Human Cyber-Physical Systems

Synopsis of Results from NSF CPS Grant #1544702

PI: Hanz Richter, PhD
Professor, Mechanical Engineering Department
Antonie van den Bogert, PhD (Mechanical Engineering)
Dan Simon, PhD (Electrical and Computer Engineering)
Kenneth Sparks, PhD (Health Sciences), co-PIs
Cleveland State University

Introduction

These documents summarize the knowledge gained from our collaborative research on human performance and machine control systems in an exercise and rehabilitation context. On the human side, we were concerned with modeling, predicting and estimating human physical and governing control actions, particularly during physical tasks involving interaction with a controlled machine.

On the machine side, we focused on the design and optimal operation (control) of these machines seeking specific objectives related to human performance. For example, we designed, built and controlled machines that guide the human to perform motions that strike a specified muscular effort distribution target. Since the dynamics of human and machine are coupled through physical and behavioral variables, we obtain a genuine cyber-physical system.

Research was supported by NSF grants. The following is an overview of the contents of the white papers. They point to relevant publications, theses and dissertations for more details. Links to code to support ideas or to reproduce published simulation results are provided for selected topics.

Setting and Objectives

We consider the interconnection of human and machine subsystems. Variables such as force and velocity are shared by both subsystems across a physical inerface, for instance an exercise machine's handle. Behavioral (non-physical) interaction may also be present, particularly directed from machine to human, in the form of algorithm-generated cues which the human must follow when performing physical activity. An example of this is a real-time graphical display of a trajectory that the human is asked to follow against interaction forces, using his own control system.

Our work was guided by the vision of "Cyber-Enabled Exercise Machines" (CEEMs) which incorporate the modules shown in Fig. 1 towards more efficient, "optimal" exercise or rehabilitation (in a sense elaborated in the subsequent documents and papers). Figure 2 exemplifies this vision.

Objectives

The project introduces new approaches to design, optimize and control (CEEMs). These machines incorporate features that are far beyond the capabilities of today's systems in terms of real-time adaptability to the user. The amounts and types of information derived from and exchanged with the user are also unprecedented. A CEEM should incorporate at least the following functions:

1. Use a combination of direct sensing and model-based estimation to generate real-time, detailed information about current human performance
2. Use current performance indications to modify its own port mechanical characteristics to maximize a pre-selected, programmable objective

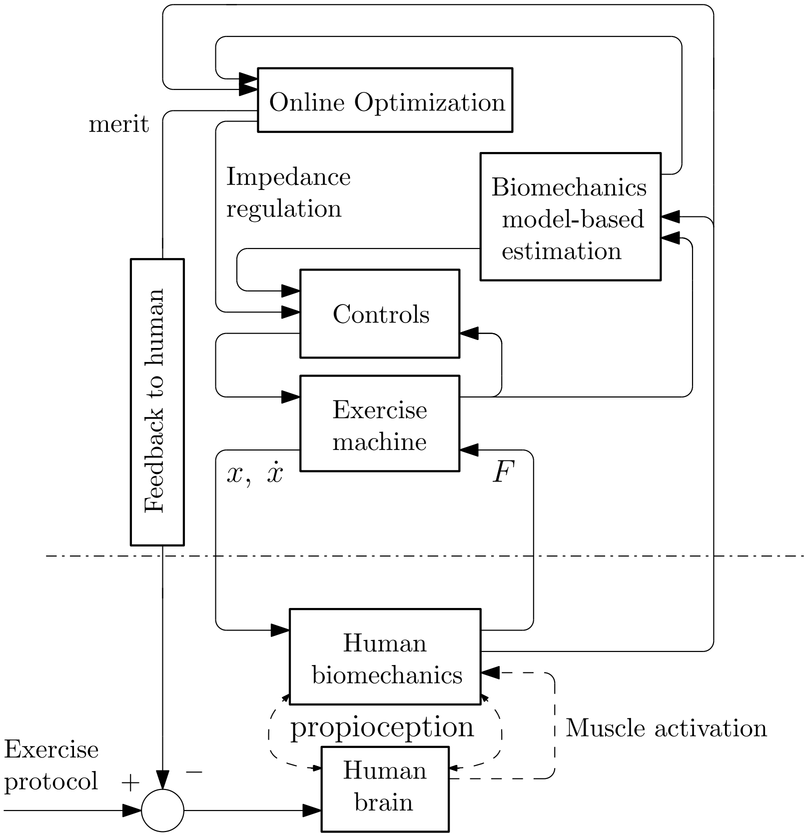

Figure 1: General setting of a human CPS

3. Use (1) to generate optimal real-time cues for trainees to modify their mechanical outputs
4. Monitor, manage and resolve conflicts between man and machine objectives with an overriding safety criterion

The invention of CEEMs brings unprecedented improvements in the effectiveness of machine-based athletic conditioning. The project has three broad research goals: i. development of foundational cyber-physical science and technology in the field of human-machine systems; ii. development of new approaches to modeling, design, control and optimization of advanced exercise machines; and, iii. application of the above results to develop two custom-built CEEMs: a rowing machine and a 4-degree-of-freedom robot for the upper limbs.

Our research took on various challenging problems associated with the CEEM vision, organized as below. Topics are outlined in the synopsis documents and detailed work is available in the listed papers, theses and dissertations.

1. **Human musculoskeletal dynamics (MSD) modeling, trajectory optimization and modeling of human control:** CEEMs are dynamic systems sharing variables (inputs, states) with the human dynamic system. The design and control of CEEMs therefore benefits from a description of human response under physical interaction with a machine. Although human dynamics are not well understood, the human control system exhibits certain features which can be exploited in the analysis of CEEMs and in the construction of models of controlled human response. These features include an excellent ability to track references (possibly after a learning period), maintaining stability and maintaining variables within safe limits.

   MSD models are typically large-scale nonlinear systems with complex mathematical descriptions, leading to time-consuming simulations. We have advanced fast MSD simulations using methods ranging from numerical optimal control to flatness-based sum-of-squares polynomial

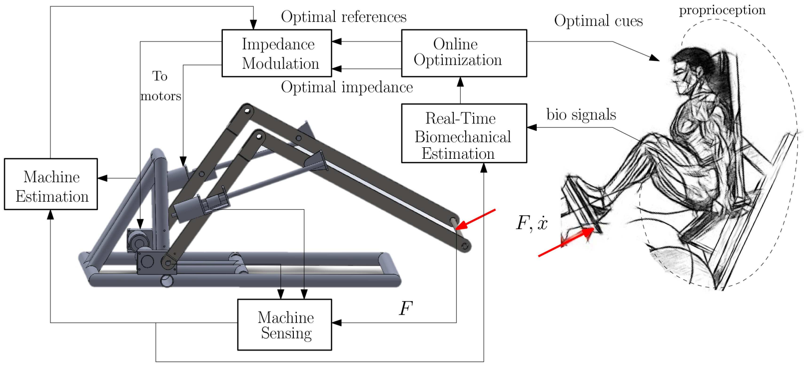

Figure 2: Vision of a Cyber-Enabled Exercise Machine

optimization. The minimization of a performance index related to human effort is a common link between these approaches.

In these efforts we also explored the Lyapunov-based control approach of backstepping for its application to MSD control.

2. **MSD estimation:** MSD models include variables which are not directly measurable, such as internal states of muscle dynamics and non-physical state definitions used with certain state-space models. Muscular activations are key variables in MSD models, which can be inputs or states according to the modeling approach. While activations can be measured with electromyography (EMG) sensors, it is not practical to directly measure all muscles involved in a study. Using MSD models, it is possible to measure a small set of variables while estimating the rest.

   We have explored the use of Kalman filters and robust estimation techniques such as sliding mode observers to determine the smallest set of measurements that can be used to obtain estimates for unmeasured states and inputs according to a desired level of accuracy.

3. **CEEM design and control:** We aimed to complete two CEEM prototypes to host selected modules from Fig. 1. First, we re-designed a rowing machine to include a motor with a torque-mode servo drive and force and motion sensing. This allowed us to test low-level machine control systems based on robust impedance control. The powered rower can be programmed to implement a desired target impedance at the user handle. For instance, we modeled and identified the parameters for the impedance of the standard air-resistance/inertia rowing machine. We used the impedance controller to reproduce its behavior. Then we defined an impedance relation that produced eccentric loading, a feature absent from standard machines.

   The 4-dof robot was designed and built for physical human-machine interaction studies. In this project, the robot was used to investigate the use of self-optimizing controls for muscular effort distribution targeting. The robot's control system is again a robust impedance controller. However, its principle was innovative, employing ideas from sliding mode control and impulse-momentum physical laws.

4. **Self-optimizing control and muscle effort distributions:** We considered an exercise or rehabilitation scenario where the user follows a reference trajectory against a resistance, both of which are machine-generated. The machine algorithn is designed to produce a reference and resistance that result in a desired balance of effort across a group of muscles. This application has important implications in physical therapy and athletic conditioning. We explored the use of Extremum Seeking Control for this purpose and conducted pilot experiments with the 4-dof robot above.

5. **Human-machine trials:** We conducted a large set of human subject tests with the rowing machines (standard and powered) to demonstrate the benefits of training with a CEEM. Pilot

trials were conducted with a few subjects to demonstrate the operation of the 4-degree robot. The COVID-19 pandemic disrupted these tests, which were then adapted and transferred to MSD model simulations with statistical techniques.