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. An existing static friction model is extended to include the effects of wear, which are analyzed and modeled. Based on this model and static friction observations, a model-based wear estimator is proposed.

As shown by simulations and experiments on an industrial robot, the method can distinguish the effects of wear even under large temperature variations, opening up for the use of *robust joint diagnosis* for industrial robots.

Friction – Observations and Models

Consider the manipulator rigid-body model:

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

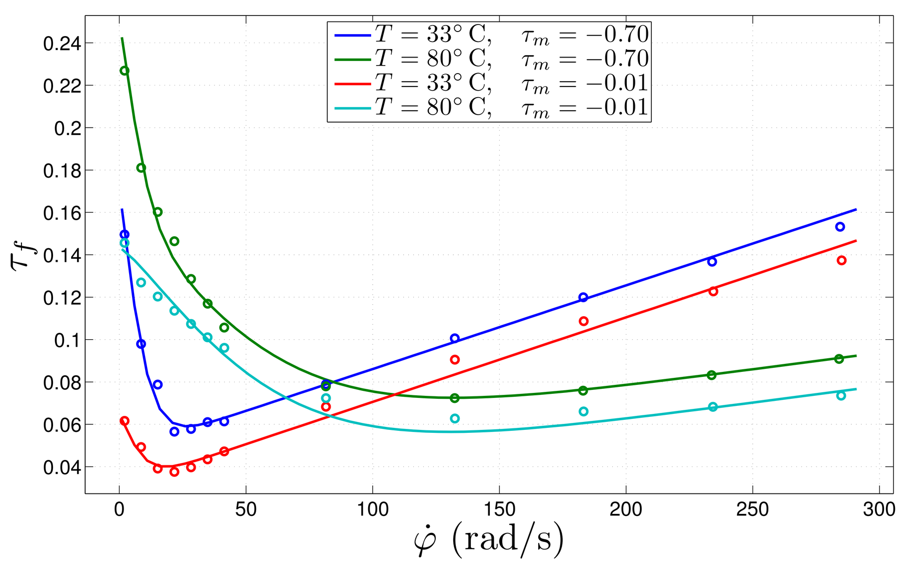
Notation	
φ	Joint angle
τ_f	Friction torque
τ_g	Gravity torque
τ_m	Load torque
T	Joint temperature
M	Inertial matrix
C	Coriolis matrix
u	Control input

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).

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

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



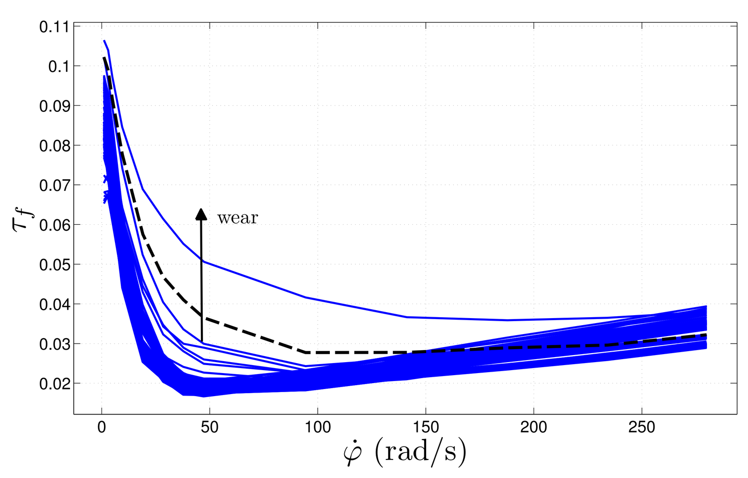
Many variables plays significant effects in the friction curve. An existing model [1] can *predict the static friction with respect to speed, temperature and load.*

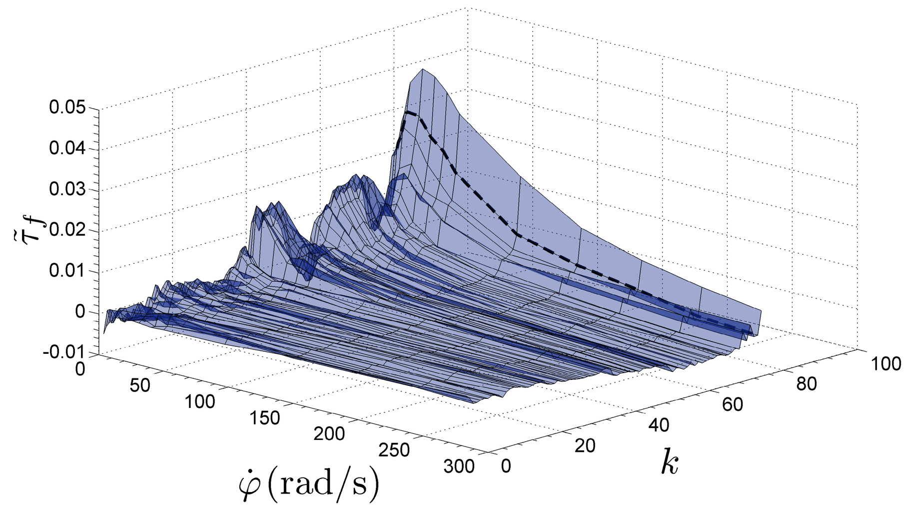
$$\boxed{\begin{aligned}\tau_f(\dot{\varphi},\tau_m,T) = &\{F_{c,0} + F_{c,\tau_m}|\tau_m|\} + F_{s,\tau_m}|\tau_m| e^{-\left|\frac{\dot{\varphi}}{\dot{\varphi}_{s,\tau_m}}\right|^{1.3}} + \\ &+ \{F_{s,0} + F_{s,T}T\} e^{-\left|\frac{\dot{\varphi}}{(\dot{\varphi}_{s,0}+\dot{\varphi}_{s,T}T)}\right|^{1.3}} + \{F_{v,0} + F_{v,T}e^{\frac{-T}{T_{V_0}}}\}\dot{\varphi}\end{aligned}}$$

[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.



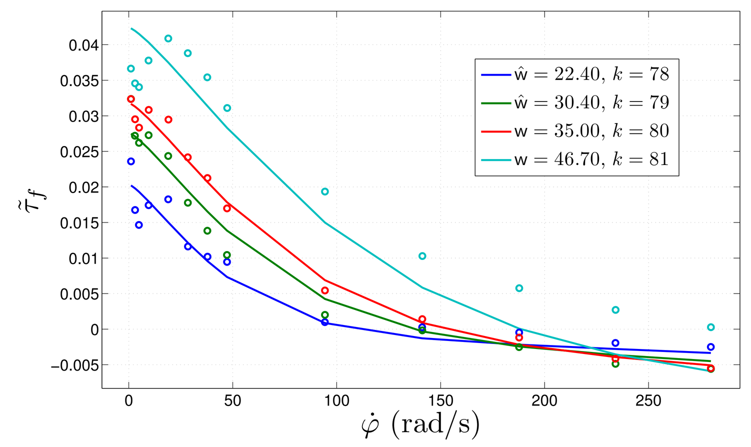


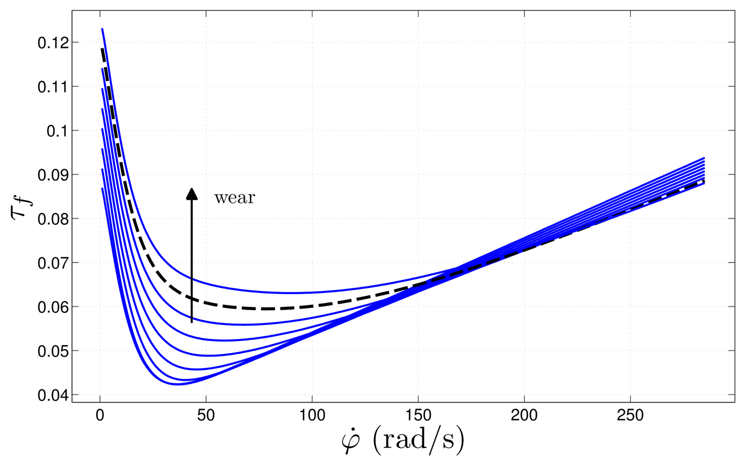
Assuming that the effects of wear are independent of those of load and temperature, a *wear profile* $\tilde{\tau}_f$ is defined as the difference between friction curves under no wear and the remaining ones.

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

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

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





When load/temperature effects are independent of those caused by wear, the existing model can be extended by simply adding the wear profile $\tilde{\tau}_f$.

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

The resulting model can be used for *model-based wear identification* under broad operation conditions. Given an observation of τ_f, find the value of w that minimizes the prediction error

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

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

A model-based Wear Estimator

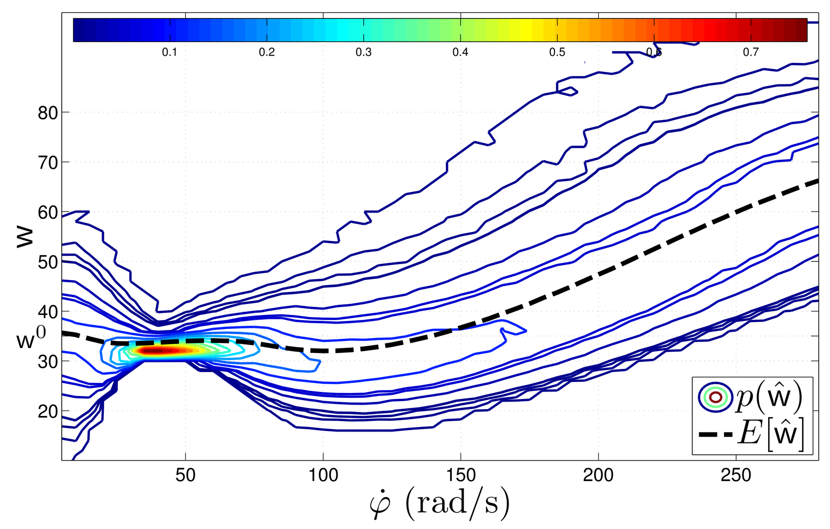
To include the effects of T in the estimator, T is considered a random variable with unknown p.d.f. but known lower and upper limits. The estimator assumes T uniformly distributed between the limits and N samples are drawn from it. The expected value of the resulting N estimates $\{\hat{\mathsf{w}}_N\}$ is then taken as the wear estimate.

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

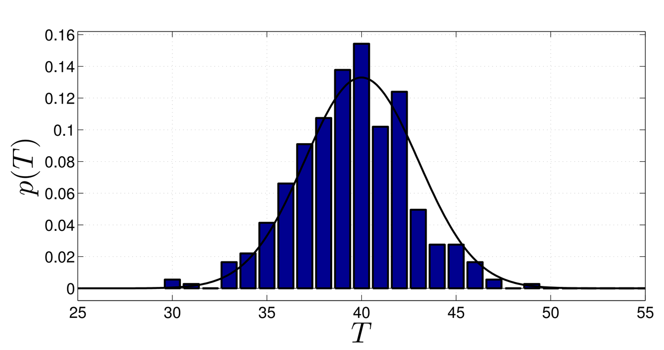
$$\hat{\mathsf{w}} = E\left[\{\hat{\mathsf{w}}_N\}\right], \quad T_i \sim \mathcal{U}(\underline{T},\overline{T}), \quad i = 1,\ldots,N \tag{2b}$$

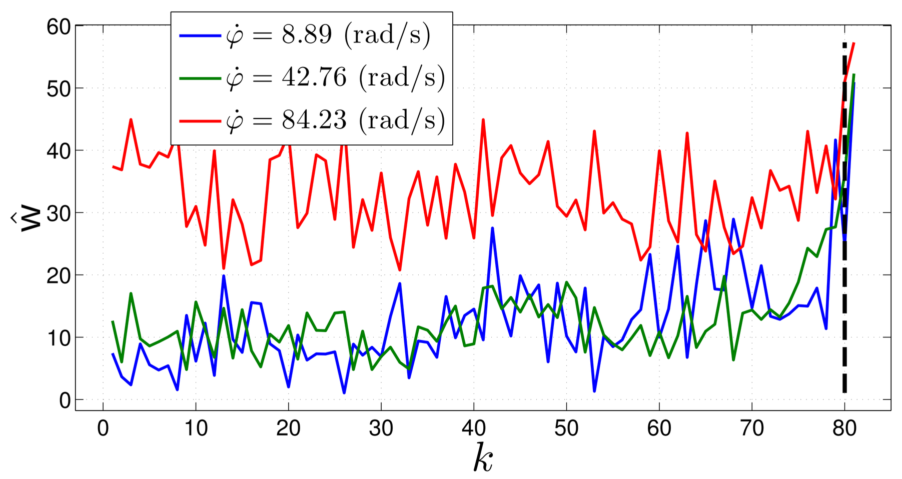
Simulation. A Monte Carlo simulation study is performed for the estimator when the observed friction τ_f has $\mathsf{w}=35$ and $T \sim \mathcal{N}(40,3)$ and the estimator is set with $N=200$, $\underline{T}=30$°C and $\overline{T}=50$°C.

- 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. An observed wear profile $\tilde{\tau}_f(k)$ is added to observed friction curves from a normal robot taken under several temperature conditions $\tau_f^0(T)$. The data for the case study is generated according to $\tau_f^*(k) = \tilde{\tau}_f(k) + \tau_f^0(T)$. 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 was submitted to the 2010 IFAC World Congress and is available as a technical report at
`http://www.control.isy.liu.se/~andrecb/publications/`