Preliminary Result on Passivity Boundary of Inertia Scaling Control for Human Interactive Robot

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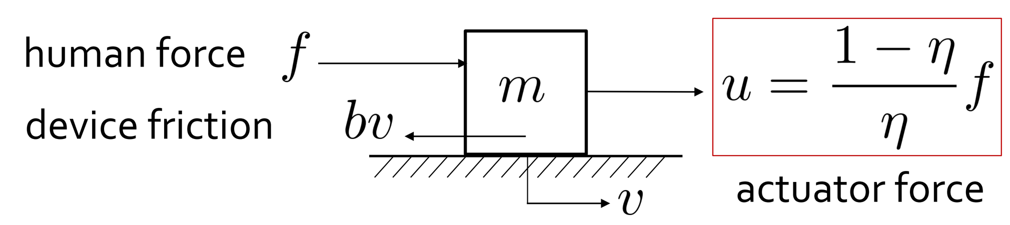
Abstract

- inertia scaling control is useful when endowing a virtual dynamics to a system, however, it shows nonpassive behavior such as vibration and instability when scale factor is too low.
- modeled the robot's imperfect force sensing mechanism such as filtering and sample/hold.
- analyzed the energetics of the model in frequency-domain using Parseval's identity.
- applied the fact that human force frequency is upper bounded.
- found minimum inertia scale factor that preserves passivity of robot while interacting with human.

Motivation

inertia scaling control (ideal)

- measures human force by force sensor and exerts additional actuator force to the opposite/same direction.



device dynamics: $m\dot{v}(t) + bv(t) = f(t) + u(t)$

- robot's apparent inertia and damping are scaled up/down by η.

resulting dynamics:

$$\eta m\dot{v}(t) + \eta bv(t) = f(t)$$

$$\Rightarrow \hat{m} = \eta m, \ \hat{b} = \eta b$$

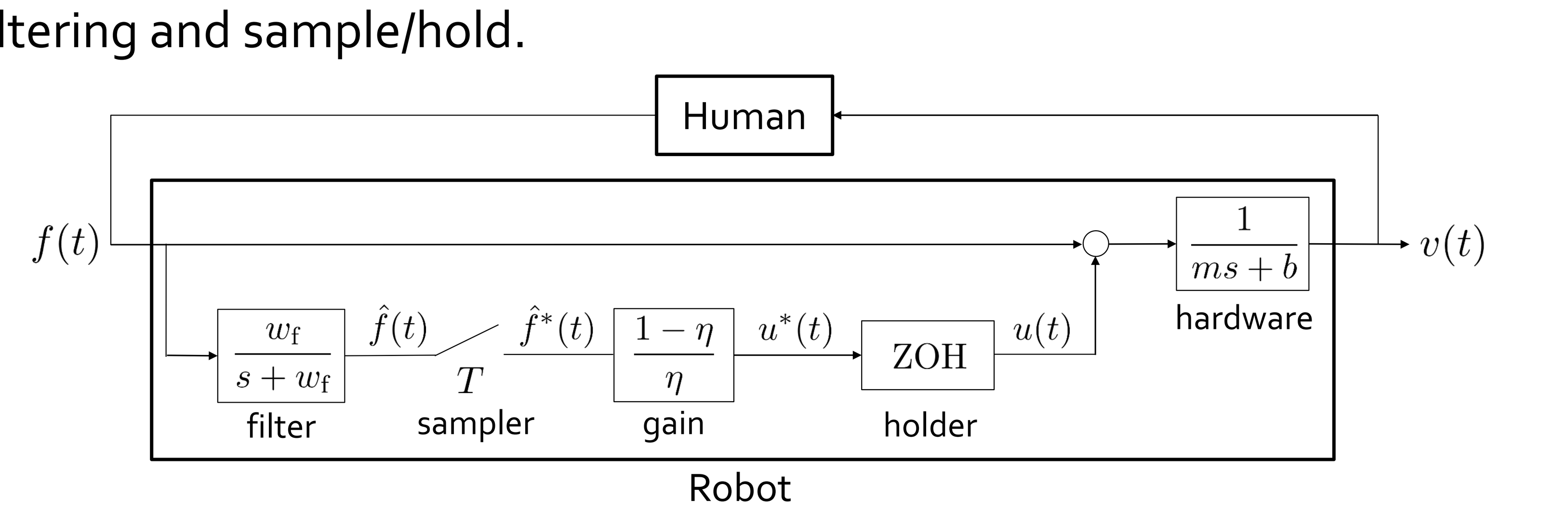
- the resulting dynamics is passive.

➡ however, when scaling factor is too low, nonpassive vibration occurs.

System Modeling and Passivity Analysis

system component modeling

- we modeled the robot including imperfect force sensing such as low-pass filtering and sample/hold.



1) low-pass filter $\quad \hat{F}(s) = \dfrac{w_f}{s+w_f}F(s)$

2) sampler $\quad \hat{F}^*(s) = \dfrac{1}{T}\displaystyle\sum_{n=-\infty}^{n=\infty} \hat{F}\left(s + j\frac{2\pi}{T}n\right)$

3) inertia scaling controller $\quad U^*(s) = \dfrac{1-\eta}{\eta}\hat{F}^*(s)$

4) zero-order holder $\quad U(s) = \dfrac{1-e^{-Ts}}{s}U^*(s)$

$$\Rightarrow \boxed{\begin{aligned} U(s) &= \frac{1-\eta}{\eta}\frac{1-e^{-Ts}}{s}\frac{1}{T}\sum_{n=-\infty}^{n=\infty}\frac{w_f}{s+j\frac{2\pi}{T}n+w_f}F\left(s+j\frac{2\pi}{T}n\right) \\ V(s) &= \frac{1}{ms+b}\{F(s)+U(s)\} \end{aligned}}$$

passivity analysis

- the extractable energy from the robot is upper bounded for all time.

$$-W_h = -\int_0^t f(\tau)v(\tau)d\tau \le c^2 \quad \forall t \ge 0 \quad \forall \text{admissible } f \quad \text{for some } c$$

$$= -\int_{-\infty}^{\infty} f_t(\tau)\tilde{v}_t(\tau)d\tau$$

f_t: truncated signal of f
$\tilde{(\cdot)}_t$: dynamic response to f_t

$$= -\int_{-\infty}^{\infty} \tilde{V}_t(jw)F_t^*(jw)dw$$

$F_t(jw) = 0 \quad \forall w \notin [-w_h, w_h]$

- we model the human force as an arbitrary but bandlimited signal.

$$= -\int_{-w_h}^{w_h} \tilde{V}_t(jw)F_t^*(jw)dw$$

$$\tilde{V}_t(s) = \frac{1}{ms+b}\left\{F_t(s)+\tilde{U}_t(s)\right\}$$

$$= -\int_{-w_h}^{w_h} \frac{F_t(jw)+\tilde{U}_t(jw)}{jmw+b}F_t^*(jw)dw$$

$$\tilde{U}_t(jw) = \frac{1-\eta}{\eta}\frac{1-e^{-jTw}}{jw}\frac{1}{T}\frac{w_f}{jw+w_f}F_t(jw) \quad \forall w \in [-w_h, w_h]$$

$$\because F_t\left(jw+j\frac{2\pi}{T}n\right) = 0 \quad \forall n \ne 0 \quad \forall w \in [-w_h, w_h]$$

- we assume the human force frequency below the Nyquist frequency. $\quad w_h < \pi/T$

$$-W_h = -\int_{-w_h}^{w_h} \frac{1}{m^2w^2+b^2}K(w)|F_t(jw)|^2dw$$

$$\text{where } K(w) = \mathrm{Re}\left[(b-jmw)\left(1+\frac{1-\eta}{\eta}\frac{1-e^{-jTw}}{jw}\frac{1}{T}\frac{w_f}{jw+w_f}\right)\right]$$

➡ the equivalent passivity condition in frequency-domain is

$$\boxed{K(w) \ge 0 \qquad \forall w \in [-w_h, w_h]}$$

Passivity Boundary

minimum-possible passive inertia scaling factor

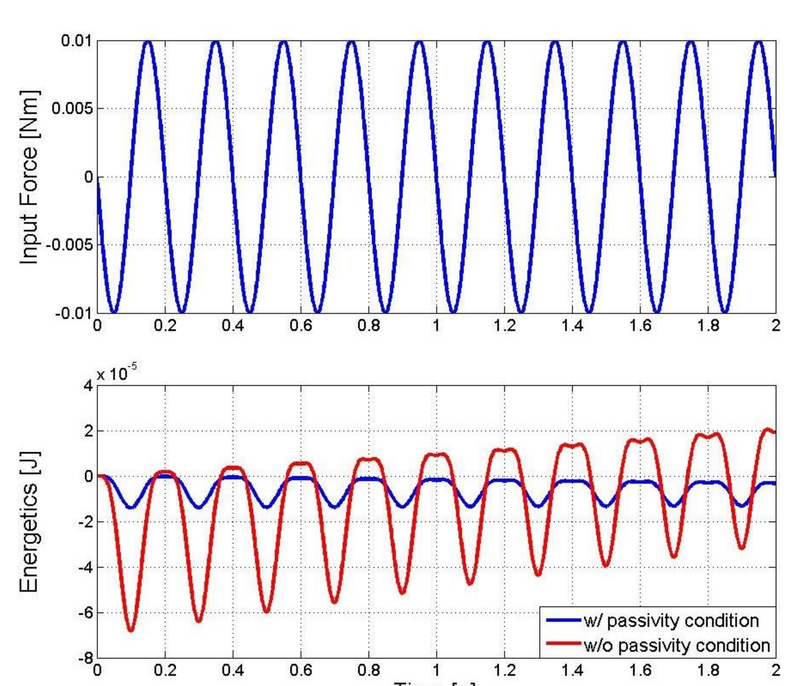
$$\boxed{\eta \ge 1 - \frac{w_c T w(w^2+w_f^2)}{g(w)} \qquad \forall w \le w_h, \qquad \eta > 0}$$

$$g(w) = w_c w_f^2(Tw - \sin Tw) + (w_f \sin Tw + w_c Tw)w^2 + w_f(w_c+w_f)w(1-\cos Tw)$$

$$w_c = b/m$$

- the range of inertia scaling factor that preserves passivity of the robot while interacting with human.

simulation verification

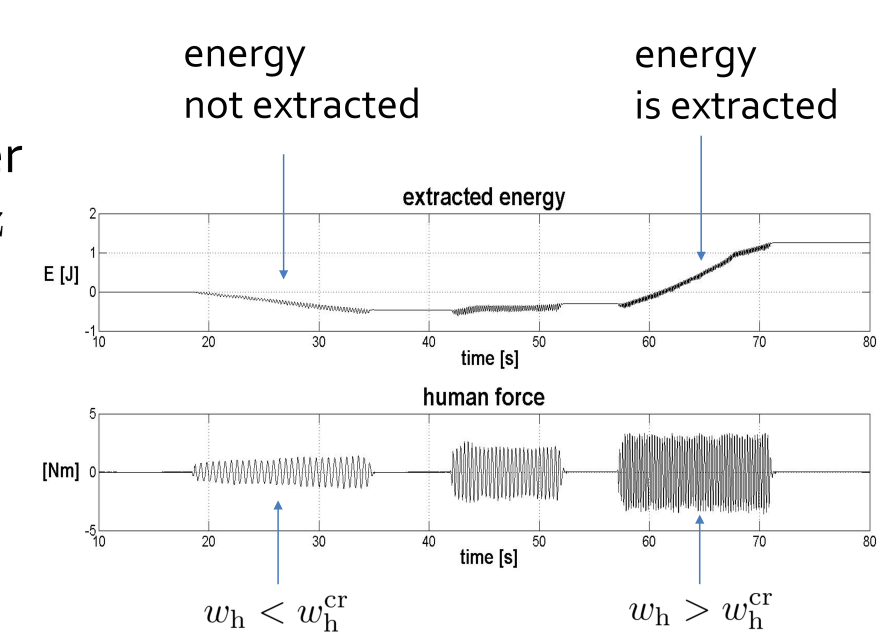


- we exerted constant frequency harmonic force as a human force to the robot.
- the robot's energetics is passive when the inertia scaling factor is greater than the minimum inertia scale factor.
- the minimum inertia scaling factor depends on the bandwidth of human force.

Experimental Validation

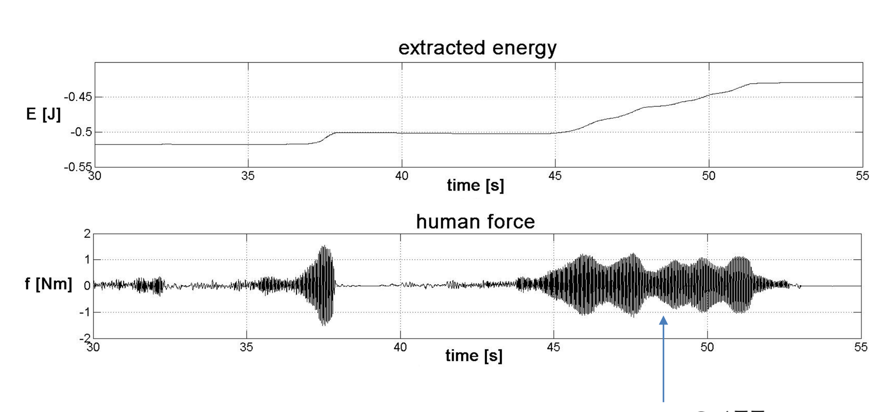
human force bandwidth vs. passivity

- experimented with $\eta = 0.3$.
- we calculated the critical bandwidth under which the robot is passive. $\quad w_h^{cr} = 5.1\mathrm{Hz}$
- when real bandwidth of human force is below this critical value, the energy could not be extracted from the robot.
- when real bandwidth of human force is higher than this critical value, the energy could be extracted from the robot.



relation to nonpassive vibration

- human force bandwidth is varying with operator's grasping posture and stiffness.
- when operator firmly grasps the robot, the passivity condition is violated due to the increase of possible human force bandwidth, thus, robot can generate energy.



when human firmly grasps the robot, vibration occurs w. frequency higher than $w_h^{cr} = 5.1\mathrm{Hz}$.

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