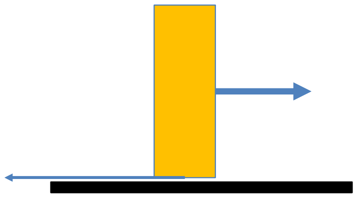
Friction

A brief introduction to «Tribology»



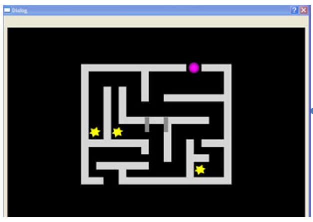
Haptic Human Robot Interfaces

(HHRI) 2024

Dr Mohamed Bouri

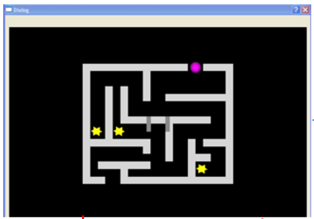
From interface to interaction

From control interfaces to haptic interfaces

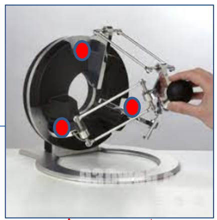


Positions
X, Y

A control interface
Controls the target position X and Y of the target in the virtual environment.



Positions
X, Y



Force X

Force Y

A haptic interface
Controls the target position X and Y of the target in the virtual environment. Thanks to the **actuators**, it **reflects** a force feedback Fx and Fy.

● actuator

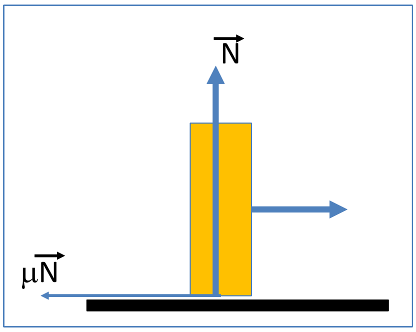
Haptic Interaction

is a bidirectional behavior

From the human hand
to the device **positions**

From the device to the human hand: **Forces**

What do you know about friction ?

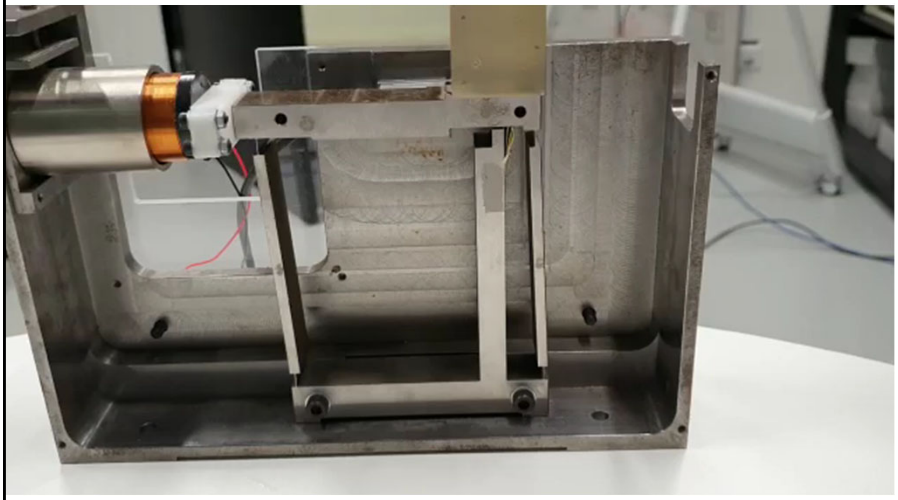


- Opposes to the movement
- Proportional to the normal contact force.
- Related to contact and thus present in mechanical transmissions
  - Depends on the type of transmission (screws, belts, cables)

  What is about guideways ?

EPFL 5

Is it possible to realize a frictionless actuation?



A flexible hinges guideway and a voice coil actuator.

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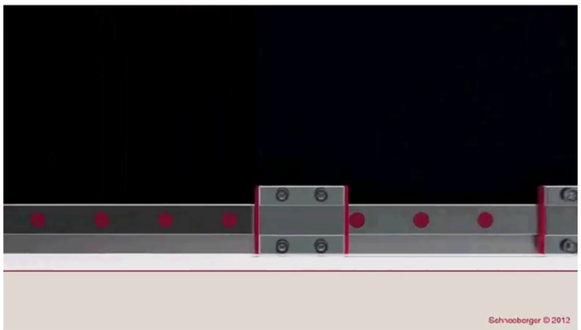
Reducing friction in guideways and screw transmissions?



Using recirculating-ball principle

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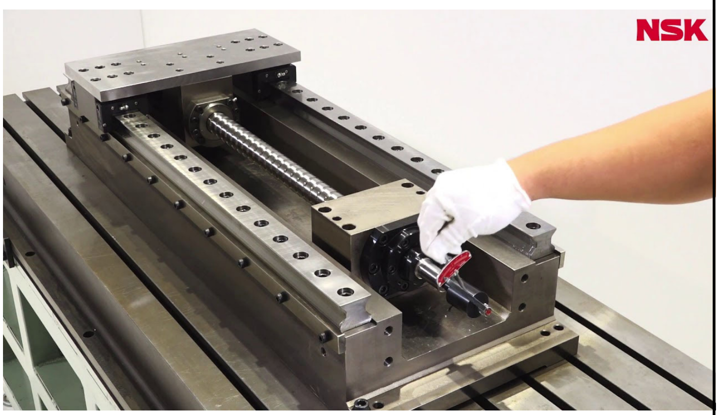
What do you know about friction ?

- Screw-Nut system….
  Friction appears in misalignment !

- Also present between the carriage and the rail



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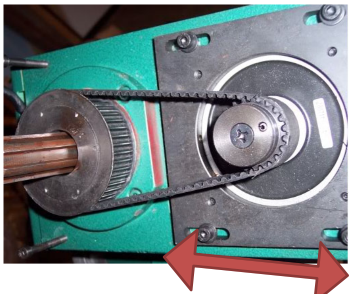
- Belt driven transmissions

Simple method for belt pretention

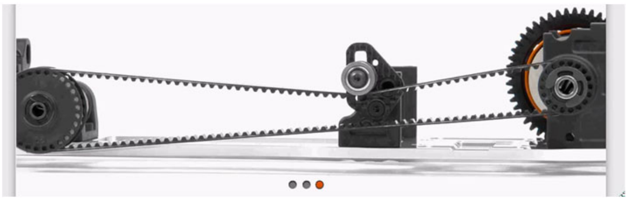
Higher is the pretention, higher is the friction

Pull the motor to pretention the belt



Pull the motor to pretention the belt

Using a pretensioner



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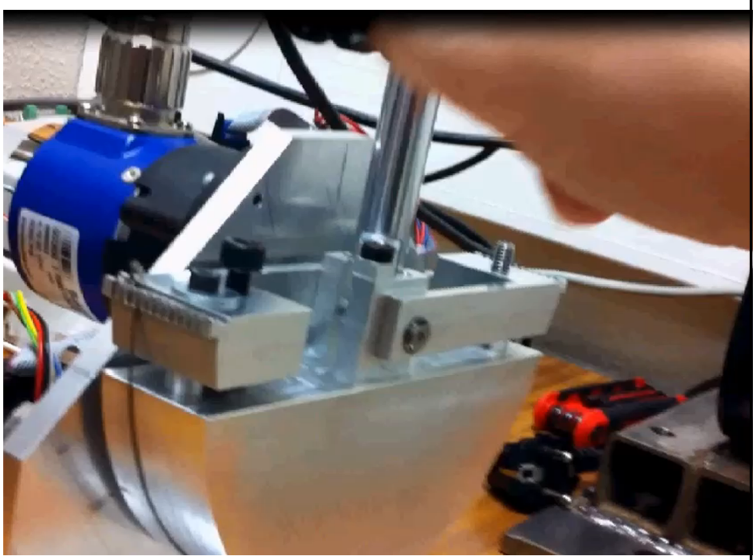
Cable transmission



- Stiffer compared to belts
- Has to be moored and pretentioned
- Efficient

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Friction opposes to the movement

- *Is friction Bad ?*

Friction forces assure contact and prevent the objects from falling or slipping !

EPFL 11

Do you all agree about what has been said ?

- Is friction constant ?
- There are 2 kinds of friction… **Dry** and **Viscous** –
  The one that has been introduced concerns only dry friction
- How is the friction characterized? (Friction models)

EPFL 12

Why understanding friction and its models ?

- To improve the implementation of motion and mechanical transmissions –

- To make the design of controllers more effective. using analytical friction models.

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Use case : spherical joints of the robot Delta

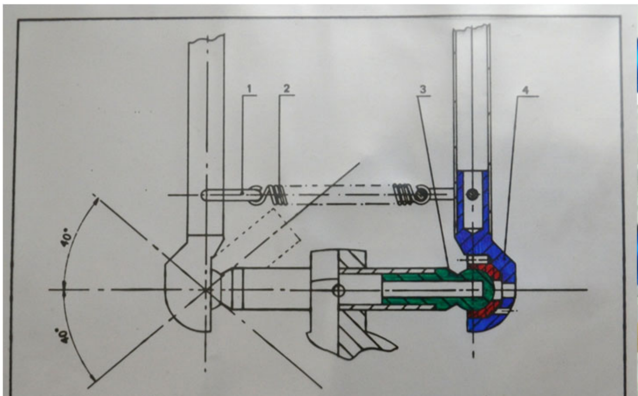
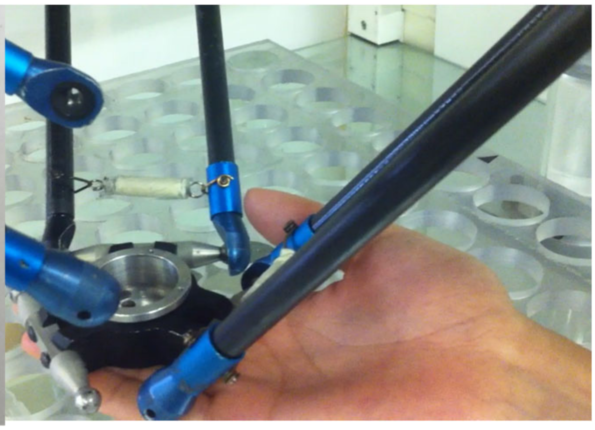


Fig.5. Detail of the construction of the arm - parallelogram joint.



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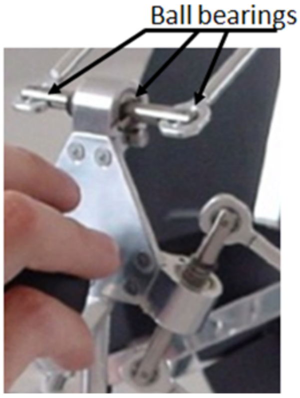
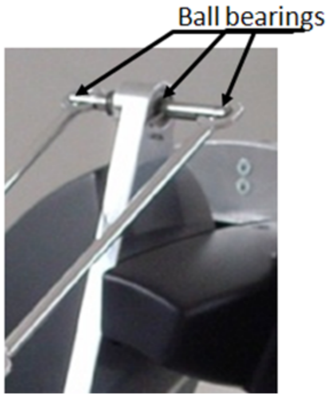
Use case


How to reduce friction in mechanical transmission ?


How to reduce friction while keeping big torques ?

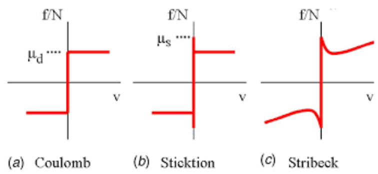
Robot Omega from Force Dimension (Nyon) for haptic feedback and tele-manipulation uses cable transmision





EPFL [Force dimension, CH, http://www.forcedimension.com/]

Standard reference for Friction Modelling: « Lund – Grenoble model » LuGre



(*)

C. **Canudas de Wit**, H. Olsson, **Karl Johann Åström**, P. Lischinsky. Dynamic friction models and control design. *Proc. 1993 American Control Conference, San Francisco, California*, pp 1920–1926, 1993

C. Canudas de Wit, Olsson, **Åström**, Lischinsky: A new model for control of systems with friction. *IEEE Trans. Automatic Control*, **40**(3):419–425, March 1995

H. Olsson. ***Control Systems with Friction.*** **PhD thesis**, Department of Automatic Control, Lund Institute of Technology, Lund, Sweden, 1996, http://www.control.lth.se/publications/.

(*) Do, N. B (2007). Efficient simulation of a dynamic system with LuGre friction. J Comp and non lin Dyn

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(LuGre suite, No 2)

Friction Models & Friction Compensation

Olson, Åström, Canudas de Wit, Gäfert, Lischinsky,

European Journal of Control (**1998**) 4, pp 176-195

This paper reviews friction phenomena and friction models of interest for automatic control. Emphasis is given to two recent dynamic friction models: the Bliman-Sorine model and the LuGre model. They capture many frictional phenomena observed experimentally. Methods for friction compensation are illustrated with practical experiments.

EPFL 17

"**Review and comparison of dry friction force models**." Pennestrì, Ettore, et al. *Nonlinear dynamics* 83.4 (**2016**): 1785-1801.

Another important review about friction models

EPFL 18

(LuGre No 3)

Revisiting the LuGre friction model, Stick-slip motion and rate dependence, Karl Johan Åström, Carlos Canudas de Wit - IEEE Control Systems Magazine, 2008, **28** (6), pp.101-114.

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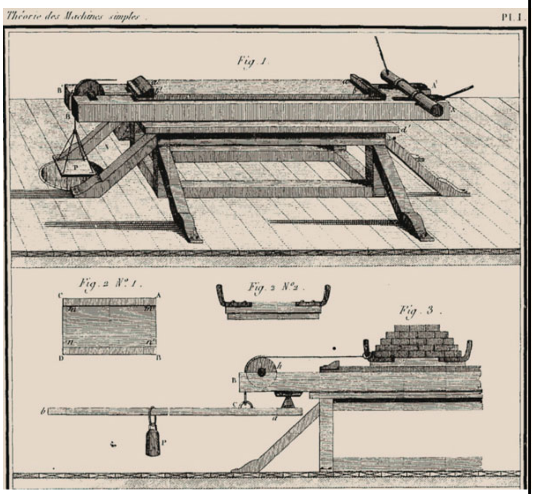
Amontons-Coulomb Paradox

Guillaume Amontons 1663 – 1705, physicien français

Friction force is proportional to normal load, but (surprisingly) **independent of** the apparent contact area.

True contact area= effective area in contact, << apparent (geometric) contact area



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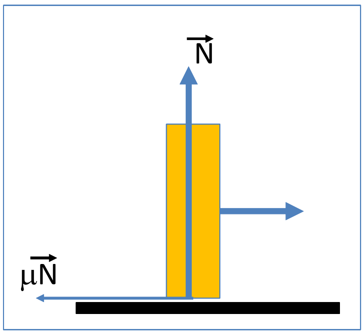
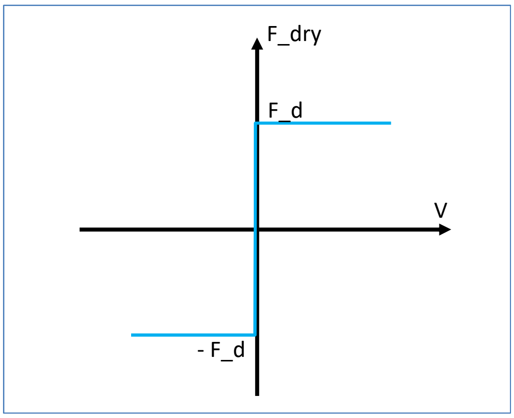
Coulomb Friction (Dry Friction, simplest model)

Charles-Augustin Coulomb 1736 - 1806





Independent of velocity
(sign opposed to velocity)

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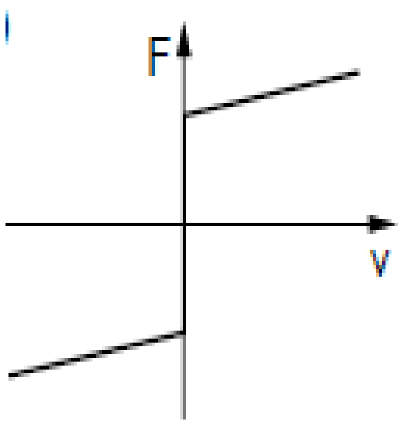
Viscous Friction

Proportional to velocity, opposed to it

(air, water, oil)

Combination of Coulomb friction
and viscous effect: Very coarse
(linear portions
do not go through zero)



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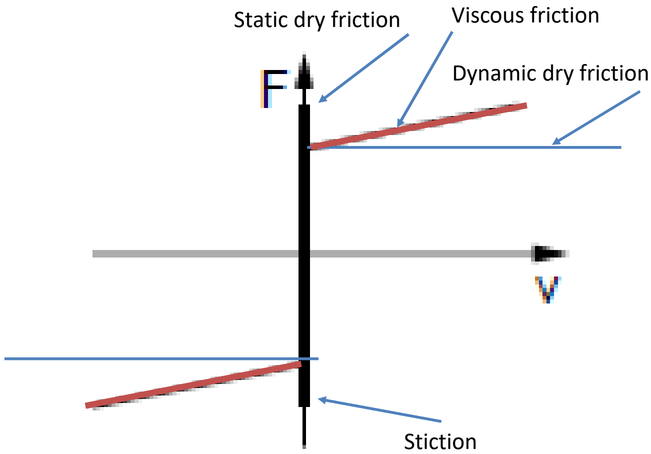
Dry friction with Stiction effect:
Friction that prevents from the start of moving
(« stick – slip effect »)

Stiction = Adhérence = Haftreibung
(no relative motion)

The value of the **break-away force** is often not at all repetitive!

Again, very coarse model!



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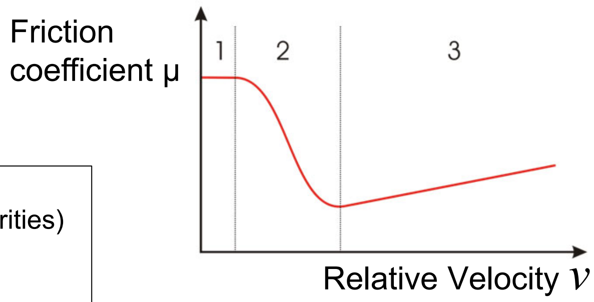
Stribeck Effect

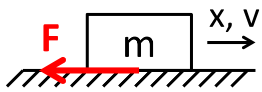
Richard Stribeck, 1861 – 1950; Krupp, Bosch

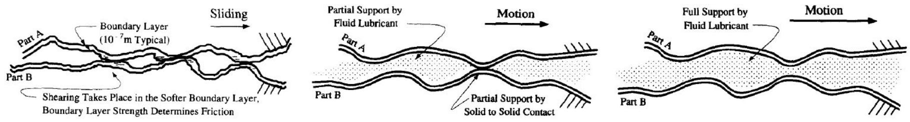


Phase 1: Boundary Lubrication (Load mainly on asperities)
Phase 2: Mixed Lubrication (Solid contact & Lubrication)
Phase 3: Hydrodynamic (viscous damping)

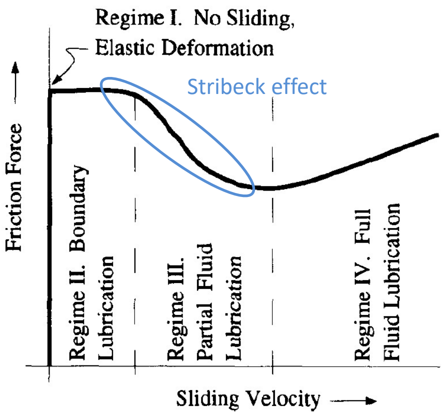
EPFL 24

Stribeck Effect

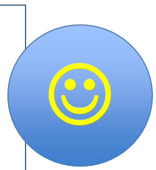




(a) Boundary lubrication (b) Partial fluid lubrication (c) Full fluid lubrication



In a BBC radio program, tribology pioneer F. P. Bowden observed that "putting two solids together is rather like turning Switzerland upside down and standing it on Austria--the area of intimate contact will be small" (Bowden, 1950).

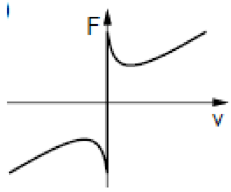


Armstrong-Hélouvry et al, 1994

Combination incl. Stribeck approximation

$F_{ss}(v)$ = steady-state force:

$$F_{ss}(v) = g(v)\,sgn(v) + f(v)$$



$f(v) = c\,\dot{v}$, $g(v)$ = Coulomb friction, F_c & Stribeck effect:

$$g(v) = F_c + (F_s - F_c)e^{-|v/v_s|^{\alpha}}$$

F_c = Stiction v_s = determines minimum of Stribeck effect, $0.5 < \alpha < 2$

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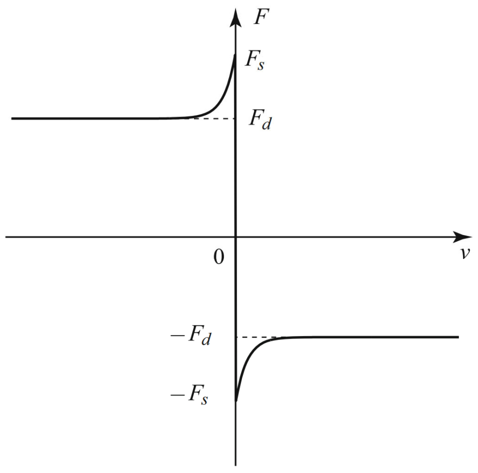
Benson Model

Benson, D.J., Hallquist, J.O., Comput. Method Appl. Mech. Eng. (1990)



Benson exponential friction model

$$F = -F_d - (F_s - F_d)e^{-c|v|}\,\mathrm{sgn}(v)$$

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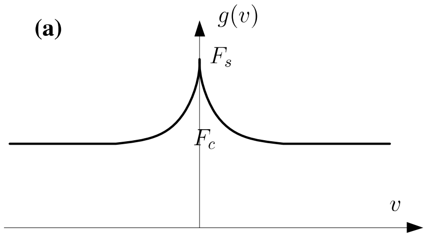
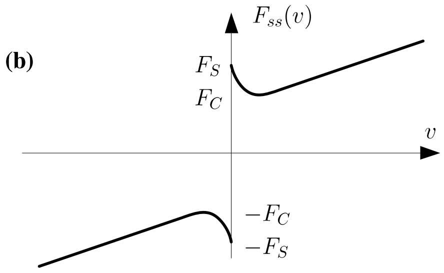
Combination incl. Stribeck approximation

$$F_{ss}(v) = g(v)sgn(v) + f(v)$$

$$g(v) = F_c + (F_s - F_c)e^{-|v/v_s|^{\alpha}}$$





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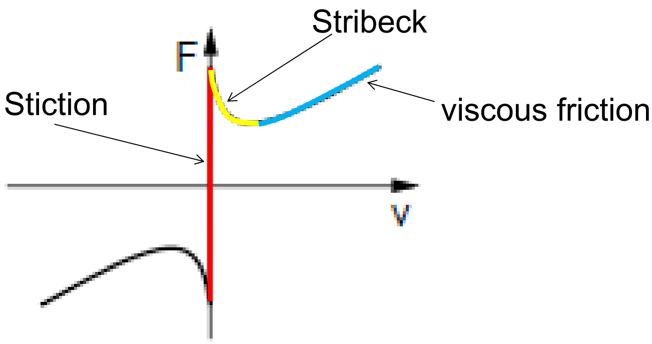
Combination of all these effects

(Summary)



But: Still completely time-independent!
(no « memory » effect)

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More Details:

Publications by K J Åström, Lund-Grenoble group, or:

« **Robot Applications** » 2014
Korondi, Halas, Samu, Bojtos, Tamás, (Chapt. 8)

http://www.mogi.bme.hu/TAMOP/robot_applications/

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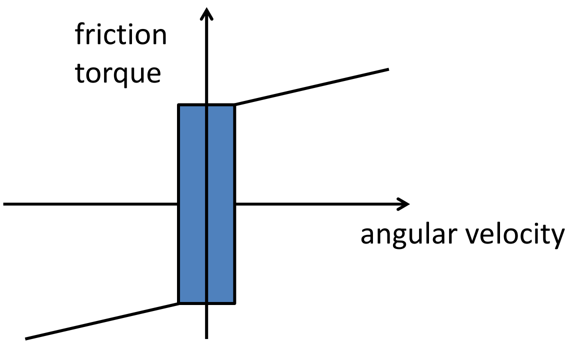
Lab implementation

Problem of implementation to friction compensation

- Time dependence (Hysteresis, memory)
- Exact Zero velocity : hard to detect in reality

=> Stiction defined within a small rectangle around zero velocity



Case 4: PD-controller in presence of viscous and dry friction

In this case, the dynamic model is expressed by the following equation:

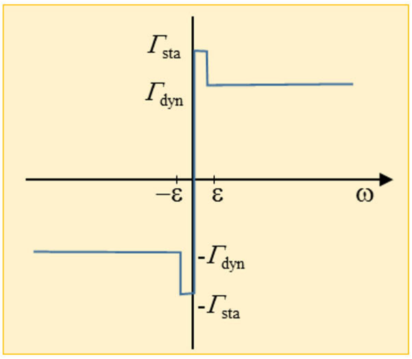
$$\sum \Gamma = J_{Rm}\ddot{\theta}_m = \Gamma_m - \Gamma_{\text{dry}} \quad (16)$$

The model of the dry friction is given by the following characteristic

The dry friction torque has two characteristic values:

The **static dry friction** corresponding to the value of the dry torque before the starting of the movement ($|\omega| < \varepsilon$).

The **dynamic dry friction** corresponding to the value of the dry torque when motion is occurring and ($|\omega| > \varepsilon$)



$$\sum \Gamma = J_{Rm}\ddot{\theta}_m = k_p(\theta_d - \theta_m) - k_D\dot{\theta}_m - k_{vis}\dot{\theta}_m - \Gamma_{dry} \quad (17)$$

To understand what happen in the static phase, we only need to cancel the first and second derivatives of the desired and measured positions.

$$\dot{\theta} \to 0, \quad \dot{\theta}_d \to 0 \quad \ddot{\theta} \to 0 \; and \; \ddot{\theta}_d \to 0$$

$$\sum \Gamma = \underbrace{J_{Rm}\ddot{\theta}_m}_{0} = k_p\underbrace{(\theta_d - \theta_m)}_{\varepsilon_{sta}} - \underbrace{k_D\dot{\theta}_m}_{0} - \underbrace{k_{vis}\dot{\theta}_m}_{0} - \Gamma_{dry} \quad (18)$$

$$\Rightarrow k_p\underbrace{(\theta_d - \theta_m)}_{\varepsilon_{sta}} = \Gamma_{dry}$$

The static error ε_{sta} may then be expressed as follows:

$$\varepsilon_{sta} = \frac{\Gamma_{dry}}{k_p} \quad (19)$$

PD (KB) implementation does not compensate friction!

Using a PID-position controller :

The PID control law is given by:

$$\Gamma_m = \boldsymbol{k_p}(\theta_d - \theta_m) - \boldsymbol{k_d}\dot{\theta}_m + \boldsymbol{k_I}\int_0^t(\theta_d - \theta_m)dt \qquad (20)$$

Closing the loop of the system (eq.16) by using the PID control law (eq.20) and using the s-transform leads to the following behavior:

$$J_{Rm}s^2\theta_m = k_p(\theta_d - \theta_m) - s\,k_D\theta_m + \frac{k_I}{s}\theta_d - \frac{k_I}{s}\theta_m - \Gamma_{dry} \qquad (21)$$

Below, eq.21 is rewritten in a very interesting manner ☺.

$$\left(J_{Rm}s^2 + k_D s + k_p + \frac{k_I}{S}\right)\theta_m = \left(k_p + \frac{k_I}{S}\right)\theta_d - \Gamma_{dry}$$

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Using a PID-position controller :

What happen in the static phase?

Regarding previous analysis, we demonstrated that the static error reaches the zero-value. The closed loop behavior may be represented by the (eq. 23) or by the following temporal representation:

$$J_{Rm}\ddot{\theta}_m = k_p\varepsilon - k_D\dot{\theta}_m + k_I\int_0^t \varepsilon(\tau)d\tau - \Gamma_{dry} \qquad (24)$$

⍰ is the regulation error.

In the static phase, $\dot{\theta}_m = \ddot{\theta}_m = \dot{\theta}_d = \ddot{\theta}_d = 0$. This leads to the following **very important** equality:

$$\boldsymbol{k_I\int_0^t \varepsilon(\tau)d\tau = \Gamma_{dry}} \qquad (25)$$

The integrator estimates the dry friction value !

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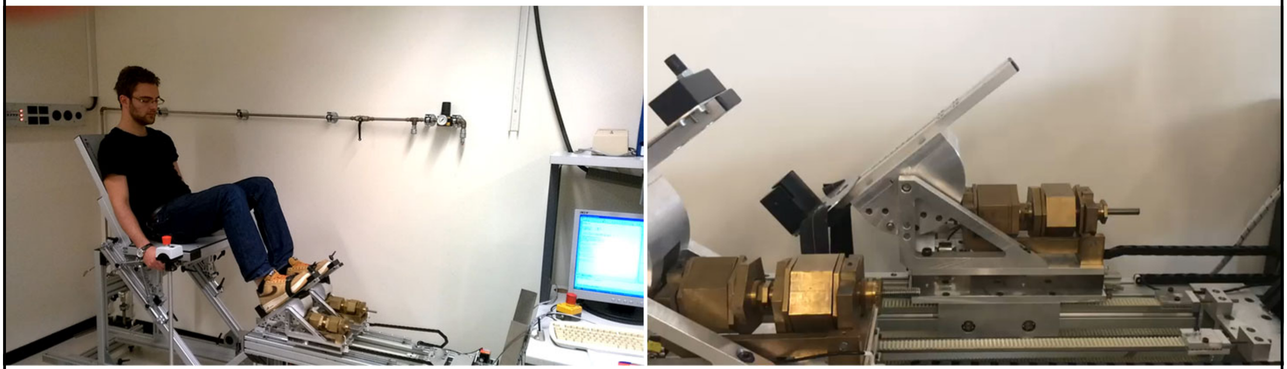
Why « Friction compensation »?



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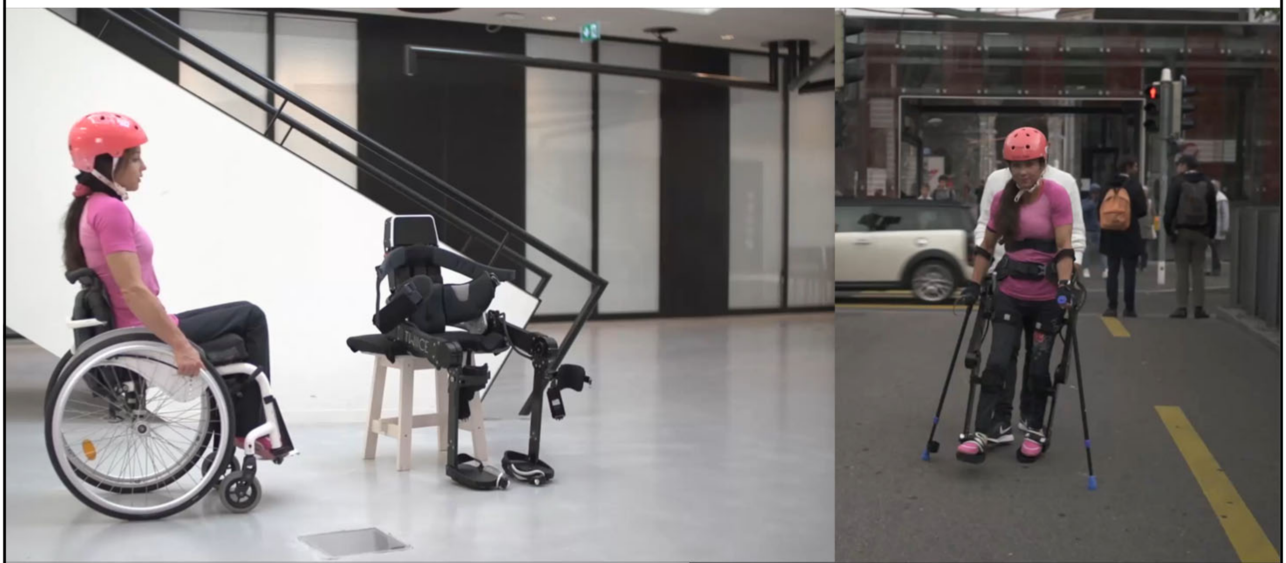
In Full mobilization

TWIICE-One 2018



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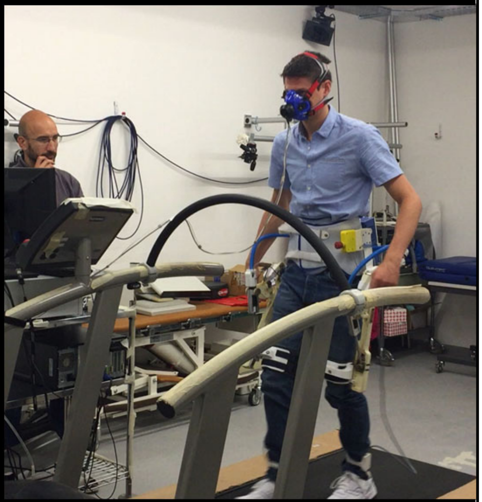
Partial assistance

Autonomyo: 3 DoF / leg



Why « Friction compensation »?

Why « Friction compensation »?

- Example of haptic-like Human-Machine Interaction: Exoskeletons
- Assistive exoskeletons for users who can move (normally **or** at reduced capacity)
- First step: **Transparency!**
- Not trivial at all!

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Transparency

- Compensate
  - weight (gravity)
  - inertia (linear, angular, centrifugal, coriolis)
  - friction!
- Weight and inertia easy to model analytically, reproducable
- Can be compensated « straight forward »
- **Friction: VERY hard to model (NL etc.)**
  & not repetitive at all !

An engineering Science: Tribology

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