An Extended Friction Model to capture Load and Temperature effects in Robot Joints

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Summary

The *static* friction phenomena in a manipulator joint is analyzed in detail regarding the influences caused by:

Joint position ⇒ related to asymmetries in the joint contact surfaces.
Joint load torques ⇒ related to the increase of adhesion between the contact surfaces in the joint.
Temperature ⇒ related to variations of lubricant viscosity and contact surfaces interaction.

A series of experiments was carried out to consider the effects of each variable independently. According to the empirical observations a *new static friction model*, based on a standard velocity dependent model, is proposed to achieve an overall improved performance.

Friction Curve Estimation

Consider the manipulator rigid-body model:

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

Notation	
φ_a	Joint arm pos
φ_m	Joint motor pos
τ_f	Friction torque
τ_g	Gravity torque
M	Inertial matrix
C	Coriolis matrix
u	Control input

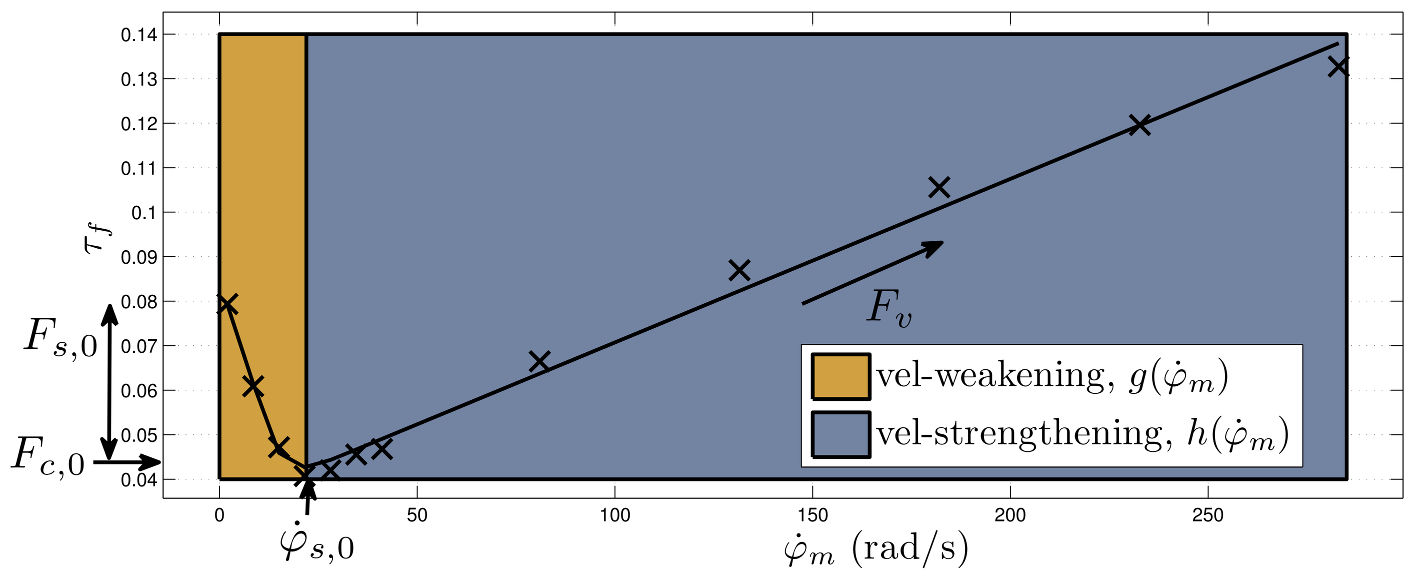
Moving *one axis at a time in steady-state velocity*, then

$$\ddot{\varphi}_a \approx 0, \quad \mathcal{C}(\varphi_a,\dot{\varphi}_a) = 0$$

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

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

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

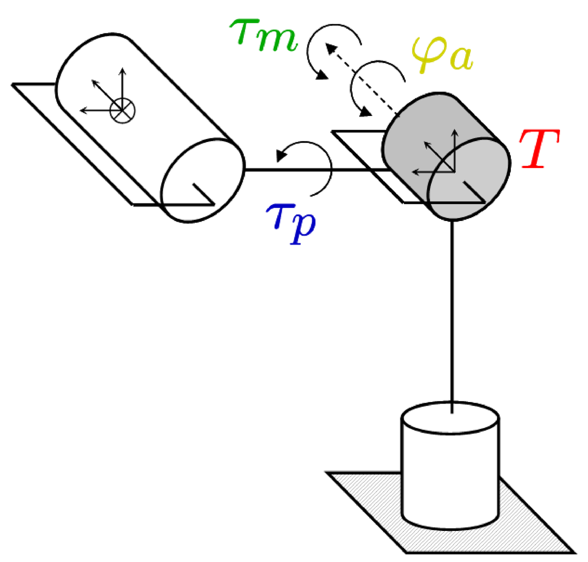


Estimated static friction curve and $\mathcal{M}_0$ model-based predictions.

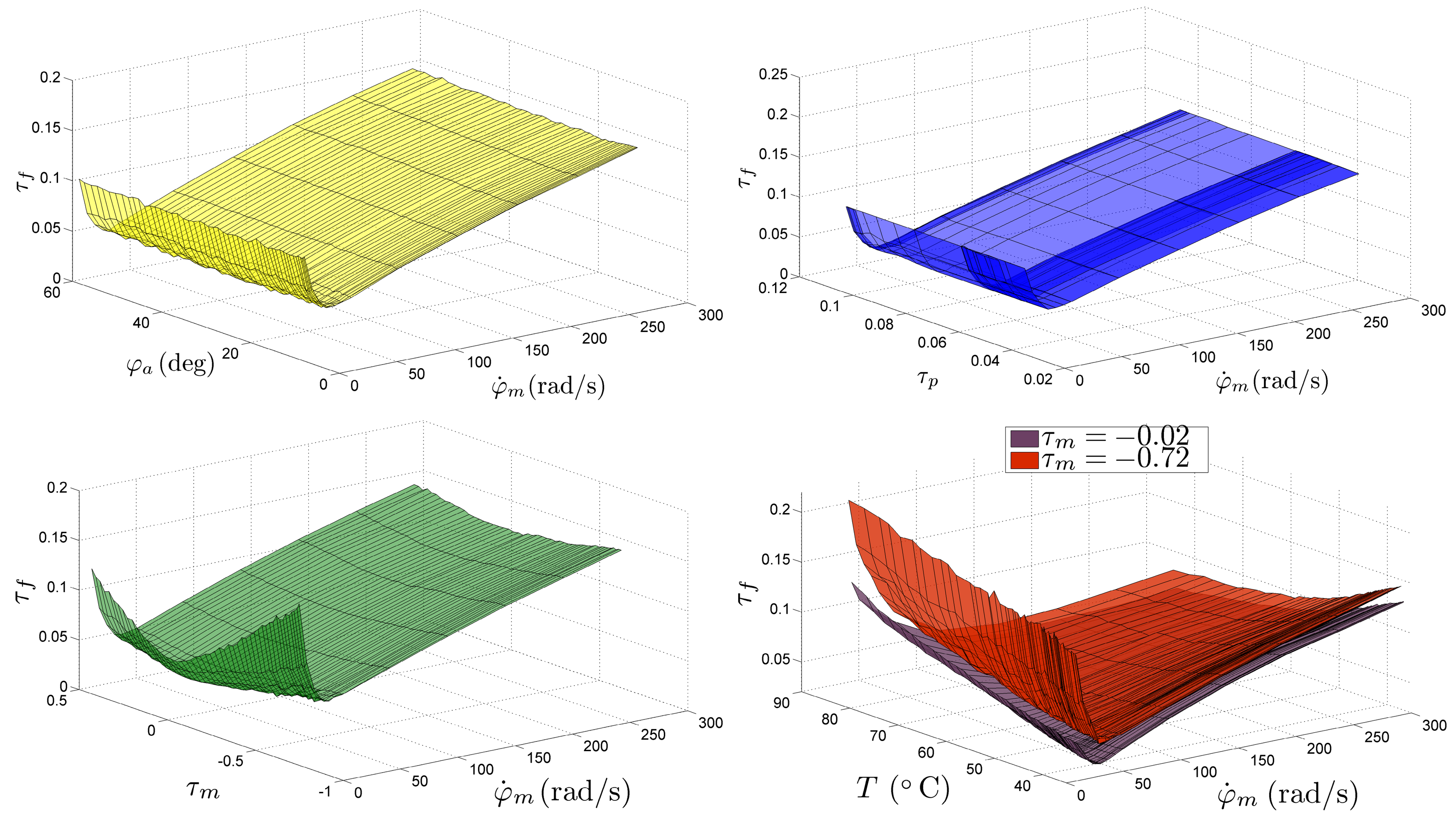
Influences Analysis

Dedicated experiments at one of the joints of a 6 axes industrial robot were taken in order to analyze the joint friction influences caused by

Position φ_a: arm positions.
Perp. load τ_p: resulting perpendicular load torque.
Manip. load τ_m: resulting manipulated load torque.
Temperature T: joint temps.



Special care was taken to *avoid combined effects* during the experiments. Using a model, a set of a configurations is chosen a priori in order to control variations of φ_a, τ_p and τ_m. Changes in T are achieved with a warm up cycle and cooling down.



Main Effects

- φ_a: no sensible effects.
- τ_p: no sensible effects (only small variations possible).
- τ_m: considerable *increase in the vel-weakening* regime.
- T: considerable *increase in the vel-weakening* regime and considerable *decrease in the vel-strengthening*.

Empirical Modeling

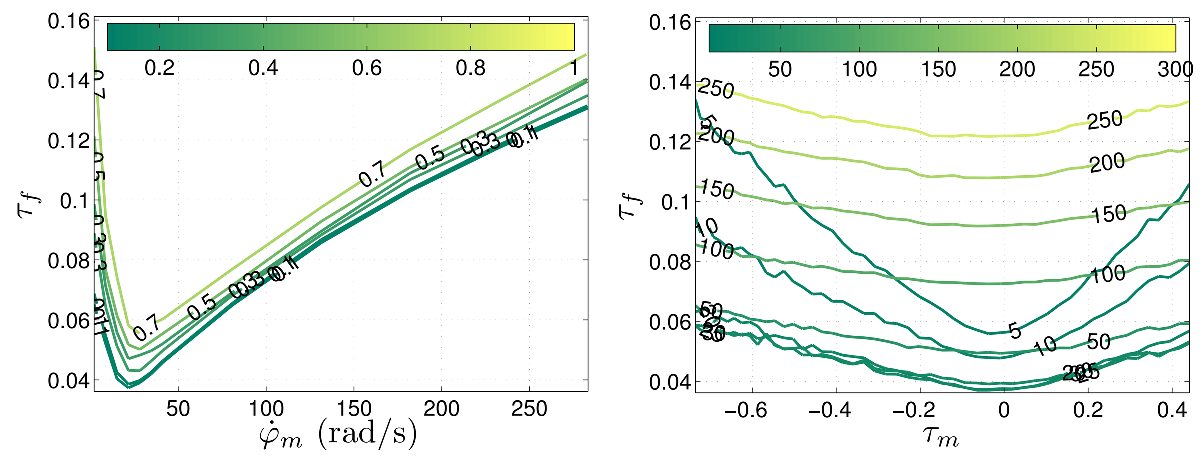
A standard parametrization of the static friction curve w.r.t. $\dot{\varphi}_m$ is

$$\tau_f(\dot{\varphi}_m) = g(\dot{\varphi}_m) + h(\dot{\varphi}_m) = \left[F_c + F_s e^{-\left|\frac{\dot{\varphi}_m}{\dot{\varphi}_s}\right|^{1.3}}\right] + \left[F_v \dot{\varphi}_m\right] \qquad (\mathcal{M}_0)$$

The effects of τ_m and T are analyzed further to argue about an extension of $\mathcal{M}_0$ that can cope with them.

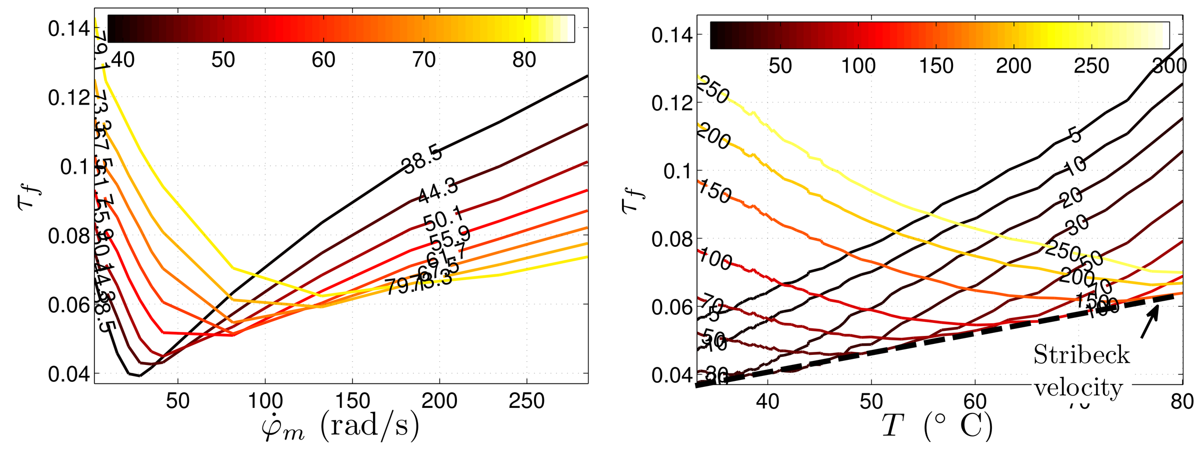
Effects of τ_m

- F_c linear inc
- F_s linear inc



Effects of T

- F_s linear inc
- $\dot{\varphi}_s$ linear inc
- F_v exp. dec



Based on the observed behavior, the extended model $\mathcal{M}^*$ is proposed

$$\tau_f(\dot{\varphi}_m,\tau_m,T) = \Big[\{F_{c,0} + F_{c,\tau_m}|\tau_m|\} + F_{s,\tau_m}|\tau_m| e^{-\left|\frac{\dot{\varphi}_m}{\dot{\varphi}_{s,\tau_m}}\right|^{1.3}} + \{F_{s,0} + F_{s,T}T\} e^{-\left|\frac{\dot{\varphi}_m}{\{\dot{\varphi}_{s,0}+\dot{\varphi}_{s,T}T\}}\right|^{1.3}}\Big] + \Big[\{F_{v,0} + F_{v,T} e^{\frac{-T}{T_{v0}}}\}\dot{\varphi}_m\Big] \qquad (\mathcal{M}^*)$$

The parameters of $\mathcal{M}^*$ are identified and it is validated over a wide operating range, reducing the average error *a factor of 6* when compared to $\mathcal{M}_0$.