Adaptive Sliding Mode Control for Lower-limb Exoskeleton with nonlinear Spring Mechanism

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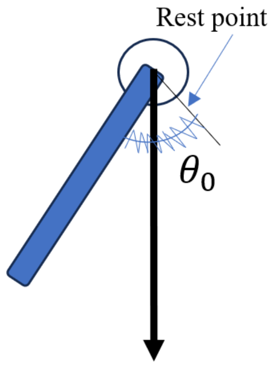
1. Project Objective

- Demonstrating advantages of spring mechanism in lower-limb exoskeleton structure.
- Designing control structure to handle the nonlinearity of spring and uncertainties in human's usage.
- Evaluating the effectiveness of control method.



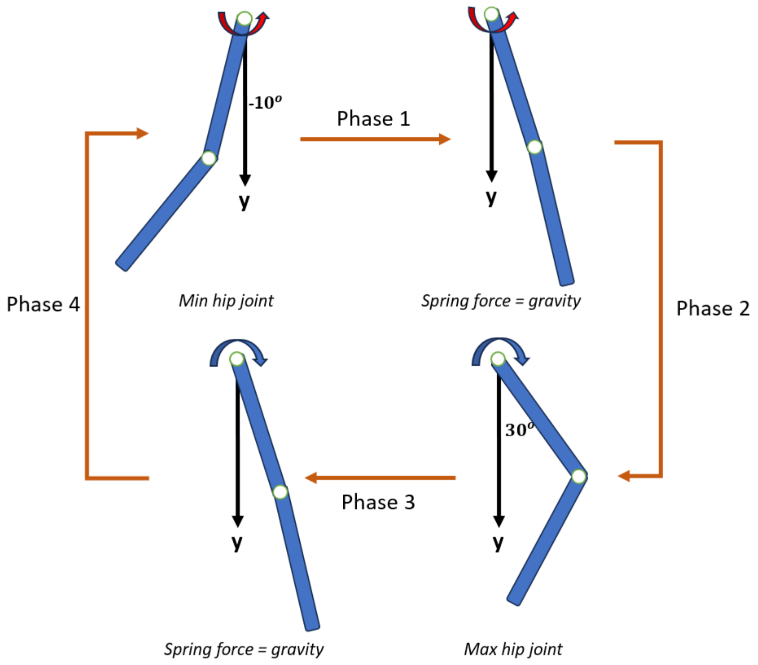
2. Project Problematic

- When humans use exoskeleton, different users have different leg's mass and inertia. It can make uncertain parameters to the model.
- Stiffness factor of spring can be changed over time or actively by human; the on/off spring mechanism cause complex term on model.
- PID controller shows bad performance on the system with spring mechanism.

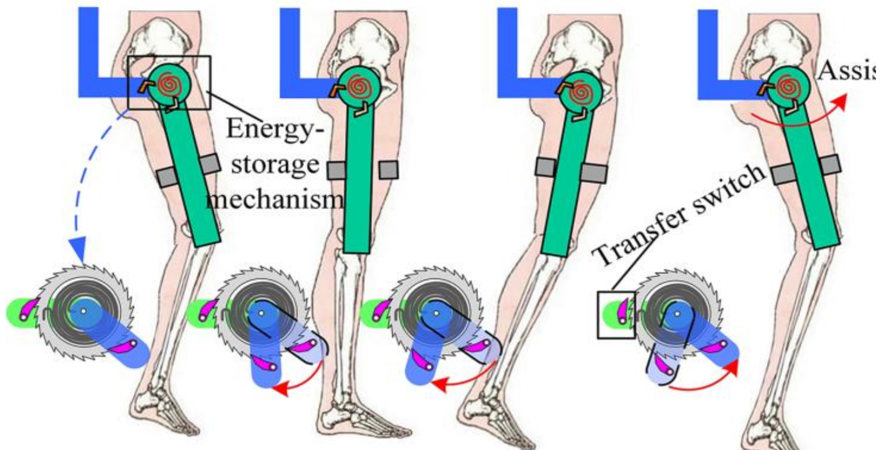
3. Project Approaches

- Using Extended State Observer (ESO) to estimate the total disturbance term.
- Using Sliding Mode Control with the estimation of ESO to ensure stability of system with unknown human leg's parameters or spring parameters.
- Using Simscape 2-DoF lower-limb exoskeleton model to evaluate the control method.

4. Advantage of Spring mechanism



- Phase 1: good or bad depends on velocity and trajectory
- Phase 2: Spring supports to lift the leg
- Phase 3: Spring supports to hold the leg (against gravity)
- Phase 4: Spring resists the motion



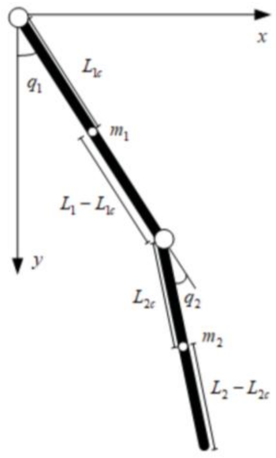
On/off mechanism:

$$s(\theta,\dot\theta) = \begin{cases} 0, & \theta < \theta_{eq} \text{ and } \dot\theta < 0, \\ 1, & \text{otherwise.} \end{cases}$$

Spring force:

$$\tau_{spring} = s(\theta,\dot\theta)K(\theta_0-\theta) - D\dot\theta$$

5. 2-DoF lower-limb exoskeleton



Certain model (exoskeleton without human and spring):

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}\dot{\mathbf{q}} + \mathbf{G} = \boldsymbol{\tau} + \boldsymbol{\tau}_s$$

Uncertain model (with spring and human):

$$\mathbf{M}_t\ddot{\mathbf{q}} + \mathbf{C}_t\dot{\mathbf{q}} + \mathbf{G}_t = \boldsymbol{\tau} + \boldsymbol{\tau}_s + \mathbf{d}(t)$$

$$\rightarrow \mathbf{M}\ddot{\mathbf{q}} = \boldsymbol{\tau} + [\boldsymbol{\tau}_s + \mathbf{d}(t) - \Delta\mathbf{M}\ddot{\mathbf{q}} - \mathbf{C}_t\dot{\mathbf{q}} - \mathbf{G}_t]$$

$$\rightarrow \ddot{\mathbf{q}} = \mathbf{M}^{-1}(\boldsymbol{\tau} + [\boldsymbol{\tau}_s + \mathbf{d}(t) - \Delta\mathbf{M}\ddot{\mathbf{q}} - \mathbf{C}_t\dot{\mathbf{q}} - \mathbf{G}_t])$$

$$\rightarrow \ddot{\mathbf{q}} = \mathbf{M}^{-1}\boldsymbol{\tau} + \underbrace{\boxed{\mathbf{M}^{-1}[\boldsymbol{\tau}_s + \mathbf{d}(t) - \Delta\mathbf{M}\ddot{\mathbf{q}} - \mathbf{C}_t\dot{\mathbf{q}} - \mathbf{G}_t]}}_{\text{Extended State } F(t)}$$

6. Extended State Observer

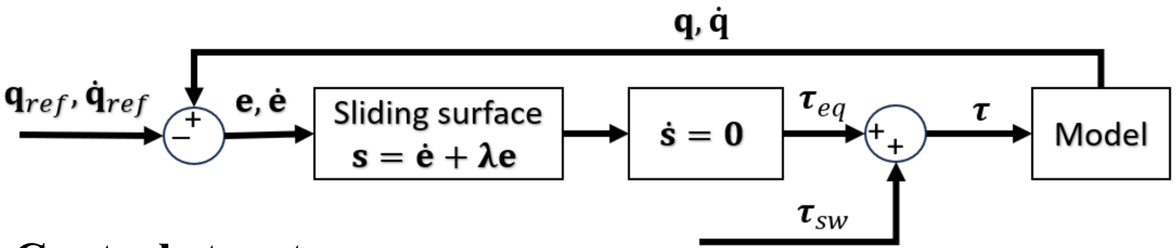
$$\dot{\hat{\mathbf{q}}}_1 = \hat{\mathbf{q}}_2 + \frac{\gamma_1}{\varepsilon}(\mathbf{q}_1 - \hat{\mathbf{q}}_1)$$

$$\dot{\hat{\mathbf{q}}}_2 = \hat{\mathbf{q}}_3 + \frac{\gamma_2}{\varepsilon^2}(\mathbf{q}_1 - \hat{\mathbf{q}}_1) + \mathbf{M}^{-1}\boldsymbol{\tau}$$

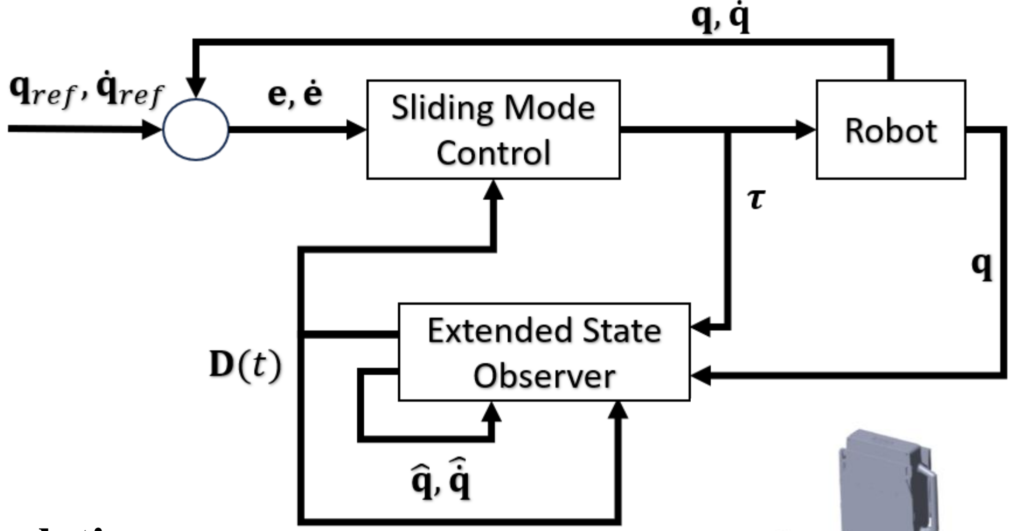
$$\dot{\hat{\mathbf{q}}}_3 = \frac{\gamma_3}{\varepsilon^3}(\mathbf{q}_1 - \hat{\mathbf{q}}_1)$$

$\mathbf{q}_1$ is the state vector
$\mathbf{q}_2$ is it derivative
$\mathbf{q}_3$ is the total disturbance
$\hat{\mathbf{q}}_1, \hat{\mathbf{q}}_2, \hat{\mathbf{q}}_3$ are corresponding estimated values

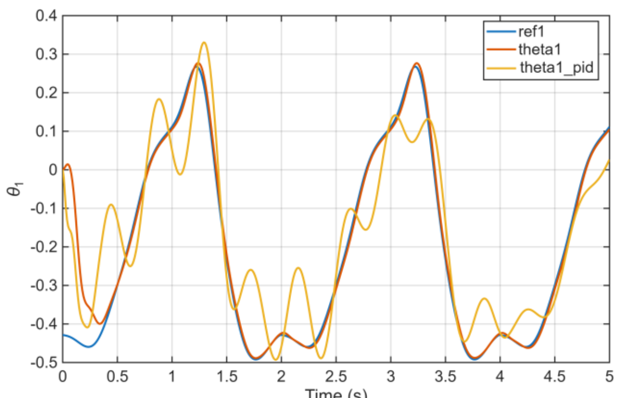
7. Sliding Mode Control

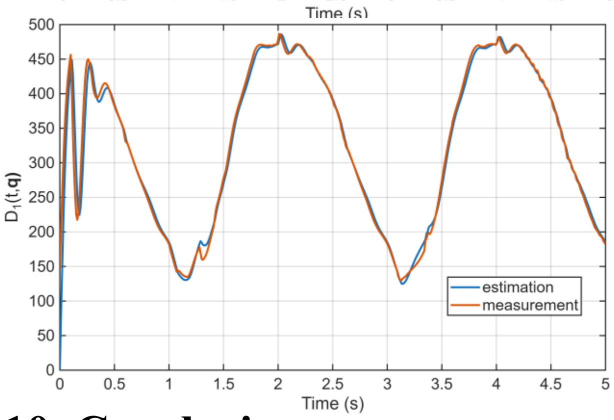


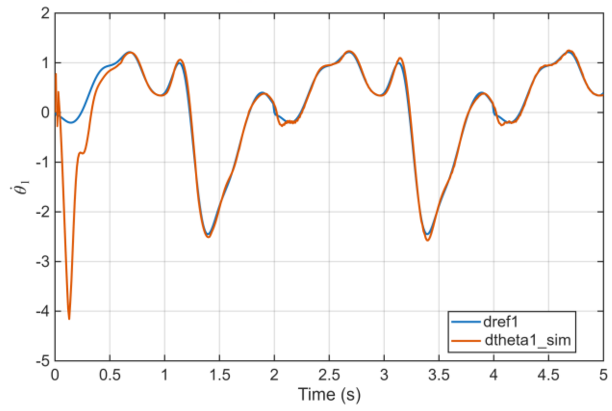
8. Control structure



9. Simulation







10. Conclusion

- Spring mechanism can support torque for movement, but can increase the complexity of model
- ESO can estimate the total disturbance for model-based controller, like SMC
- Future work: optimize on/off switch for phase 1, Impedance/Admittance Control,…