Research Goals

- Human control modeling: this will enable us to design prosthesis controllers that mimic human control at both the knee and ankle
- Energy regeneration: this will enable us to design a prosthetic system that harvests energy at the knee and stores it for later use by the knee and ankle
- Prosthesis design: the above technologies will enable us to develop a new prosthesis design that promises greater flexibility and fewer adverse side effects than current prostheses

Publications


Identification of Human Impedance Control

Model for joint torque control
- Function of gait phase $\theta$ and joint angle $\phi$
- $M = -K_j(\phi)\dot{\theta} - K_{\phi}(\phi) + M^*(\phi)$

- $K_j(\phi), K_{\phi}(\phi), M^*(\phi)$ estimated from human data
- 8 minutes of treadmill walking
- Belt speed perturbations
- Motion capture and force plate
- Angles, torques sampled at 100 Hz
- 48000 samples of data
- Linear least-squares curve fit

Preliminary results (mean of 10 subjects)

- Estimated stiffness consistent with known muscle properties and reflexes
- Negative damping may be an artifact of open-loop identification
- Closed-loop identification methods are currently being developed
- Computational challenge: Simulate skeleton dynamics for 6 minutes in a nonlinear optimization routine
- Model-constrained optimization
- Direct collocation approach

Evolutionary Design and Control Optimization

Idealized Prosthesis Schematic

- Knee torque is an input due to ground contact
- The motor operates in generating mode
- Energy is stored in the supercapacitor

Prosthesis Design Optimization

- An evolutionary algorithm minimizes knee angle tracking error while at the same time charging the supercapacitor
- Design parameters to optimize:
  - Spring constant
  - Gear design and gear ratio
  - DC/DC converter ratio and switching logic
  - Supercapacitor specifications

Motor Mode vs. Generator Mode

- During able-bodied human walking, the knee is a net absorber of energy
- Therefore, a properly-design prosthetic leg should not require an external energy supply
- Prosthesis energy can be supplied by the amputee’s hip and thigh motions
- Prosthesis Motor Mode:
  - Power is produced by the knee (positive power)
  - Energy transferred from supercapacitor to motor
- Prosthesis Generator Mode:
  - Power is absorbed by the knee (negative power)
  - Energy transferred from motor to supercapacitor

Semiactive Virtual Control

- Multi-joint prosthesis with power converter control and supercapacitor:
  - $M(q)\ddot{q} + C(q,\dot{q})\dot{q} + R + g \sum_i m_i \dot{x}_i = u$
  - $u_i = a_i \tau_j^i x / C_j R_i$ are virtual control components
- Semiactive virtual control (SVC) is a theory allowing $u$ (virtual input) to be designed by standard control methods, then converter ratios $a$ are found by a matching law
- Upon exact matching, the system inherits the stability, tracking performance, and robustness properties of the virtual design
- Internal (zero) dynamics given in integral form by capacitor energy:
  - $\Delta E_C = \int u_i^j \dot{q}_i^j \tau_j^i x_i^j dt$
- SVC simplifies design and enables explicit treatment of energy regeneration; some key optimization problems have closed-form solutions

Simultaneous Robust Tracking and Regeneration

- Tracking results during the first power generation region (K1) of a typical stride
- Capacitor charge increases during the first power generation region (K1). We obtain positive energy storage in the supercapacitor over one gait cycle.

Optimal Prosthesis Design with Energy Regeneration

Dan Simon, Hanz Richter, and Antonie van den Bogert
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Motor Mode

Generator Mode