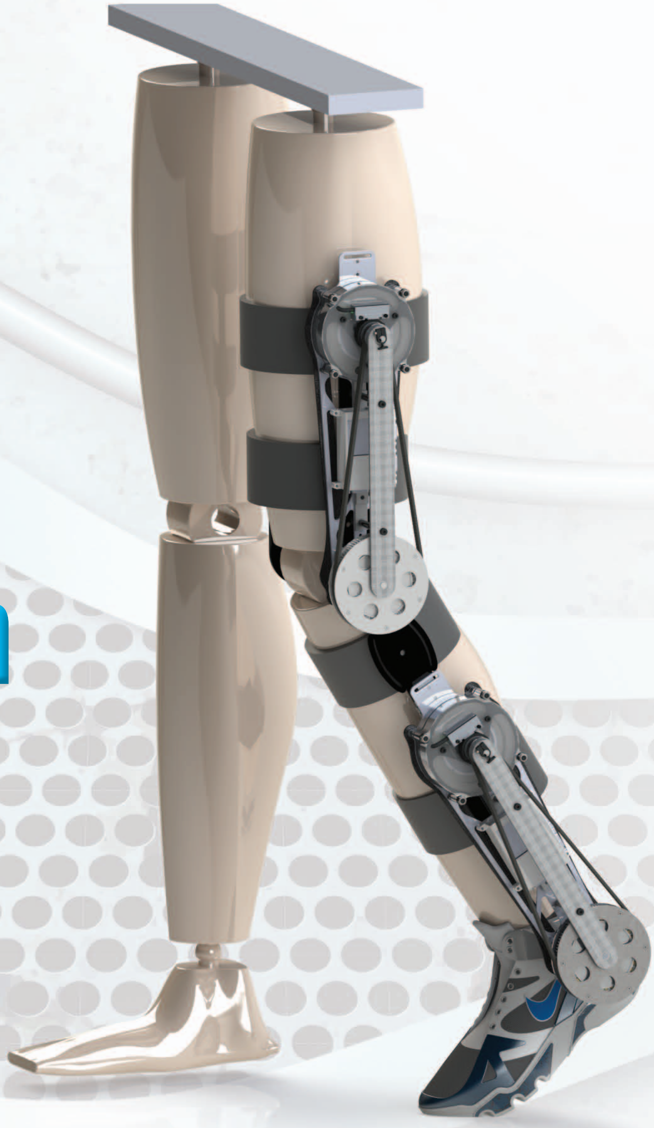

Control Systems for Assistive and Rehabilitation Robotics

AN INTRODUCTION TO THE SPECIAL ISSUE

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COURTESY OF HANQI ZHU AND ROBERT GREGG;
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Daily activities can become more challenging for people as they age or if they have a medical condition that inhibits their manipulation or mobility capabilities. Such individuals often engage in rehabilitation to improve or restore their abilities. Yet their diminished strength, endurance, or ability can limit the intensity and number of repetitions (the rehabilitation dosage) needed to achieve the desired training effects. As a result, therapeutic adjuvants, such as functional electrical stimulation (FES) and/or rehabilitation robotics, are often used by therapists to facilitate musculoskeletal and cardiorespiratory fitness as well as other neurological, physiological, and psychological measures.

A critical factor for facilitating nervous system reorganization and potentially beneficial change in the neuromuscular system is sufficient intensity and repetitive practice of coordinated limb movements [1], [2]. As described in such results as those reported in [3]–[16], robotic technologies excel at repetitive accurate positioning and hold significant promise to augment or rehabilitate a person's capabilities. Moreover, robotic systems can provide load bearing, suppress undesired motions, extend a person's range of motion, incorporate programmed load/motion disturbances, and offer other benefits for rehabilitation. However, such outcomes are challenging due

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to the complexities of the inherent physical human–machine interaction. The focus of this special issue is to highlight some recent insights and advances in rehabilitation robotics, with a particular focus on control design challenges and methods.

TECHNICAL CHALLENGES

Rehabilitation robots face many barriers to yield desired clinical outcomes. Some challenges stem from engineering questions related to human–machine interaction. These questions can be related to the electromechanical design, such as the following:

- » When should soft robots or robots with series elastic actuators be used versus traditional actuators with high stiffness?
- » How can the robot be designed to be minimally invasive or wearable?
- » What actuation method (for example, hydraulic, pneumatic, or electric) is best suited for different applications, loads, and settings?

The following questions relate to the closed-loop control system.

- » How can the controller compensate for the different time scales between the human and machine, including inherent delays in the human response?
- » What methods are best suited to predict the desired intent of the person?
- » How can intent and delays be incorporated in the control design to eliminate a lagged response by the robot?
- » How can the controller adapt to the variety of dynamic behaviors among different people or the differences within the same person as people continually adapt to an environment, especially when augmenting their capabilities with a new tool, such as an assistive device?
- » Can adaptive and robust methods provide a person-specific treatment that continually adjusts to a person's needs, constraints, and changes?
- » Should the closed-loop control system dictate a response and reject disturbances or allow the disturbances (for example, a person having a muscle spasm) to dictate the response (that is, the robot will admit [17], [18] or be passive [19] to the user)?
- » How much effort should be provided by the robot, and how much effort should be required by the person, potentially including forced computer control of the person's muscles?

Some challenges also result from clinical questions related to the different theories of rehabilitation (for example, neurophysiology, neurodevelopment, and motor learning) and what roles robots play in these theories [20]. The challenges associated with physical human–machine interaction also vary if the robot is acting as an assistive device (an orthotic) or is replacing a capability (a prosthetic).

CONTRIBUTIONS OF THE SPECIAL ISSUE

While a wide range of challenges give rise to a spectrum of questions from various communities, this special issue is focused on timely outcomes that consider some of the open questions related to the design and control of assistive rehabilitation robotics. Specifically, each of the articles in this issue investigates the use of powered exoskeletons as aides for mobility.

Most powered orthoses use task-/user-specific controllers to track predefined trajectories or setpoints, which are different across users and tasks. Moreover, the nonbackdrivable actuator designs of these devices do not allow the user to influence his or her own joint motion. "On the Design and Control of Highly Backdrivable Lower-Limb Exoskeletons," by Lv, Zhu, and Gregg [21], discusses the development of a wearable, mobile-powered, knee-ankle exoskeleton with a high torque-density electrical motor and a custom low-ratio transmission to avoid sacrificing intrinsic backdrivability or efficiency. A task-invariant, energy-shaping control methodology is then provided that incorporates both environmental and human interaction for such powered orthotic technologies, which is demonstrated through experiments on a healthy normal individual.

New methods for hands-free exoskeleton-assisted walking could be obtained by leveraging advances in formal stability and robust development of bipedal robotics systems. "Feedback Control of an Exoskeleton for Paraplegics: Toward Robustly Stable Hands-Free Dynamic Walking," by Harib et al. [22], investigates this potential using supervised machine learning for an exoskeleton control system for tracking target speeds and heading while being robust to disturbances. The training set for supervised learning is obtained from optimization problems requiring the system to transition from one periodic gait to another while satisfying dynamical feasibility and torque limits. In addition, a method for the exoskeleton to capture steering commands from the user's torso motion is described, modeled, and simulated. Robustness is demonstrated by having the exoskeleton recover from external forces pushing the system and walking on unknown uneven terrain. Experiments are performed on individuals who are complete paraplegics.

To restore walking and standing function in persons with paraplegia, a hybrid walking neuroprosthesis that combines a powered exoskeleton and FES can be more advantageous than using either FES or powered exoskeleton technologies alone. However, the hybrid actuation structure introduces certain control challenges: actuator redundancy, cascaded muscle activation dynamics, FES-induced muscle fatigue, and unmeasurable states. "A Muscle Synergy Inspired Control Design to Coordinate Functional Electrical Stimulation and a Powered Exoskeleton," by Alibeji et al. [23], focuses on a human-motor-control-inspired scheme that is combined with a dynamic surface control (DSC) method to overcome these challenges.

The new controller has an adaptive muscle synergy-based feedforward component that requires fewer control signals to actuate multiple effectors in a hybrid neuroprosthesis. Moreover, the feedforward component has an inverse fatigue signal to counteract the effects of muscle fatigue. The DSC method is used to address the cascaded actuation dynamics without the need for acceleration signals. The DSC structure was modified with a delay compensation term to address the electromechanical delays due to FES. A model-based estimator is used to estimate the unmeasurable fatigue and actuator activation signals. A formal Lyapunov-based stability analysis is provided, along with experimental results on a control subject and a person with a spinal cord injury.

AUTHOR INFORMATION

Warren Dixon (wdixon@ufl.edu) received the Ph.D. degree from Clemson University, South Carolina, in 2000. He is with the University of Florida Mechanical and Aerospace Engineering Department in Gainesville. He was a research staff member and Eugene P. Wigner Fellow at Oak Ridge National Laboratory, Tennessee, until 2004. His main research interest is the development and application of Lyapunov-based control techniques for uncertain nonlinear systems. His work has been recognized by the 2015 and 2009 American Automatic Control Council O. Hugo Schuck Best Paper Award, the 2013 Fred Ellersick Award for Best Overall MILCOM Paper, the 2011 American Society of Mechanical Engineers Dynamics Systems and Control Division Outstanding Young Investigator Award, the 2006 IEEE Robotics and Automation Society Early Academic Career Award, an NSF CAREER Award (2006–2011), the 2004 Department of Energy Outstanding Mentor Award, the 2001 ORNL Early Career Award for Engineering Achievement, and has received multiple awards for the mentoring of Ph.D. students from the University of Florida College of Engineering. He has been an associate editor for *ASME Journal of Dynamic Systems, Measurement and Control*; *Automatica*; *IEEE Control Systems Magazine*; *IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics*; and *International Journal of Robust and Nonlinear Control*. He is a Fellow of the IEEE and the American Society of Mechanical Engineers. He is Distinguished Lecturer for the IEEE Control Systems Society (CSS) and served as the director of operations for the Executive Committee of the IEEE CSS Board of Governors from 2012 through 2015. In 2016, he was awarded the Air Force Commander's Public Service Award for his contributions to the U.S. Air Force Science Advisory Board.

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