Energy-Oriented Design, Control and Optimization of Robotic Systems

Synopsis of Results from NSF Grant #1536035

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Introduction

These documents summarize the knowledge gained from our research on energy-aware design, control and optimization of robots. 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 is provided within each document.

Setting and Objectives

We consider two interconnected subsystems. One of the system is the *machine*, which has to meet a primary control objective. Our research has focused on robotic mechanisms with tracking or impedance control as their primary tasks. More recently, we are considering jet engines and UAV propellers as the machine.

The other system is the *drive*. It represents an actuator that powers the machine and also controls it. We are concerned with *regenerative* drives, capable of exchanging power with the machine in both directions, and also store energy.

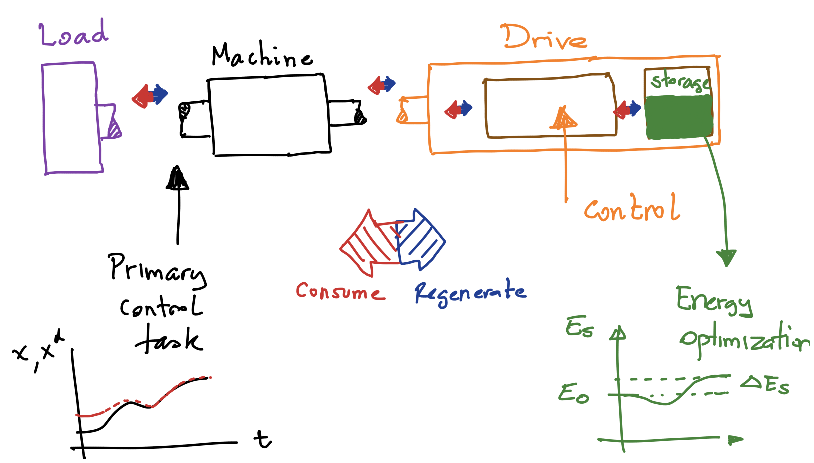

Figure 1: General research setting

Most of our work considers electromechanical drives, such as DC machines connected to controllable power converters and electric storage media (batteries or supercapacitors). We have also examined hydraulic drives, where energy is stored in accumulators [5].

To a large extent, the modeling and control approach we proposed is valid regardless of whether the drive is electromechanical, hydraulic, purely mechanical or something else. Bond graphs and analogies across domains have helped us do this. Paper [4] elaborates on this aspect.

Our drives are called *semiactive*. This reflects:

1. The energy required to operate the system is contained in the drive's storage element, without an external connection. That is, the drive can only exchange mechanical power with the machine. The drive also contains dissipation elements such as friction and resistance. This makes the drive a *dissipative system* in the theoretical sense, where the energy of the storage element can be used as storage function, and the power at the machine interface as the supply rate.

2. The drive is controllable. In electromechanical drives, we consider that control is introduced through the power converter, as a voltage ratio between the two ports. This is the same as a physical converter's *duty ratio*, but negative ratios are allowed to reflect bidirectional power flow.

Objectives

If we view the actuator only as a way to control the machine, we have many ways to design controllers that meet the primary control objective, for example tracking. But the problems of interest require that we examine the energy associated with each control task, the control law itself and the design parameters. For instance, we are interested in performing a control task so that the storage element is minimally discharged, or even recharged through regeneration.

- In industry, robots oftern perform repetitive motions between 2 points. Part of the motion is an acceleration, part a deceleration. Also, part of the motion demands power (to increase the robot's kinetic energy and perhaps increase gravitational potential energy), and the other part attempts to discard this power. *How do we control the robot so that it still moves between the 2 points, but consumes the least amount of energy in one cycle?*

- In biomedical robotics, exoskeletons and other powered orthoses and prostheses exchange mechanical power with the human. This includes phases where power flows from the device to the human, providing power assistance. But there are also phases where power must flow from the human back to the device, providing support. *How to we harvest this power maximally, without compromising the naturalness of human motion?*

Literature Review

The most comprehensive review of research concerning energy-oriented robot control and regenerative systems is probably in Poya Khalaf's 2019 dissertation [2]. Recent (2017-2019) papers covering energy optimization in robots are Carabin *et. al.* [1] and Laschowski *et.al.* [3].

References

[1] Giovanni Carabin, Erich Wehrle, and Renato Vidoni. A review on energy-saving optimization methods for robotic and automatic systems. *Robotics*, 6(4):39, 2017.

[2] P. Khalaf. *Design, Control, and Optimization of Robots with Advanced Energy Regenerative Drive Systems.* PhD thesis, Cleveland State University, 2019.

[3] B. Laschowsi, J. McPhee, and J. Andrysek. Lower-limb prostheses and exoskeletons with energy regeneration: Mechatronic design and optimization review. *Journal of Mechanisms and Robotics*, 11:040801 1–8, 2019.

[4] Hanz Richter. A framework for control of robots with energy regeneration. *Journal of Dynamic Systems, Measurement, and Control*, 137(9):091004, 2015.

[5] Hanz Richter, Xin Hui, Antonie J van den Bogert, and Dan Simon. Semiactive virtual control of a hydraulic prosthetic knee. In *2016 IEEE Conference on Control Applications (CCA)*, pages 422–429. IEEE, 2016.