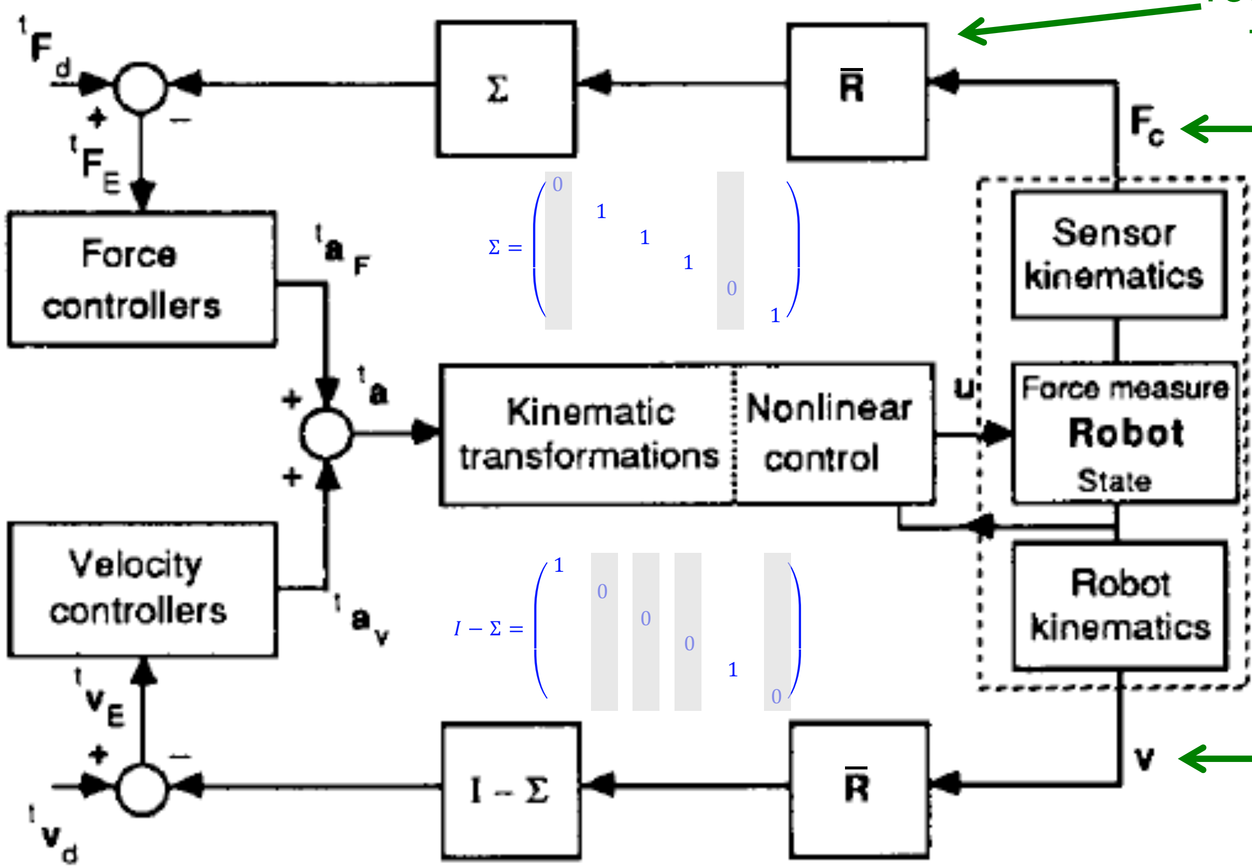
Block diagram of hybrid control

simpler case of 0/1 selection matrices

compact notation in this slide

$$F = \begin{pmatrix} f \\ \mu \end{pmatrix} \qquad V = \begin{pmatrix} v \\ \omega \end{pmatrix} \qquad \bar{R} = \begin{pmatrix} R & 0 \\ 0 & R \end{pmatrix}$$



$$\Sigma = \begin{pmatrix} 0 & & & & & \\ & 1 & & & & \\ & & 1 & & & \\ & & & 1 & & \\ & & & & 0 & \\ & & & & & 1 \end{pmatrix} \qquad I - \Sigma = \begin{pmatrix} 1 & & & & & \\ & 0 & & & & \\ & & 0 & & & \\ & & & 0 & & \\ & & & & 1 & \\ & & & & & 0 \end{pmatrix}$$

rotation matrices to task frame RF_t

in base frame RF_0

in sensor frame RF_s

in base frame RF_0

λ and $\dot{s}$ are just single components of f (or μ) and v (or ω)

Y and T are replaced by 0/1 selection matrices: Σ and $\mathrm{I} - \Sigma$

illustrated here for example 1, slide #5 (discarding **zero** columns to get Y and T)

Force control via an impedance model

- in a force-controlled direction of the hybrid task space, when the contact stiffness is limited (i.e., far from infinite, as assumed in the ideal case), one may use impedance model ideas to explicitly control the contact force
  - let x be the position of the robot along such a direction, x_d the (constant) contact point, $k_s > 0$ the contact (viz., sensor) stiffness, and $f_d > 0$ the desired contact force
- the impedance model is chosen then as

$$m_m \ddot{x} + d_m \dot{x} + k_s(x - x_d) = f_d$$

where the force sensor measures $f_s = k_s(x - x_d)$, and only $m_m > 0$ and $d_m > 0$ are free model parameters

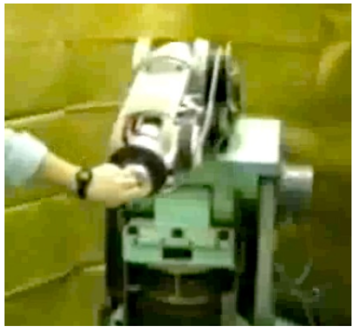
- after feedback linearization ($\ddot{x} = a_x$), the command a_x is designed as

$$a_x = (1/m_m)[(f_d - f_s) - d_m \dot{x}]$$

which is a P-regulator of the desired force, with velocity damping

- the same control law works also before the contact ($f_s = 0$), guaranteeing a steady-state speed $\dot{x}_{ss} = f_d/d_m > 0$ in the approaching phase

First experiments with hybrid control



video

video

MIMO-CRF robot
(DIS, Laboratorio di Robotica, 1991)

Sources of inconsistency
in force and velocity measurements

1. presence of friction at the contact
   - ➜ a reaction force component appears that opposes motion in a "free" motion direction (in case of Coulomb friction, the tangent force intensity depends also on the applied normal force ...)
2. compliance in the robot structure and/or at the contact
   - ➜ a (small) displacement may be present also along directions that are nominally "constrained" by the environment

NOTE: if the environment geometry at the contact is perfectly known, the task inconsistencies due to 1. and 2. on parameters s and λ are already filtered out by the pseudo-inversion of matrices T and Y

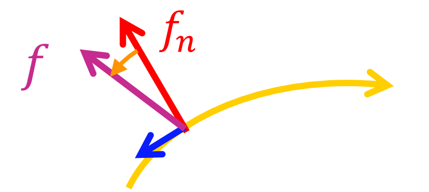
3. uncertainty on environment geometry at the contact
   - ➜ can be reduced/eliminated by real-time estimation processes driven by external sensors (e.g., vision –but also force!)

Estimation of an unknown surface

how difficult is to estimate the unknown profile of the environment surface, using information from velocity and force measurements at the contact?

1. normal = nominal direction of measured force

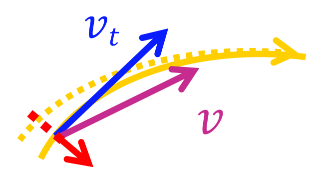
   ... in the presence of contact motion with friction, the measured force f is slightly rotated from the actual normal by an (unknown) angle γ



$f_t = \rho f_n = \tan\gamma\, f_n \neq 0$

2. tangent = nominal direction of measured velocity

   ... compliance in the robot structure (joints) and/or at the contact may lead to a computed velocity v having a small component along the actual normal to the surface

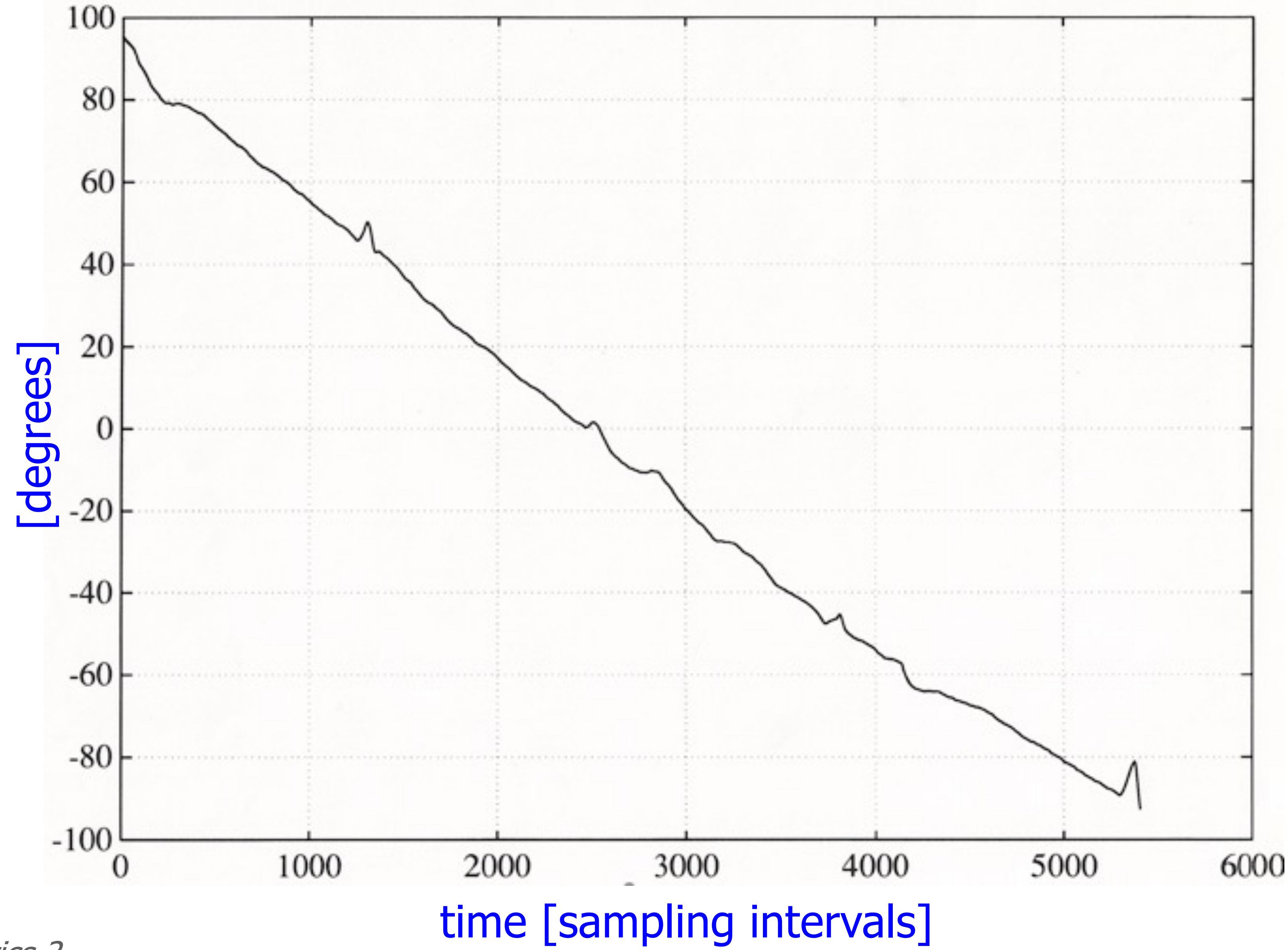


3. mixed method (sensor fusion) with RLS
   a. tangent direction is estimated by a recursive least squares method from position measurements
   b. friction angle is also estimated by a recursive least squares method, using the current estimate of the tangent direction and from force measurements

to approach an unknown surface or to recover contact (in case of loss), the robot uses simple exploratory moves

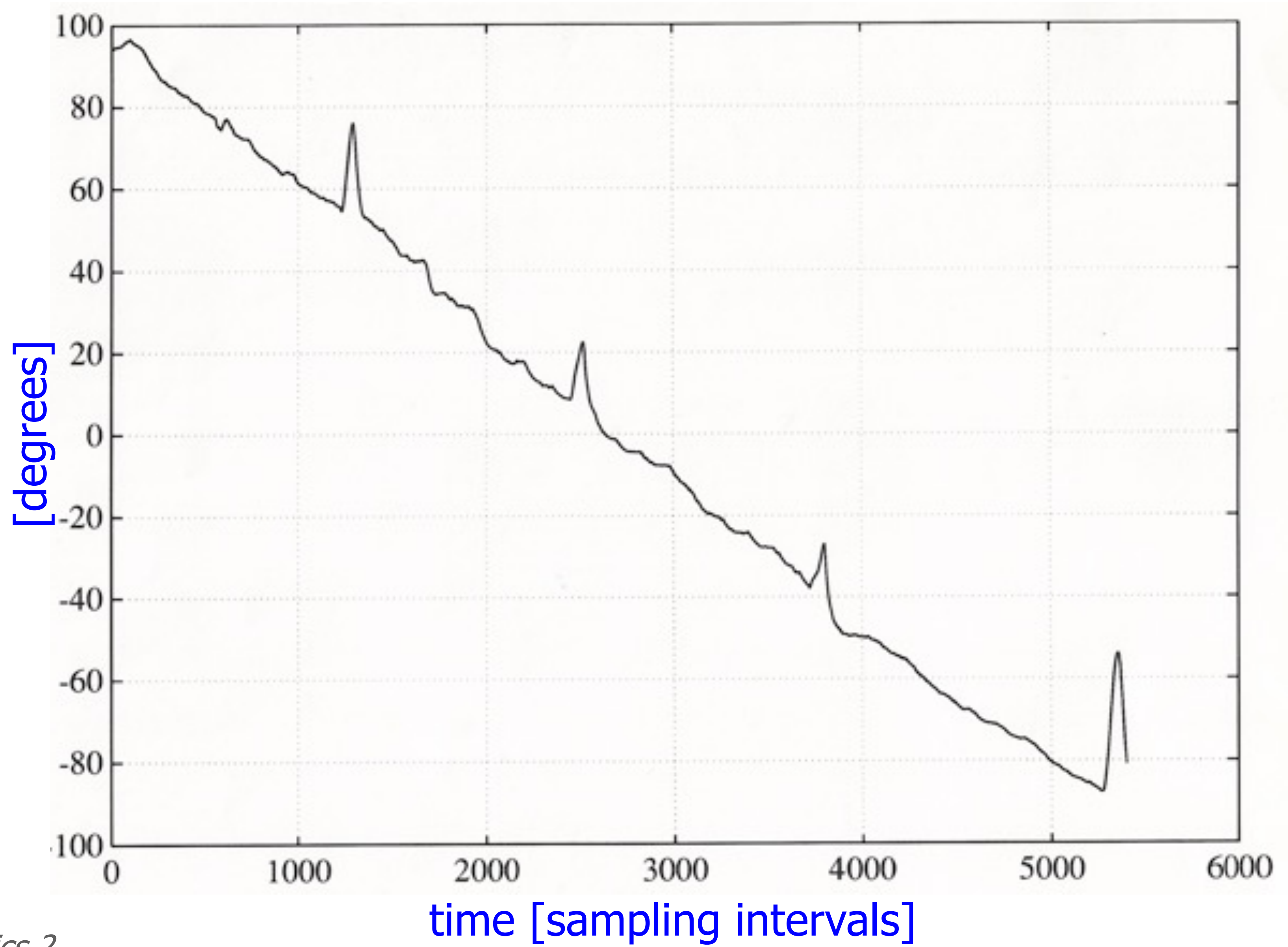
Position-based estimation of the tangent

(for a circular surface traced at constant speed)

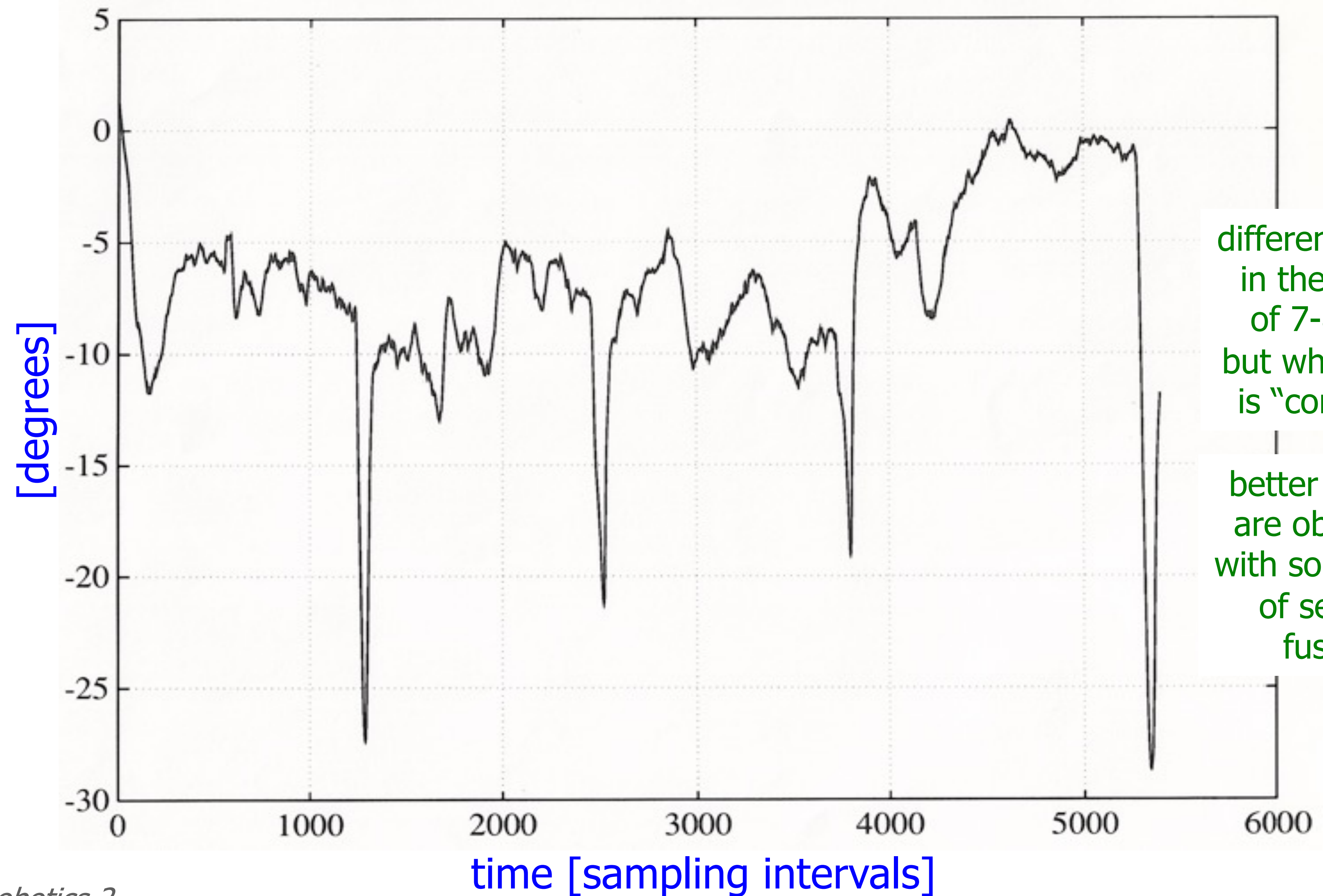


Force-based estimation of the tangent

(for the same circular surface traced at constant speed)



Difference between estimated tangents

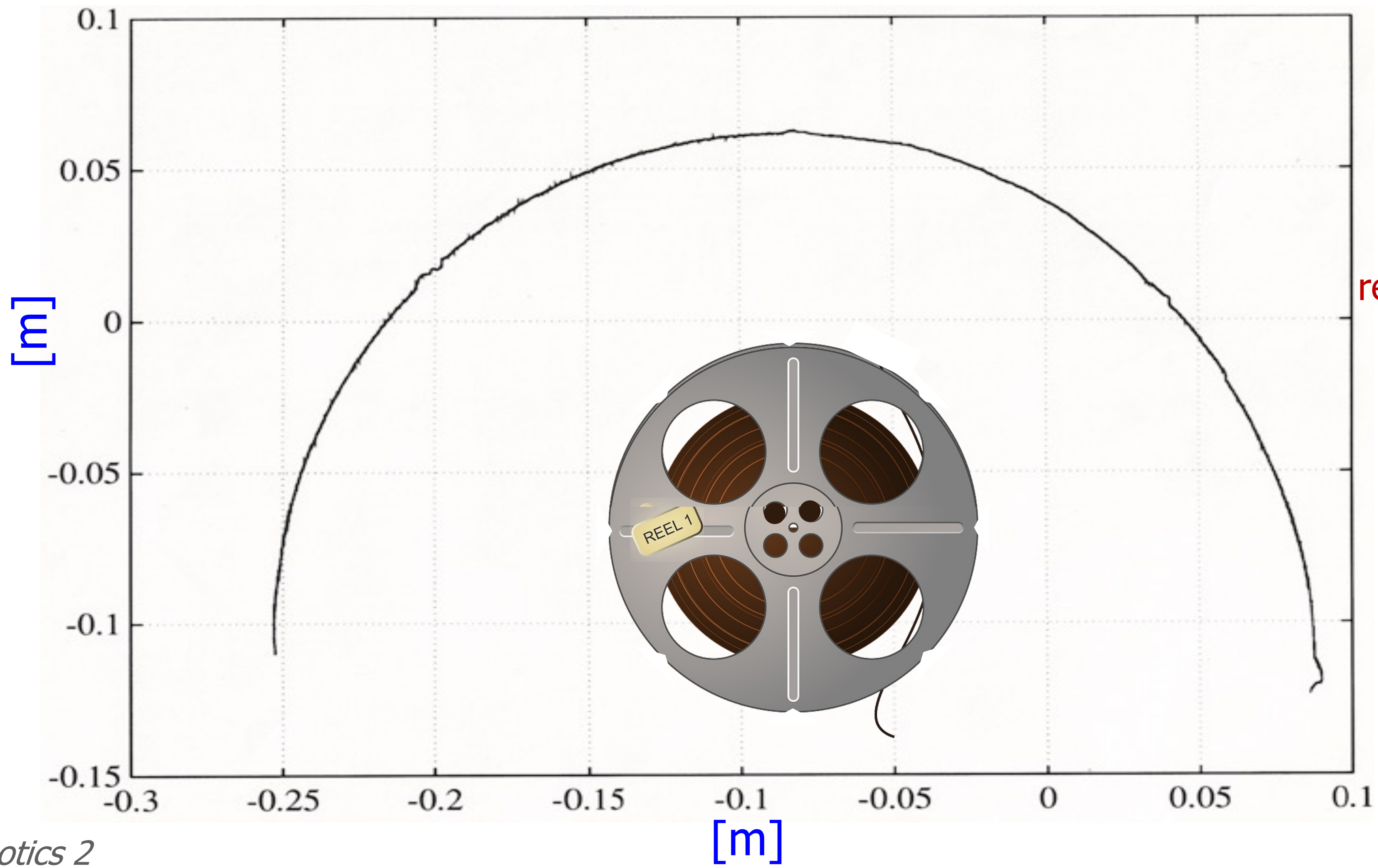


differences are in the order of 7-8° ... but which one is "correct"?

better results are obtained with some kind of sensor fusion

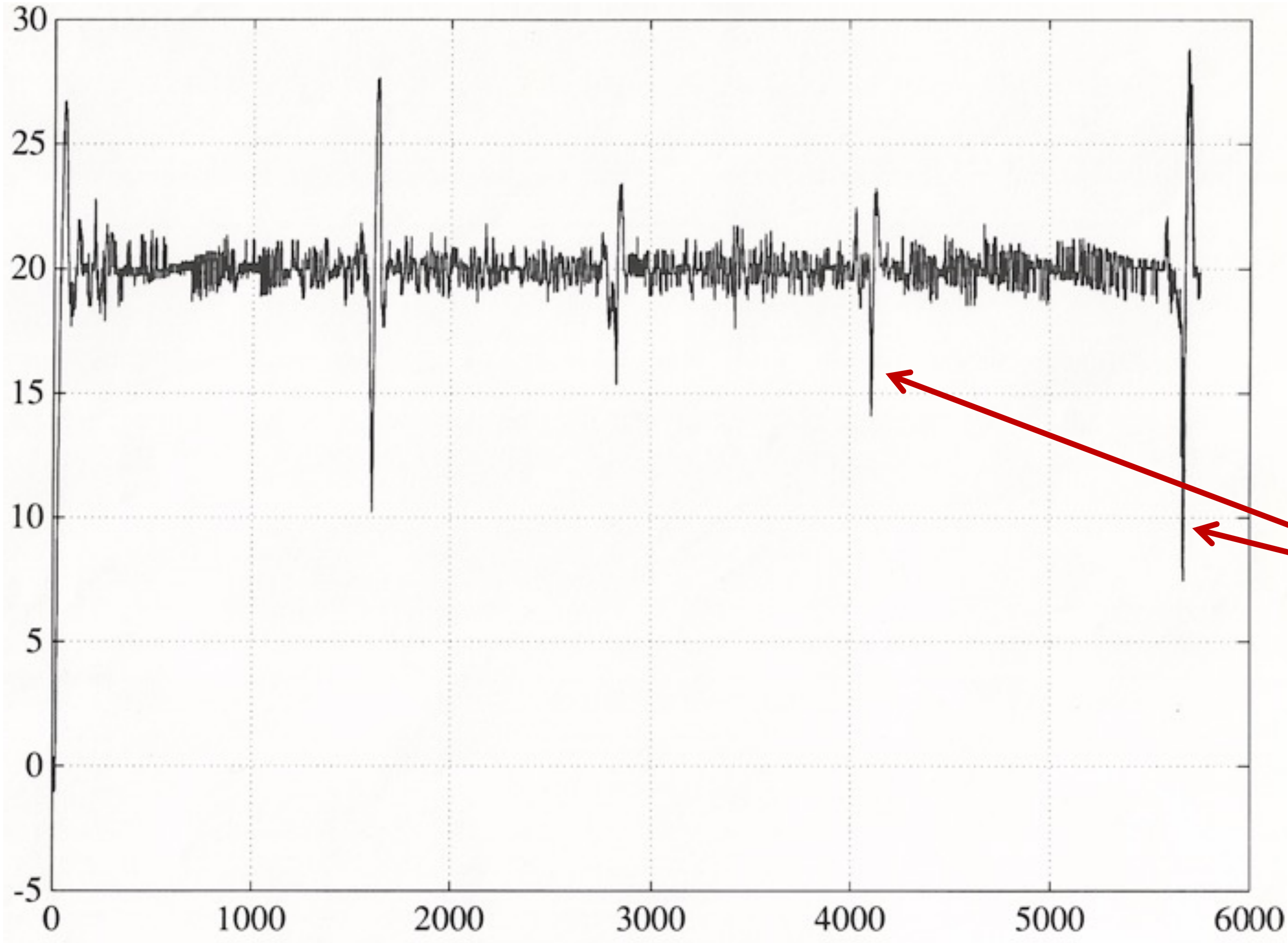
Reconstructed surface profile

estimation by a RLS (Recursive Least Squares) method: we continuously update the coefficients of two quadratic polynomials that fit locally the unknown contour, using data fusion from both force and position/velocity measurements



this is the reconstructed contour of a cinema "film reel" (of radius = 17 cm)

Normal force



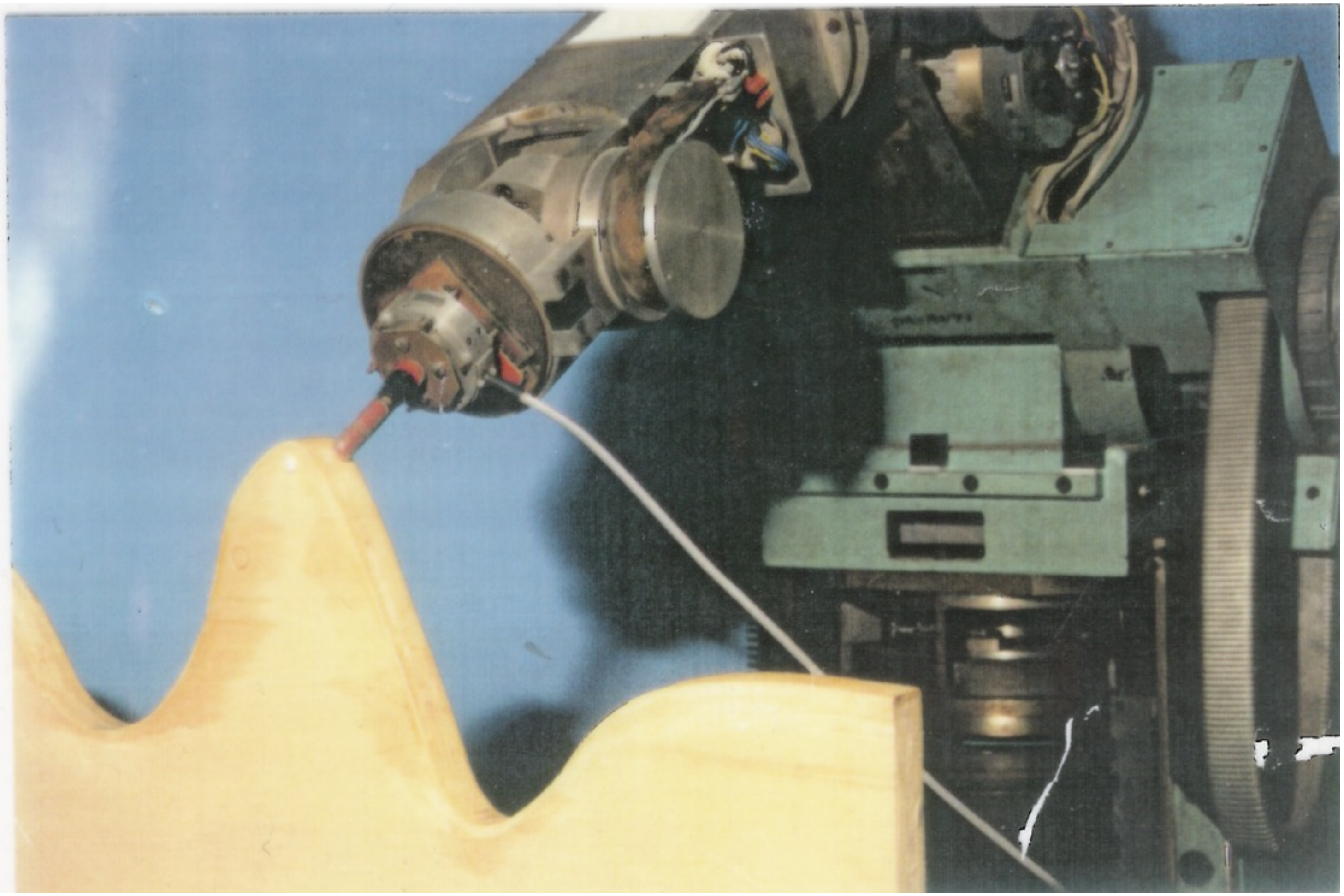
[N]

time [sampling intervals]

regulated to 20 N during simultaneous motion and estimation

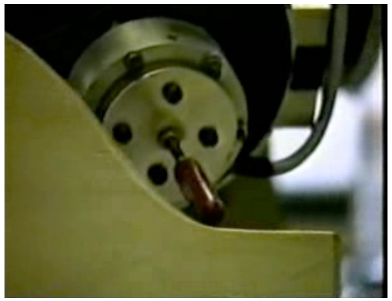
force peaks correspond to the grooves on the surface contour

Contour estimation and hybrid control
performed simultaneously



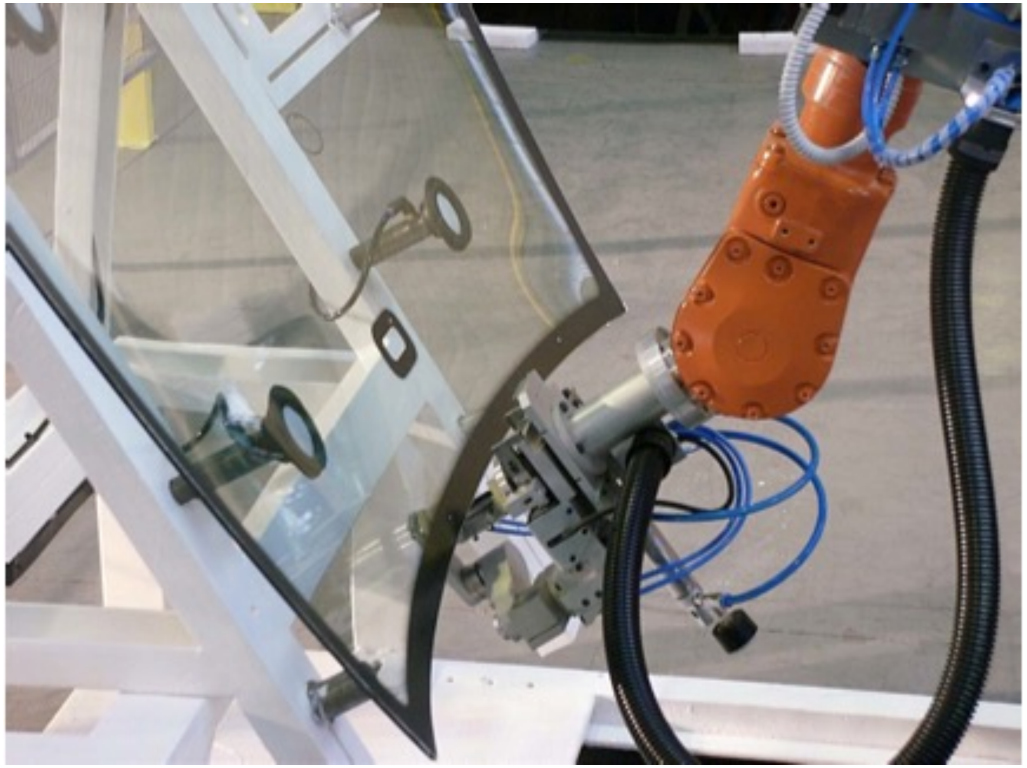
MIMO-CRF robot (DIS, Laboratorio di Robotica, 1992)

Contour estimation and hybrid control



video

Robotized deburring of car windshields

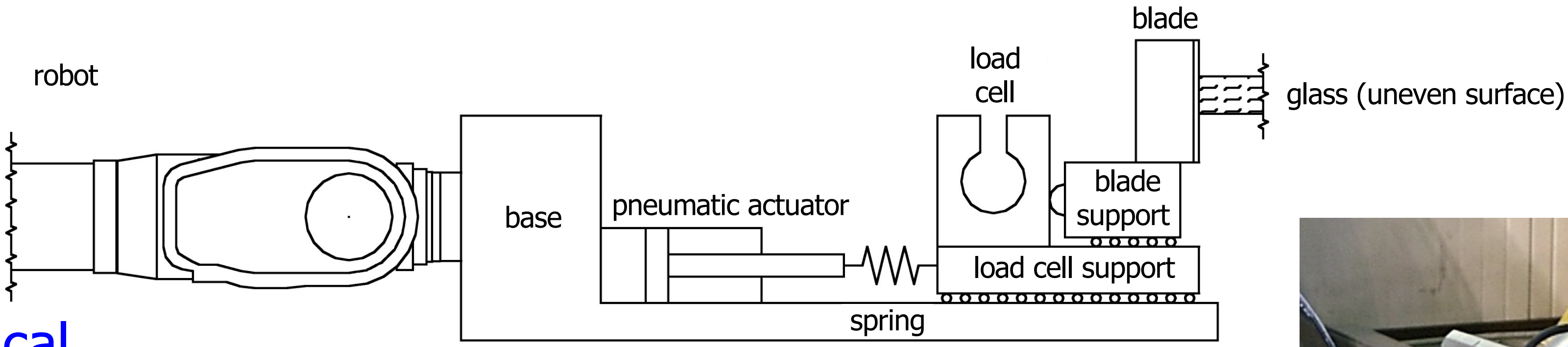


- car windshield with sharp edges and fabrication tolerances, with excess of material (PVB = Polyvinyl butyral for gluing glass layers) on the contour
- robot end-effector follows the pre-programmed path, despite the small errors w.r.t. the nominal windshield profile, thanks to the compliance of the deburring tool
- contact force between tool blades and workpiece can be independently controlled by a pneumatic actuator in the tool

the robotic deburring tool contains in particular

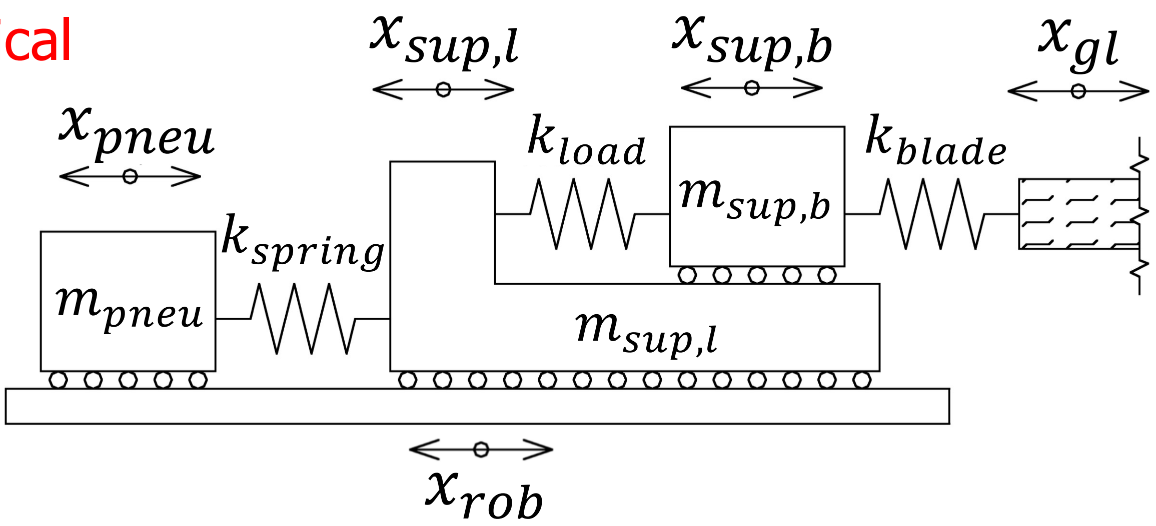
- two blades for cutting the exceeding plastic material (PVB), the first one actuated, the second passively pushed against the surface by a spring
- a load cell for measuring the 1D applied normal force at the contact
- on-board control system, exchanging data with the ABB robot controller

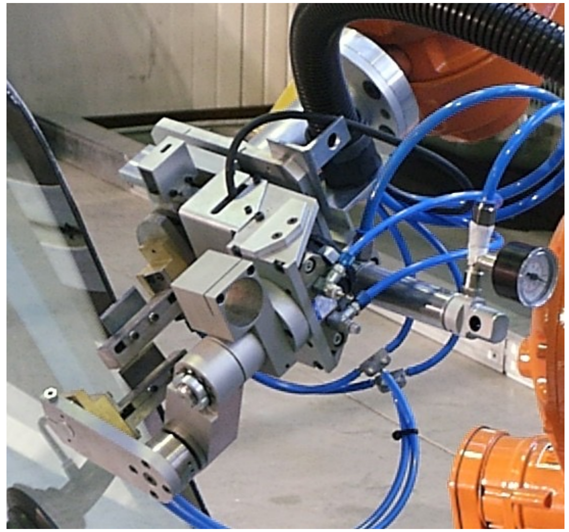
Model of the deburring work tool



physical

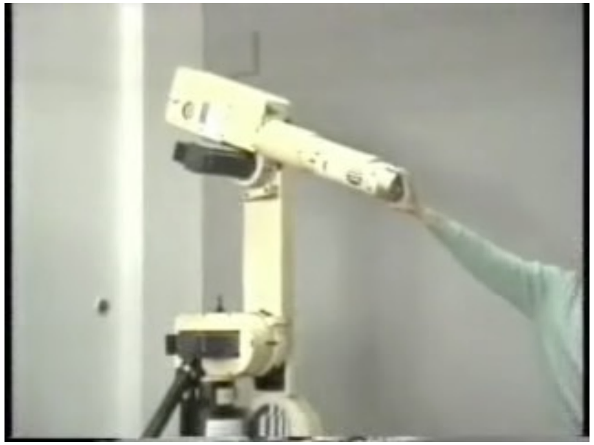
mathematical



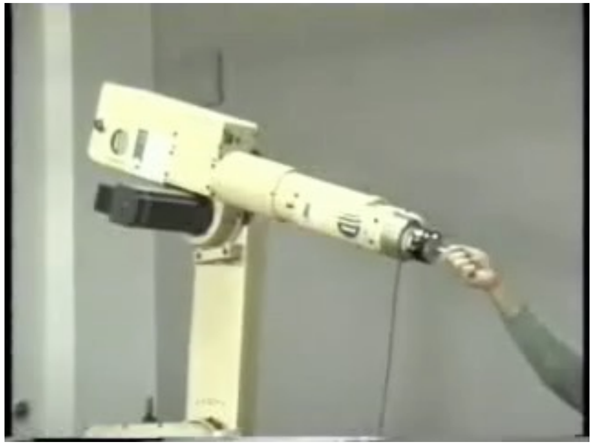


for a stability analysis (based on linear models and root locus techniques)
of force control in a single direction and in presence of multiple masses/springs,
see again Eppinger & Seering, IEEE CSM, 1987 (material in the course web site)

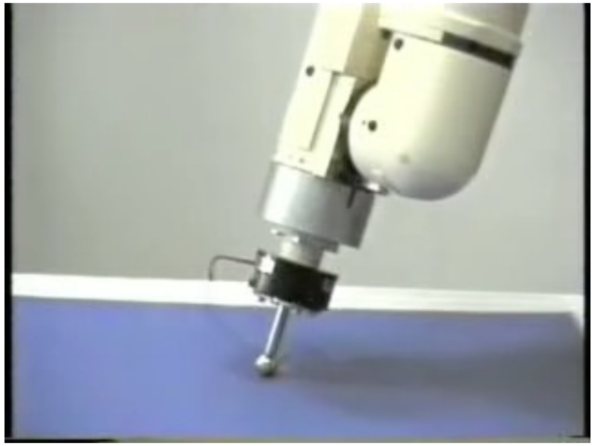
Summary through video segments



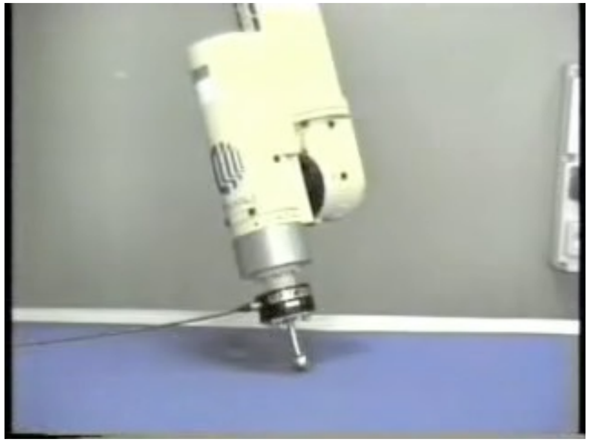
compliance control
(active Cartesian stiffness control without F/T sensor)



impedance control
(with F/T sensor)



force control
(realized as external loop providing the reference to an internal position loop –see Appendix)



hybrid force/position control

COMAU Smart robot
c/o Università di Napoli, 1994
(full video on course web site)

Appendix

- force control can also be realized as an external loop providing reference values to an internal motion loop (see video in slide #32)
- inner-outer (or cascaded) control scheme
  - angular position quantities (E-E orientation, errors, commands) can be expressed in different ways (Euler angles $\boldsymbol{\phi}$, rotation matrices $\boldsymbol{R}$, ...)