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Chapter IX

Control of Man-Machine FES Systems

Rahman Davoodi, University of Southern California, USA

Gerald E. Loeb, University of Southern California, USA

ABSTRACT

Movement disabilities due to spinal cord injury (SCI) are usually incomplete, leaving the patients with partially functioning movement system. As a result, functional electrical stimulation (FES) systems for restoration of movement to the paralyzed limbs must operate in parallel with the residual voluntary movements of the patient. In the resulting man-machine system, the central nervous system (CNS) controls the residual voluntary movements while the FES system controls the paralyzed muscles of the same limbs. Clearly, these two control systems must work in synchrony to benefit the patient. In this chapter we will discuss different methods for cooperative control of man-machine FES systems and use a clinical FES system to demonstrate the successful application of these strategies.

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BACKGROUND

Advances in rehabilitation technology are producing increasingly complex and sophisticated rehabilitation devices that must interact closely with the residual neural control of patients. The successful operation and optimal performance of the resulting man-machine system depends on a precise coordination and integration between the man and the machine. The same is true when the humans operate machinery such as driving a car, operating an anti-aircraft gunner, or flying an airplane. All of these tasks have had the benefit of over 100 years of development of user interfaces and training methods. To develop a systematic approach for analyzing such man-machine systems, control engineers model the human operator as an element of the automatic control system. Early models of the human operator were linear transfer functions that could be analyzed by linear control theories (Mcruer & Graham, 1967; Kleinman & Perkins, 1974). Later, the models of the human operator were expanded to multi-input multi-output nonlinear systems using optimal control theory, neural networks, and fuzzy logic control (Doman & Anderson, 2000; Zapata, Galvao, & Yoneyama, 1999). The focus of these expanded models was still the manual operation of machinery by well-trained human operators.

Man-machine rehabilitation systems are similar in that the human subject must voluntarily produce commands to operate the rehabilitation device but there are also stark differences. For example, the rehabilitation device is not an independent, well-behaved machine, but an integral part of the limb that is supposed to operate it. For example, the artificial hand is attached to an amputated arm that should produce the command signals to operate it as well as some of its movement through space. Similarly, in a FES reaching system, the intact shoulder joint may have to produce voluntary commands to operate the FES control of the paralyzed elbow joint (Popovic & Popovic, 2001). Instead or in addition, the FES controller may be driven by residual movement of unrelated body parts (e.g., tongue or contralateral arm), electromyography (EMG) of the intact muscles, or electrical activity of the neural cells in the sensorimotor cerebral cortex. Development of mathematical models for the human operator in these man-machine systems is a challenging task and has been studied only in simple, well-defined tasks. For example, Davoodi et al. used fuzzy logic (Davoodi & Andrews, 1998) and neural network (Davoodi et al., 1998; Davoodi, Kamnik, Andrews, & Bajd, 2001) models to simulate the CNS control of the arm forces in FES assisted standing up, which is a highly constrained and relatively simple movement. Until we have a better understanding of the principles underlying the operation of the CNS, the development of a formal analysis that applies to all man-machine FES systems is unlikely. In the absence of formal systematic analysis, creative methods have been used to design coordinated man-machine FES systems that are discussed next.

MAN-MACHINE COORDINATION IN FES

In order to improve performance and patient acceptance, FES systems must provide natural and intuitive interfaces that allow the patients to be in full control of the combined man-machine system. The extent of the man-machine interactions between the patient and FES depends on the level and type of the spinal cord injury. A complete paralysis in the lower thorax paralyses the legs but the arms and trunk muscles are still under

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