist their desired movement in order to promote the therapeutic effect gained over repeated performance of the tracking task. The trajectories used will be elliptical and will approximate reaching movements commonly encountered in everyday life. During treatment they will be tracked using the impaired arm, and are designed to target the difficulty most stroke patients have in performing full elbow extension. The exact sequence is that the patient has to try to complete the movement, their arm is then returned to the starting position, and the task repeated. During each repetition of the tracking task, the performance can be measured and a natural approach is to use this information to adjust the stimulation to produce improved performance on the next (and successive) attempts. This scenario fits exactly within the iterative learning control (ILC) setting for processes which are required to continually repeat the same task over a finite interval with resetting between trials. The salient feature of ILC is to use information from previous trials to update the current trial input so that performance is successively improved, making it a natural candidate for the stroke rehabilitation task considered here.

ILC has been able to provide high levels of accuracy in the presence of significant plant uncertainty in a wide variety of applications (see Ahn, Chen, & Moore, 2007, for a comprehensive

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doi:10.1016/j.conengprac.2008.08.003

review). Prior to the application of ILC, a feedback controller is typically first implemented to act as a prestabilizer. Using this arrangement, even simple ILC structures have been shown to provide significant improvement in tracking performance compared with the use of feedback controllers alone (Ratcliffe, 2005). Using data from tests conducted on stroke patients, it has been shown that the presence of voluntary effort occurring during the application of electrical stimulation to the arm can be accounted for by an additive disturbance acting on the stimulation input signal (see Freeman et al., 2008a, for details). Furthermore, if the stimulation does not change significantly over repeated tracking tasks (as can be ensured using ILC), this disturbance has been seen to be reasonably small and to change only slowly between trials. Therefore a simple approach to incorporating voluntary effort is to design algorithms which exhibit sufficient robustness to operate in the presence of this form of disturbance appearing on the plant input. It has been shown that ILC provides such a framework (see, for example, Moore, 1992). The initial step is therefore to confirm the performance of controllers in the absence of voluntary effort (the results gained in this process also providing evidence that the controller is also appropriate for use by paralysed subjects in order to perform accurate reaching movements necessary for daily living).

Although ILC is an obvious choice for the current application, it is possible that a suitable method exists among those already applied in this area. Unfortunately, open-loop methods for the control of FES for upper limb movements (see for example Davoodi & Andrews, 2004; Popovic & Popovic, 1998) have not been able to provide the high level of performance which is necessary to fully promote the required association between the subject's intended movement, and the action of the applied electrical stimulation in realizing it. A wide variety of model-based controllers for electrical stimulation have been implemented which may be able to produce such accuracy. These include the use of H_∞ (Hunt, Jaime, & Gollee, 2001), optimal control (Hunt, Munih, & Donaldson, 1997) and fuzzy logic control (Davoodi & Andrews, 1998) for paraplegic standing, and the use of neural networks (Hatwell, Oderkerk, Sacher, & Inbar, 1991) and data-driven control (Previdi, Ferrarin, Savaresi, & Bittanti, 2005) for control of the paraplegic knee joint. Few such model-based schemes have been applied to upper limb movement, exceptions principally comprising the use of neural nets for paraplegic arm movements (see for example Lan, Feng, & Crago, 1994; Tresadern, Thies, Kenney, Howard, & Goulermas, 2006). Unfortunately these require extensive training and have unresolved stability issues due to their black-box structure. Another factor is that any suitable control method selected for the stimulation must also operate in the presence of voluntary effort supplied by the patient. A simple method of achieving this is for the controller to directly use electromyographic (EMG) or myoelectric activity of the muscle being stimulated (see for example Thorsen, Spadone, & Ferrarin, 2001). However, model-based control methods have not yet incorporated this information since it does not directly relate to the force or torque generated by the muscle, and because the signal is often either weak and unreliable or that the artefact produced by the stimulation signal corrupts the natural EMG signal (although in this case blanking techniques may be applied). ILC is one of the few advanced controllers that has previously been applied to control the upper limb, although a high level of performance has not been achieved in practice (Dou, Tan, Lee, & Zhou, 1999). The motivation for this paper is therefore the lack of controllers for upper limb electrical stimulation that are capable of providing a high level of performance, but which do not require extensive tuning. A future concern is then the need for the controller to operate whilst voluntary effort is simultaneously supplied by the subject.

The need for a controlled environment in which to apply stimulation has inspired the design and construction of an experimental test facility incorporating a five-link planar robotic arm and an overhead trajectory projection system (see Freeman et al., 2008b, for further details). The subject is seated with their arm strapped to the robot, and the trajectory is projected onto a target mounted above their hand. Their task is to repeatedly track it using a combination of voluntary control and surface FES applied to muscles in their impaired shoulder and arm. During the tests carried out, the robotic arm provides control over the dynamics experienced by the patient, and produces an assistive torque when necessary. Whilst there exist several robotic devices for the application of robotic therapy to stroke patients through purely mechanical manipulation of their arms (e.g. the MIT Manus system, Krebs, Hogan, Aisen, & Volpe, 1998), this form of treatment has hitherto not been combined with the application of FES. In this paper a dual control scheme is formulated to govern both the application of stimulation and the assistance provided by the robotic arm. Tests are conducted on 18 unimpaired subjects who do not provide voluntary effort. The results illustrate how stimulation and robotics can be successfully combined in order to perform reaching tasks, and confirm the efficacy of the system prior to its use by stroke patients. This study has received ethical approval (reference no. 505-12/1).

2. Workstation description

The robotic workstation is shown in Fig. 1 and consists of a five-link planar robotic arm rigidly connected to an overhead projection system. The links of the robot are labelled 1–5, and the upper arm and forearm are labelled u and f, respectively. The vectors $\boldsymbol{x}_0$, $\boldsymbol{y}_0$ and $\boldsymbol{z}_0$ are components of the robotic base coordinate frame, and $\boldsymbol{x}_1$, $\boldsymbol{y}_1$ and $\boldsymbol{z}_1$ are those of the human arm base coordinate frame, the two systems being related by a translation. Two coaxially mounted DC brushless motors actuate links 1 and 2, and a 4000-line encoder is mounted on each motor shaft to record the angle of these links. The subject is strapped to the extreme fifth link, and grips a cushioned handle which is rigidly connected to a 6 axis force/torque sensor which records the force they apply to the robotic end effector. Forces can be measured of up to 200 N applied in the horizontal plane with a resolution of 0.0122 N. The fifth link also contains a 4000-line encoder to measures its angle, and LEDs to provide visual feedback of the tracking performance. The robotic arm is used

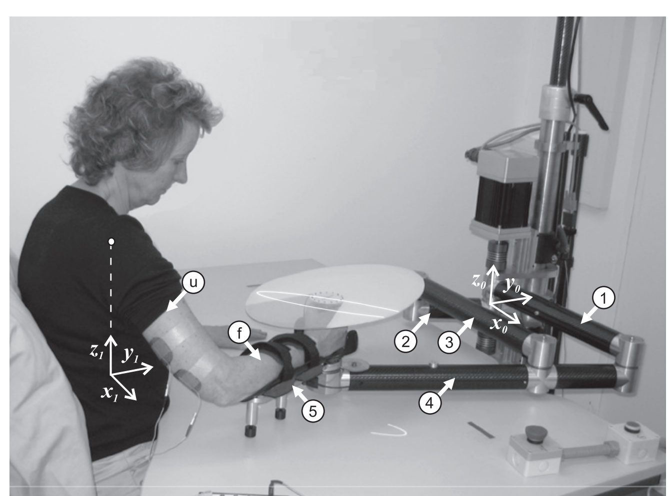

Fig. 1. Unimpaired subject using the robotic workstation.