Modeling and Identification of Wear in a Robot Joint under Temperature Uncertainties

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Summary

The fact that the *wear process in a robot joint relates to the increase of friction in the joint* is explored:

- wear effects are analyzed and modeled,
- a wear estimator is proposed,
- achievable estimator performance is discussed.

Simulations and experiments show that robust wear estimates are possible even under large temperature variations.

Friction – Observations and Models

Consider the manipulator rigid-body model:

$$M(\varphi)\,\ddot{\varphi} + C(\varphi,\dot{\varphi}) + \\ + \tau_g(\varphi) + \tau_f(\dot{\varphi}) = u$$

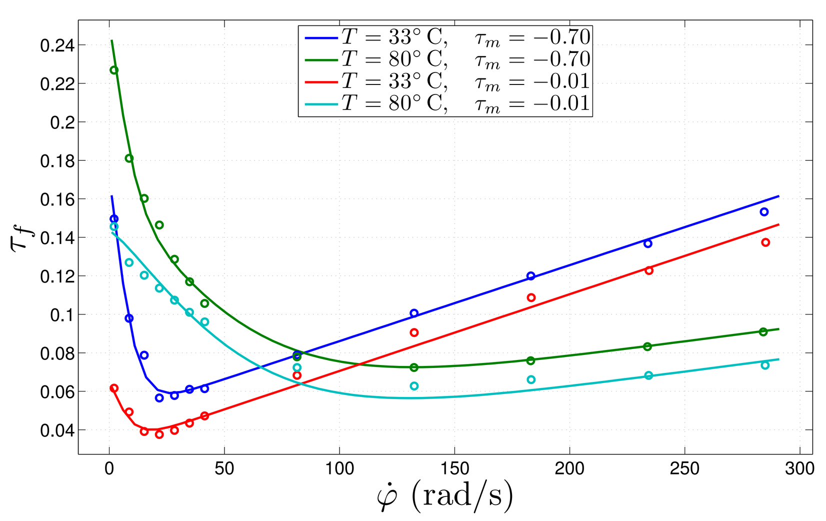
Notation	
φ	Joint angle
τ_f	Friction torque
τ_g	Gravity torque
τ_m	Load torque
T	Joint temperature
M	Inertial matrix
C	Coriolis matrix
u	Control input

Moving *one axis at a time in steady-state velocity*, then $\ddot{\varphi} \approx 0$ and $C(\varphi,\dot{\varphi}) = 0$.

Take movements over the same position $\bar{\varphi}$ in forward u^+ and backward u^- directions, for a constant speed $\bar{\dot{\varphi}}$. Under the assumption that $\tau_f(-\dot{\varphi}) = -\tau_f(\dot{\varphi})$ (direction independence).

$$\begin{aligned} \tau_f(\bar{\dot{\varphi}}) + \tau_g(\bar{\varphi}) &= u^+, \\ \tau_f(-\bar{\dot{\varphi}}) + \tau_g(\bar{\varphi}) &= u^- \end{aligned} \quad \Rightarrow \quad \tau_f(\bar{\dot{\varphi}}) = \frac{u^+ - u^-}{2} \tag{1}$$

Moving the joint through several steady-state velocities back and forth, it is possible to estimate a *static friction curve* using (1).



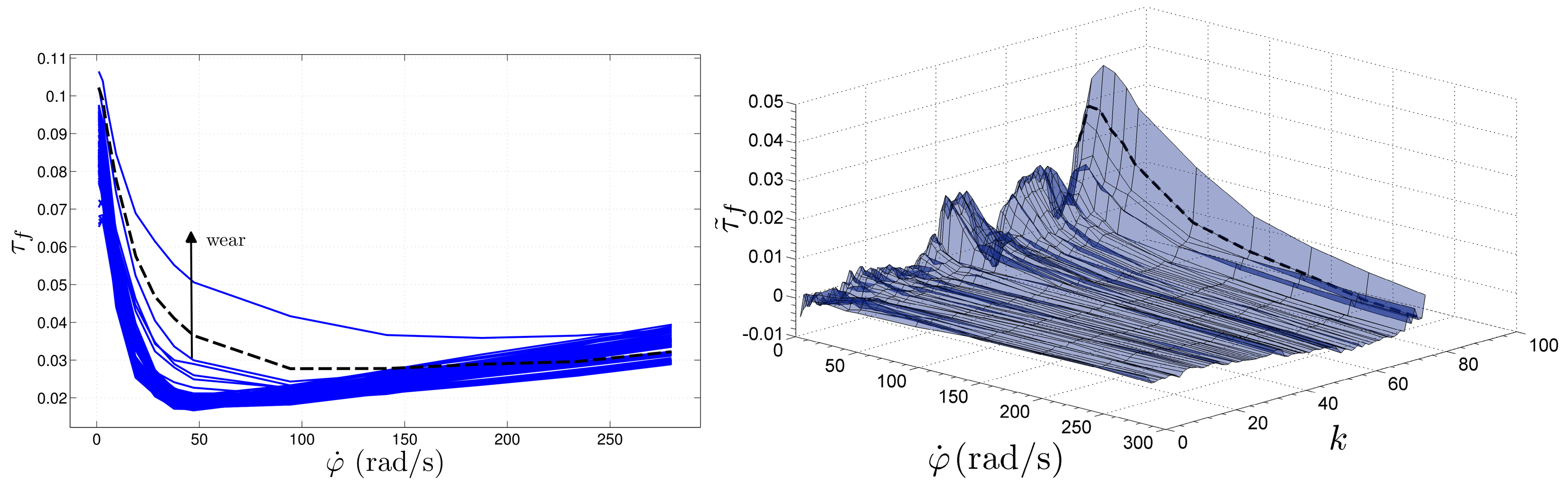
An existing model [1] can *predict the static friction with respect to speed, temperature and load.*

$$\tau_f(\dot{\varphi},\tau_m,T) = \{F_{c,0} + F_{c,\tau_m}|\tau_m|\} + F_{s,\tau_m}|\tau_m| e^{-\left|\frac{\dot{\varphi}}{\dot{\varphi}_{s,\tau_m}}\right|^{1.3}} + \\ + \{F_{s,0} + F_{s,T}T\} e^{-\left|\frac{\dot{\varphi}}{(\dot{\varphi}_{s,0}+\dot{\varphi}_{s,T}T)}\right|^{1.3}} + \{F_{v,0} + F_{v,T} e^{\frac{-T}{T_{\mathrm{Vo}}}}\}\dot{\varphi}$$

[1] Bittencourt et al. *An Extended Friction Model to Capture Load and Temperature Effects in Robot Joints.* In IROS 2010, Taiwan, Taipei.

Wear – Analysis and Modeling

Accelerated wear tests were taken at one of the joints of a 6 axes industrial robot in order to analyze the effects of wear in friction.

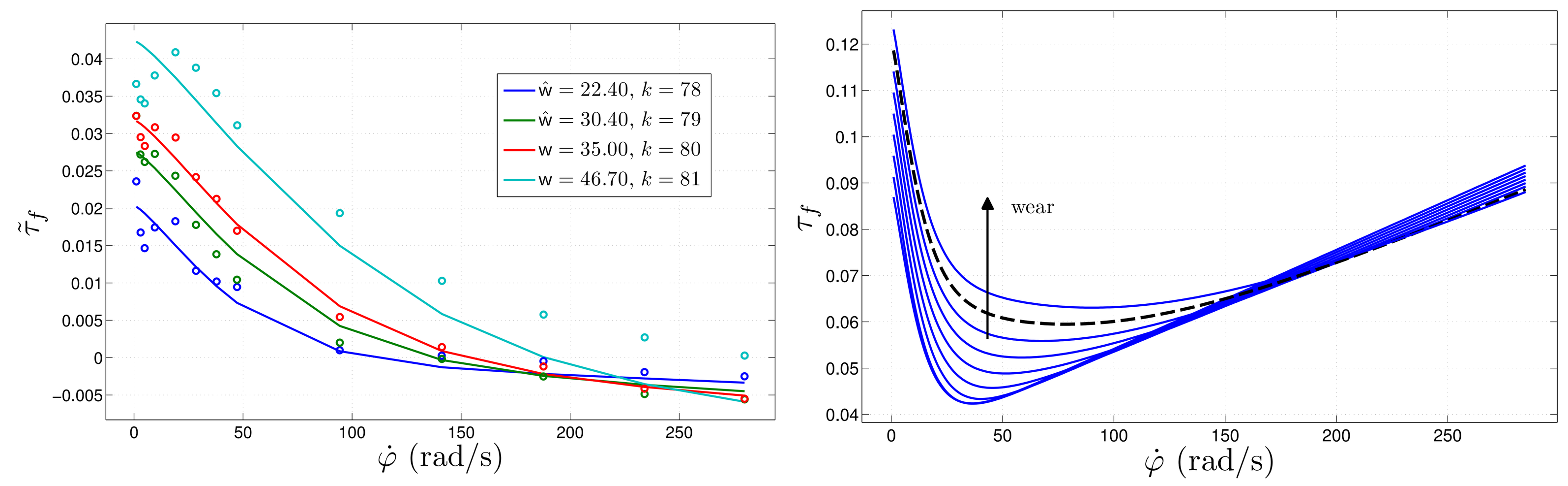


A *wear profile* $\tilde{\tau}_f$ is defined as the difference between friction curves under no wear and the remaining ones.

Introducing w, with values between $[0, 100]$, a model is proposed for $\tilde{\tau}_f$.

$$\tilde{\tau}_f(\dot{\varphi},\mathsf{w}) = F_{s,\mathsf{w}}\mathsf{w}e^{-\left|\frac{\dot{\varphi}}{\dot{\varphi}_{s,\mathsf{ww}}}\right|^{1.3}} + F_{v,\mathsf{w}}\mathsf{w}\dot{\varphi}$$

The parameters for the wear profile are identified with the convention that $\mathsf{w} = 35$ at $k = 80$.



The existing model can be extended by simply adding the wear profile $\tilde{\tau}_f$.

$$\tau_f(\dot{\varphi},\tau_m,T,\mathsf{w}) = \\ \tau_f(\dot{\varphi},\tau_m,T) + \tilde{\tau}_f(\dot{\varphi},\mathsf{w})$$

The resulting model can be used for *model-based wear identification* under broad operation conditions.

$$\hat{\mathsf{w}} = \arg\min_{\mathsf{w}} V\left(\tau_f - \hat{\tau}_f(\dot{\varphi},\tau_m,T,\mathsf{w})\right),$$

Joint temperature measurements are however not possible in usual industrial applications, but should be distinguished from wear effects.

A model-based Wear Estimator

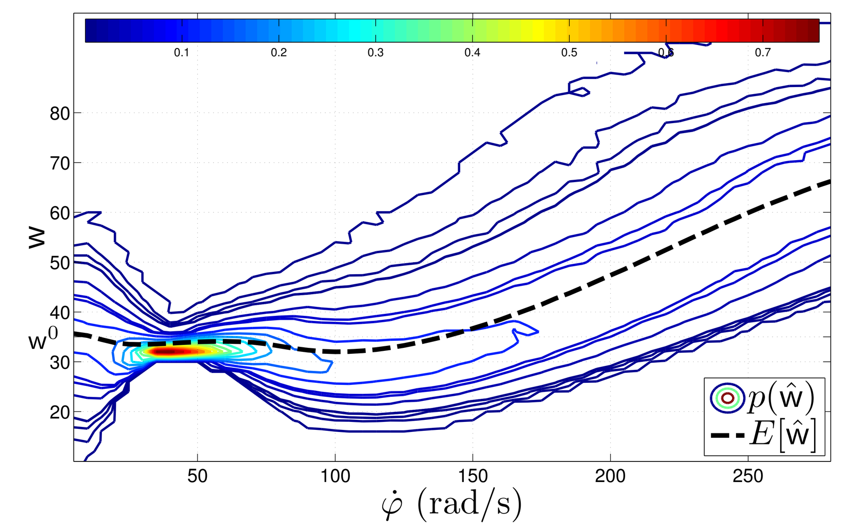
The estimator assumes T uniformly distributed between the limits and N samples are drawn from it. The expected value of the resulting N estimates $\{\hat{\mathsf{w}}_N\}$ is then taken as the wear estimate.

$$\hat{\mathsf{w}}_i = \arg\min_{\mathsf{w}} V\left(\tau_f - \hat{\tau}_f(\dot{\varphi},\tau_m,T_i,\mathsf{w})\right) \tag{2a}$$

$$\hat{\mathsf{w}} = E\left[\{\hat{\mathsf{w}}_N\}\right], \quad T_i \sim \mathcal{U}(\underline{T},\overline{T}), \quad i = 1,\dots,N \tag{2b}$$

Simulation. A Monte Carlo simulation study is performed for the estimator when the observed friction τ_f has $\mathsf{w}=35$ and $T \sim \mathcal{N}(40,3)$ and the estimator is set with $N=200$, $\underline{T}=30°\mathrm{C}$ and $\overline{T}=50°\mathrm{C}$.

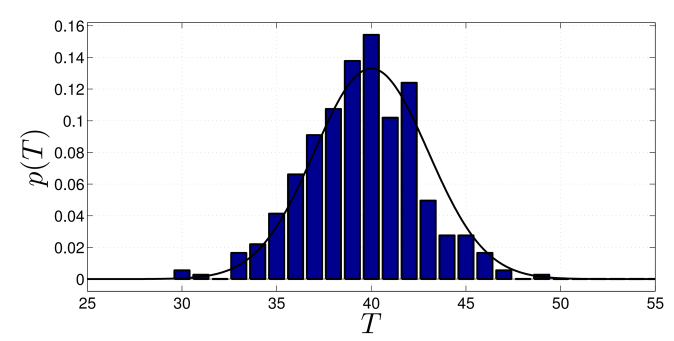
- Large bias at high $\dot{\varphi}$.
- Large var. at low/high $\dot{\varphi}$.
- *Selective $\dot{\varphi}$ region* where $\hat{\mathsf{w}}$ estimates are useful.

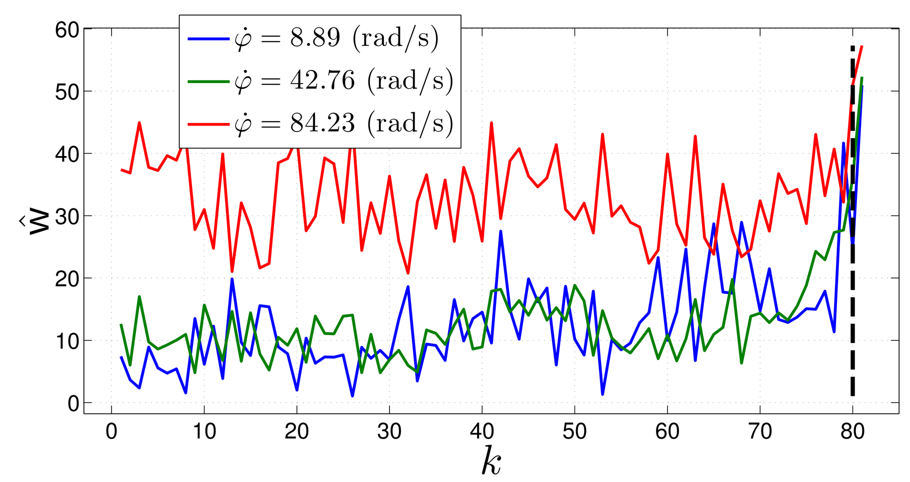


Case Study. Data from a wear profile $\tilde{\tau}_f$ is added to friction curves from a normal robot $\tau_f^0(T)$ under several T conditions.

$$\tau_f^*(k) = \tilde{\tau}_f(k) + \tau_f^0(T) \tag{3}$$

The data for $\tau_f^0(T)$ are sampled according to a desired temperature distribution and w is estimated.





With the estimates of w at $\dot{\varphi} = 42.76$ rad/s, *even a simple threshold* set at $\mathsf{w} = 35$ could detect the friction increase at a critical wear level (indicated by the dashed line).

For more. This work is available as a technical report at
`http://www.control.isy.liu.se/~andrecb/publications/`