A Learning Approach for Feed-Forward Friction Compensation

Viktor Johansson, viktor.johansson@astazero.com
Stig Moberg, stig.moberg@se.abb.com
Erik Hedberg, erik.hedberg@liu.se
Mikael Norrlöf, mikael.norrlof@se.abb.com
Svante Gunnarsson, svante.gunnarsson@liu.se

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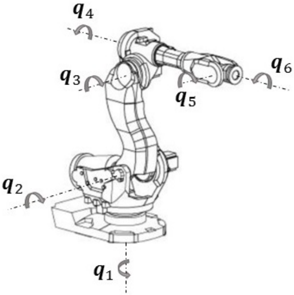
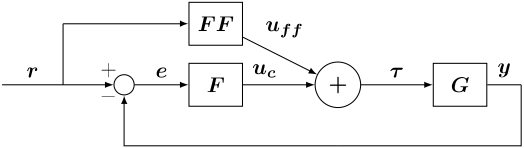
Main message

- The paper is based on the Master's thesis by Viktor Johansson.
- A comparison of two approaches for feed-forward friction compensation:
  - Grey-box friction model (LuGre) using previously identified parameters.
  - Black-box friction model using B-spline networks (BSN), where the parameters are learned from experiments.
- Experimental evaluation using a six degrees-of-freedom industrial robot.
- The two approaches give comparable performance.
- The BSN approach requires very limited a priori insight about the friction behavior.

Problem description



$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + g(q) + \tau_f(\dot{q}) = \tau$$



LuGre friction model

$$\dot{z} = v - \sigma_0 \frac{|v|}{g(v)} z$$

$$g(v) = f_c + (f_s - f_c) e^{-(v/v_s)^2}$$

$$\tau_f(v) = \sigma_0 z + \sigma_1 \dot{z} + f(v)$$

where

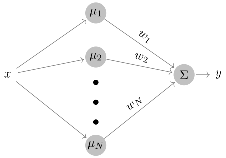
- z is the internal state.
- v is the relative velocity.
- $f(v)$ is the viscous friction. Here $f(v) = f_v v$.
- $g(v)$ captures the Coulomb and Stribeck effects.

B-spline network (BSN) friction model

General:

$$y(x) = \sum_{i=1}^{N} \mu_i(x) \cdot w_i$$

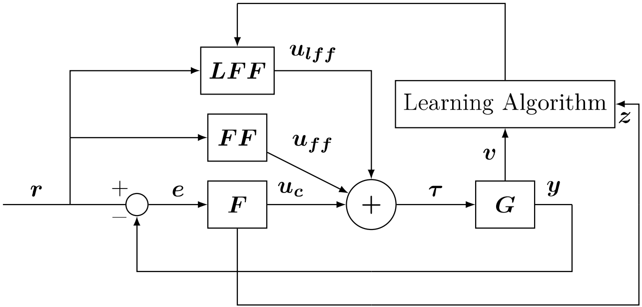
where $\mu_i(x)$ is the spline function.



Here:

$$\tau_f(v) = \sum_{i=1}^{N} \mu_i(v) \cdot w_i$$

Friction compensation using BSN



Friction compensation using BSN

The BSN is trained using

$$\Delta w_{i,j} = \gamma \frac{\sum_{k=1}^{N_s} u_{i,p}(k)\mu(\dot{q}_i^{ref}(k))}{\sum_{k=1}^{N_s} \mu(\dot{q}_i^{ref}(k))}$$

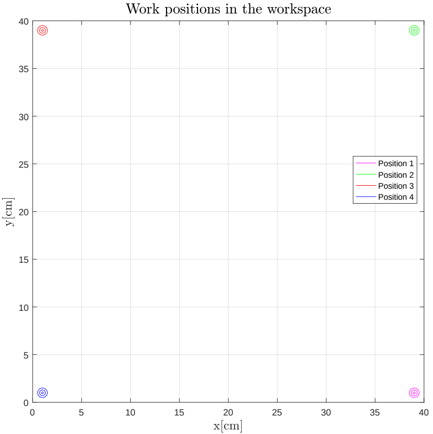
where

- i - joint number, j - spline number
- $\dot{q}_i^{ref}$ - velocity reference
- N_s - number of samples
- $u_p = u_c - u_I$ where u_c is the controller output and u_I is the integral part of the control signal

Experimental setup

- Six degrees-of-freedom experimental robot.
- Four operating points located in the corners of a square of the size 40×40 cm.
- Circular motions with radii $1, 3$ and 5 mm respectively.
- TCP velocities $10, 40$ and 100 mm/s respectively. Here: Only TCP velocity 40 mm/s.
- The learning process was run for ten iterations using $\gamma = 0.95$.
- A suitable number and distribution of the knots in the BSN was selected. A denser distribution was used for low velocities.
- The learning procedure was carried out for each of the three selected TCP velocities.
- Extended version where two different networks were trained and used depending on the sign of the angular acceleration.

Experimental setup



Results - Maximum TCP deviation

No feed-forward:

	Pos. 1	Pos. 2	Pos. 3	Pos. 4
Circ. r1	0.5	0.63	0.91	0.58
Circ. r3	0.41	0.35	0.38	0.46
Circ. r5	0.31	0.28	0.35	0.36

Feed-forward using static LuGre model:

	Pos. 1	Pos. 2	Pos. 3	Pos. 4
Circ. r1	0.48	0.52	0.93	0.59
Circ. r3	0.2	0.3	0.32	0.23
Circ. r5	0.14	0.25	0.18	0.2

Feed-forward using BSN model:

	Pos. 1	Pos. 2	Pos. 3	Pos. 4
Circ. r1	0.47	0.61	0.86	0.53
Circ. r3	0.17	0.3	0.4	0.2
Circ. r5	0.17	0.21	0.24	0.19

Results - RMS of TCP deviation

No feed-forward:

	Pos. 1	Pos. 2	Pos. 3	Pos. 4
Circ. r1	0.362	0.324	0.41	0.343
Circ. r3	0.187	0.188	0.206	0.209
Circ. r5	0.12	0.141	0.14	0.147

Feed-forward using static LuGre model:

	Pos. 1	Pos. 2	Pos. 3	Pos. 4
Circ. r1	0.307	0.263	0.378	0.28
Circ. r3	0.109	0.133	0.133	0.117
Circ. r5	0.066	0.115	0.084	0.083

Feed-forward using BSN model:

	Pos. 1	Pos. 2	Pos. 3	Pos. 4
Circ. r1	0.263	0.264	0.377	0.25
Circ. r3	0.099	0.131	0.145	0.112
Circ. r5	0.085	0.106	0.088	0.093

Observations

- Larger error for smaller radii.
- Variations in performance between the four positions.
- Comparabel performance of the two approaches:
  - Average max error for r5 over the four positions: 0.1925 for LuGre and 0.2025 for BSN.
  - Average max error for r3 over the four positions: 0.2625 for LuGre and 0.2675 for BSN.
  - Average max error for r1 over the four positions: 0.63 for LuGre and 0.6175 for BSN.

Observations (cont.)

Reduction of the MSE for feed-forward using static LuGre model:

	Pos. 1	Pos. 2	Pos. 3	Pos. 4
Circ. r1	-15 %	-19 %	-8 %	-18%
Circ. r3	-42 %	-29 %	-35 %	-44 %
Circ. r5	-45 %	-18 %	-40 %	-44 %

Reduction of the MSE for feed-forward using BSN:

	Pos. 1	Pos. 2	Pos. 3	Pos. 4
Circ. r1	-27 %	-19 %	-8 %	-27 %
Circ. r3	-47 %	-30 %	-30 %	-46 %
Circ. r5	-29 %	-25 %	-37 %	-37 %

Summary

- A comparison of two approaches for feed-forward friction compensation:
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Further work:

- Additional experiments.
- “Fair” comparison of the time and efforts needed for the two methods.

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