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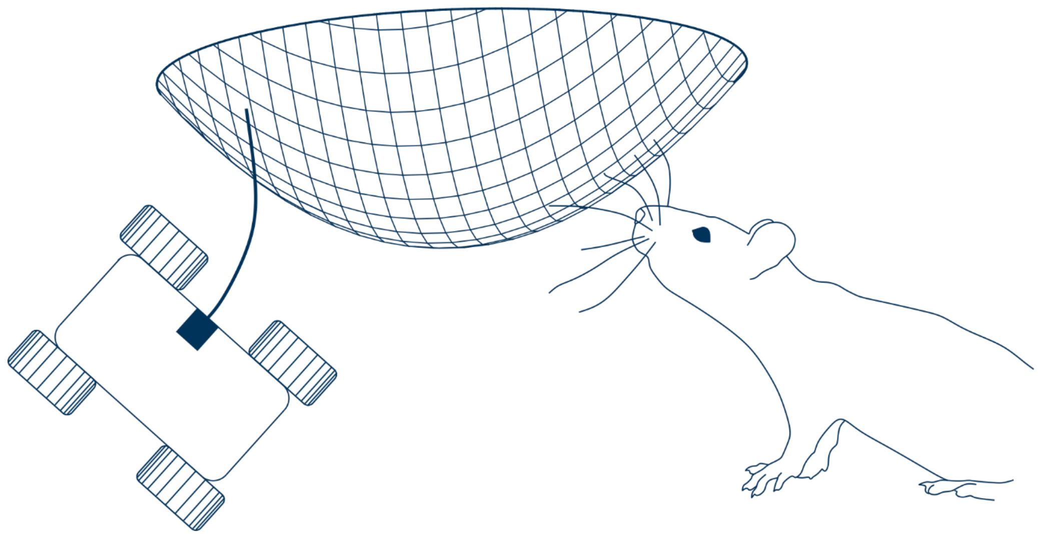

Steps towards the Modeling of Animal Vibrissa Using Adaptive Control

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Short Resume of the Presenter and corr. Author

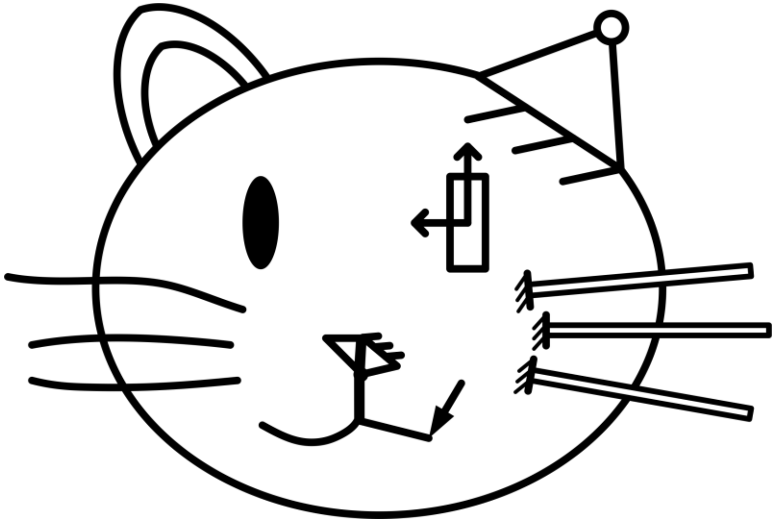
Carsten Behn received the diploma degree in Mathematics in 2001 and the Ph.D degree in Mechanics and Control Theory in 2005 from the Technische Universität Ilmenau, Germany. He has been working as a Post-Doc and an Assistant Professor at the Dept. of Mechanical Engineering at TU Ilmenau. After finishing his habilitation in 2013 he was an Associate Professor for Technical Mechanics. 2018-2019 he was a Full-Professor for Vibration Engineering and Dynamics of Machines at Merseburg University of Applied Sciences. Since 2019 he is a Full-Professor for Applied Mathematics and Mechanics at Schmalkalden University of Applied Sciences. His research interests mainly encompass modeling, analysis and robust control of biologically inspired motion systems with adaptive features.

Outline

1. Introduction & Motivation
2. Biology of Vibrissae
3. State of the Art
4. Mechanical Vibrissa Model
5. Control Objective
6. Numerical Simulations
7. Conclusions & Outlook

ViBeamS^3

- est. 2013 -



Technical Beam Vibrissae

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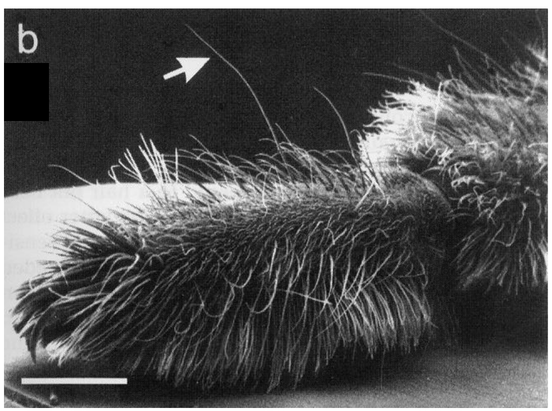
Shape & Surface Scanning

1. Introduction & Motivation – Live paradigm

Different names:
vibrissa, whisker, tactile hair, sensory hair, sensillum, ...



[www]

→ variability in length, diameter, shape (curvature) and conical contour

Tactile sensing of environmental informations

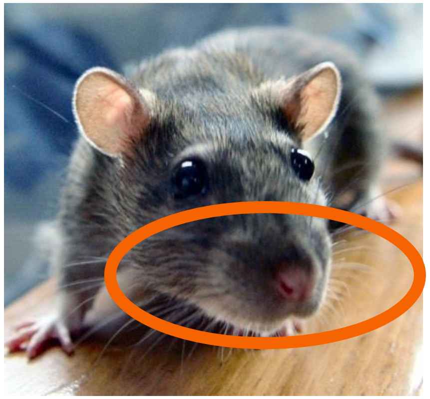
- „near field"-sense in contrast to „far field"-senses (e.g., vision)

- complex tactile sensory organ: sense of vibrations

- tactile hairs / vibrissae in the region around the snout: *mystacial vibrissae*

- vibrissa is used as lever for force transmission

- found in nocturnal / non-visual animals (best developed in rodents e.g. rats)



1. Introduction & Motivation – Bionic Aspects

1. analyzing live biological systems, e.g. vibrissae,

2. quantifying the mechanical and environmental behavior: identifying and quantifying mechanosensitive responses (e.g., pressure, vibrations) and their mechanisms as adaptation,

3. modeling live paradigms with basic features developed before,

4. exploiting corresponding mathematical models in order to understand details of internal processes and,

5. coming to artificial prototypes (e.g., sensors in robotics), which exhibit features of the real paradigms.

Important:

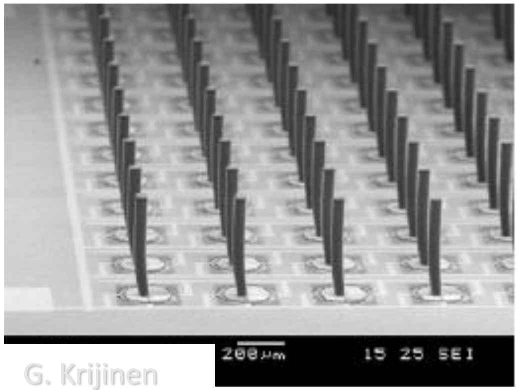
- focus is not on “copying” the solution from biology / animality

- not to construct prototypes with one-to-one properties of, e.g., a vibrissa

Paradigms of tactile sensors for perceptions in applications:

- quality assurance (e.g., coordinate measuring machines)
- measurements of flow rates
- detection of packaged goods on conveyor belts

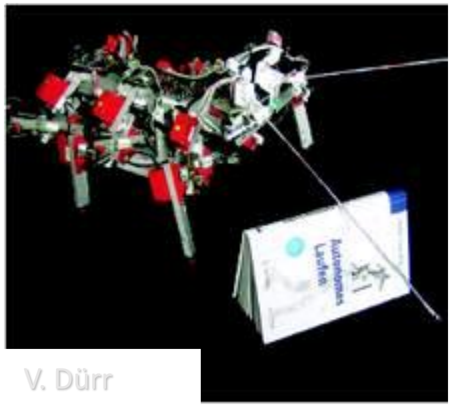
Microsystem Technology



G. Krijinen

detection of flow rates

Robotics

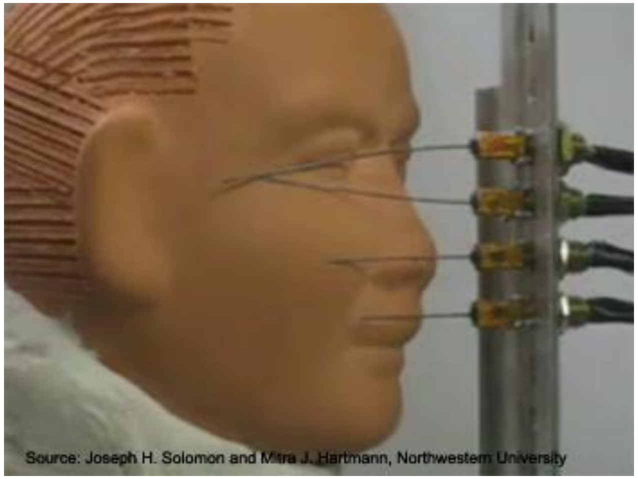


V. Dürr

object localization

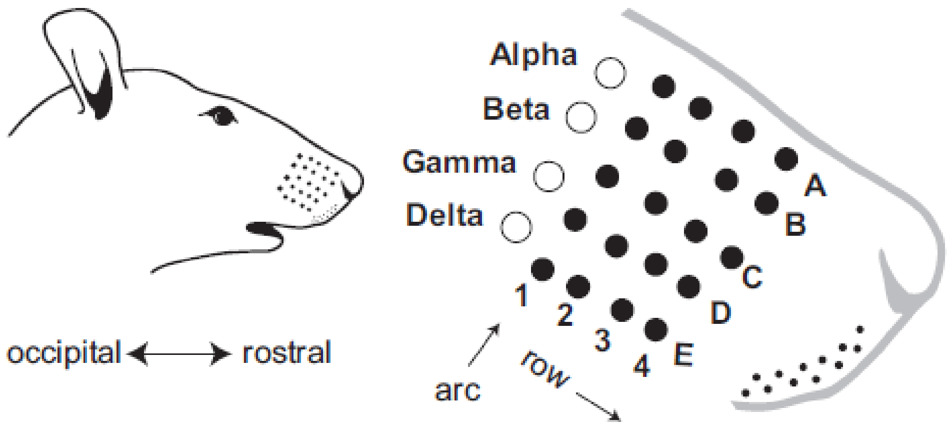
M. Fend

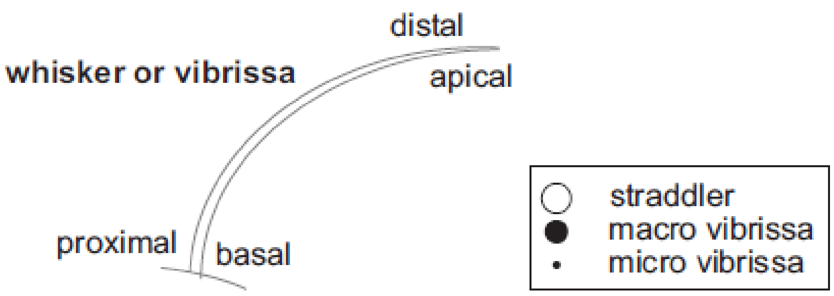
detection of texture



detection of surfaces

2. Biology of Vibrissae - Anatomy



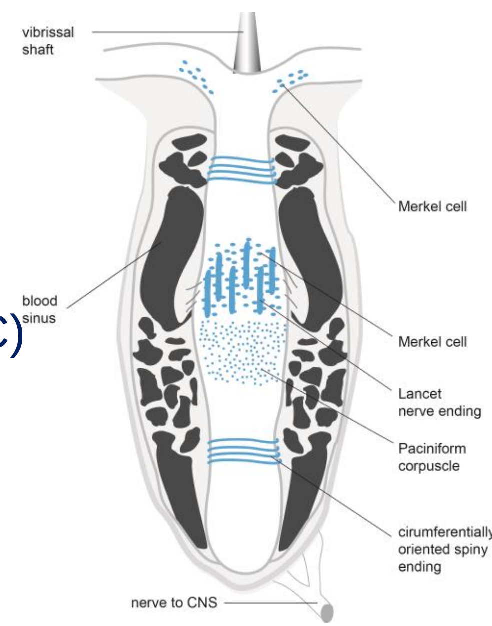


[Carl et. al. 2012b]

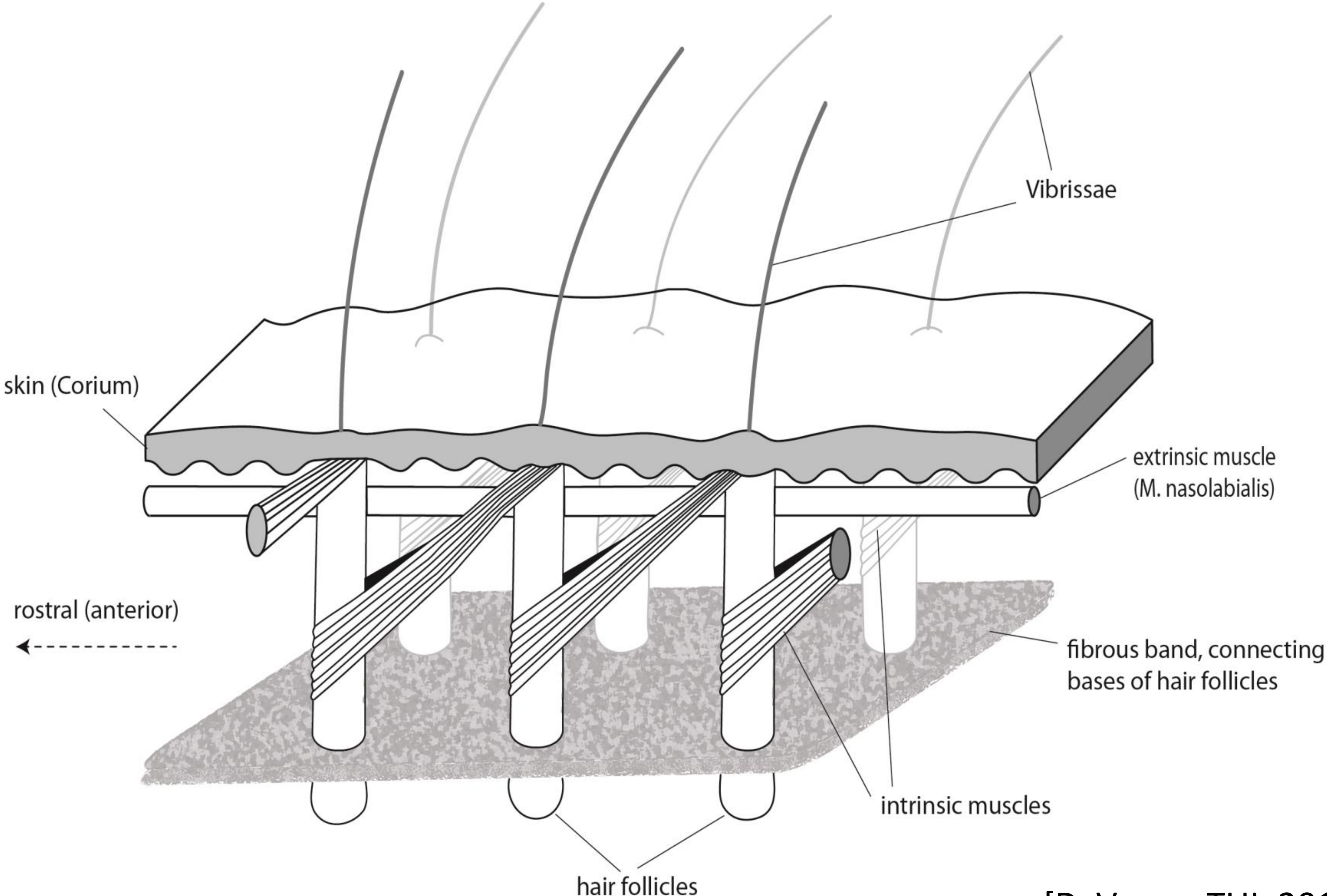
two components: sinus hair and own hair follicle

elastical, hollow and conically shaped

Follicle-Sinus-Complex (FSC)
blood vessels and nerves (mechanoreceptors)
→ viscoelastic support

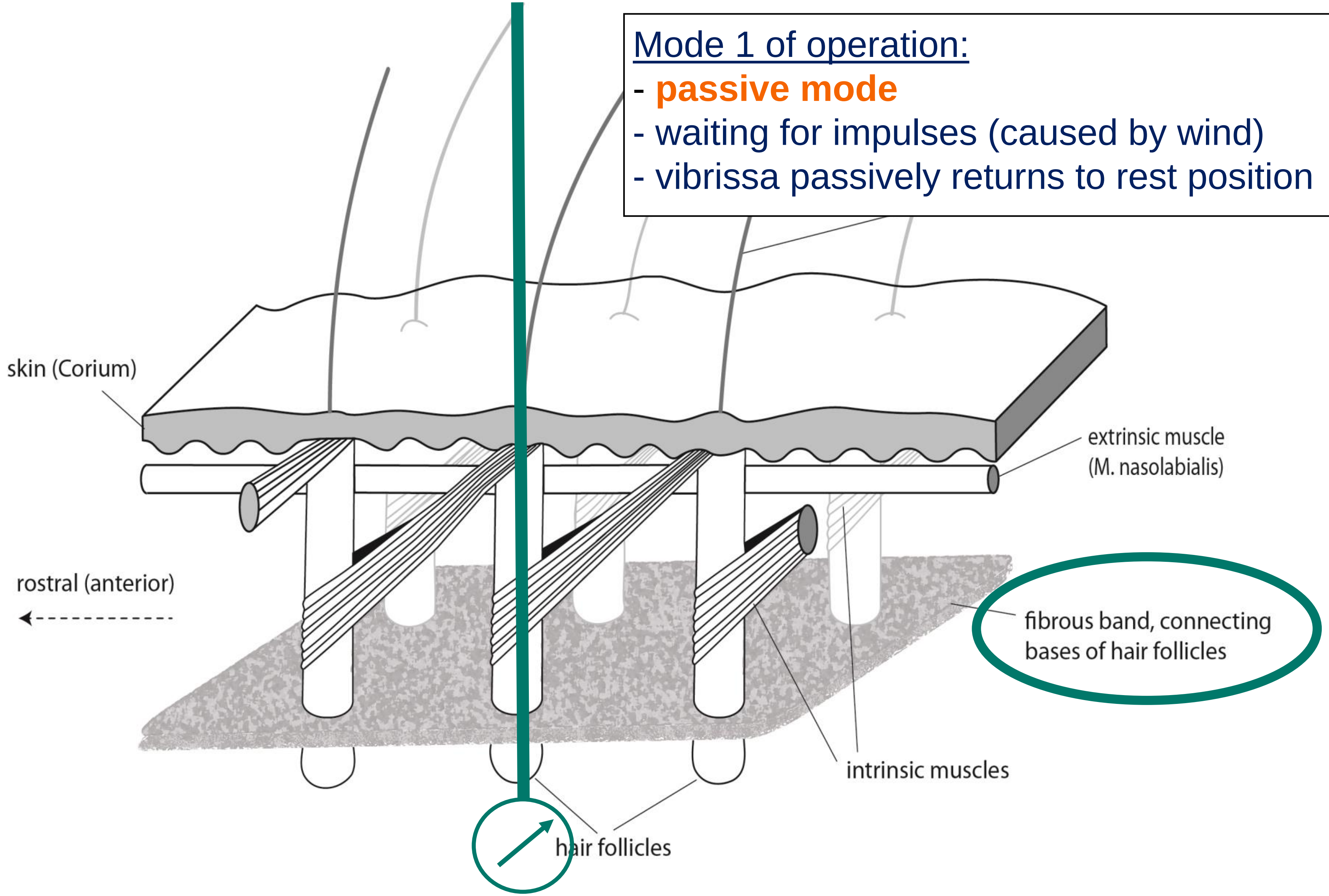


2. Biology of Vibrissae - Anatomy



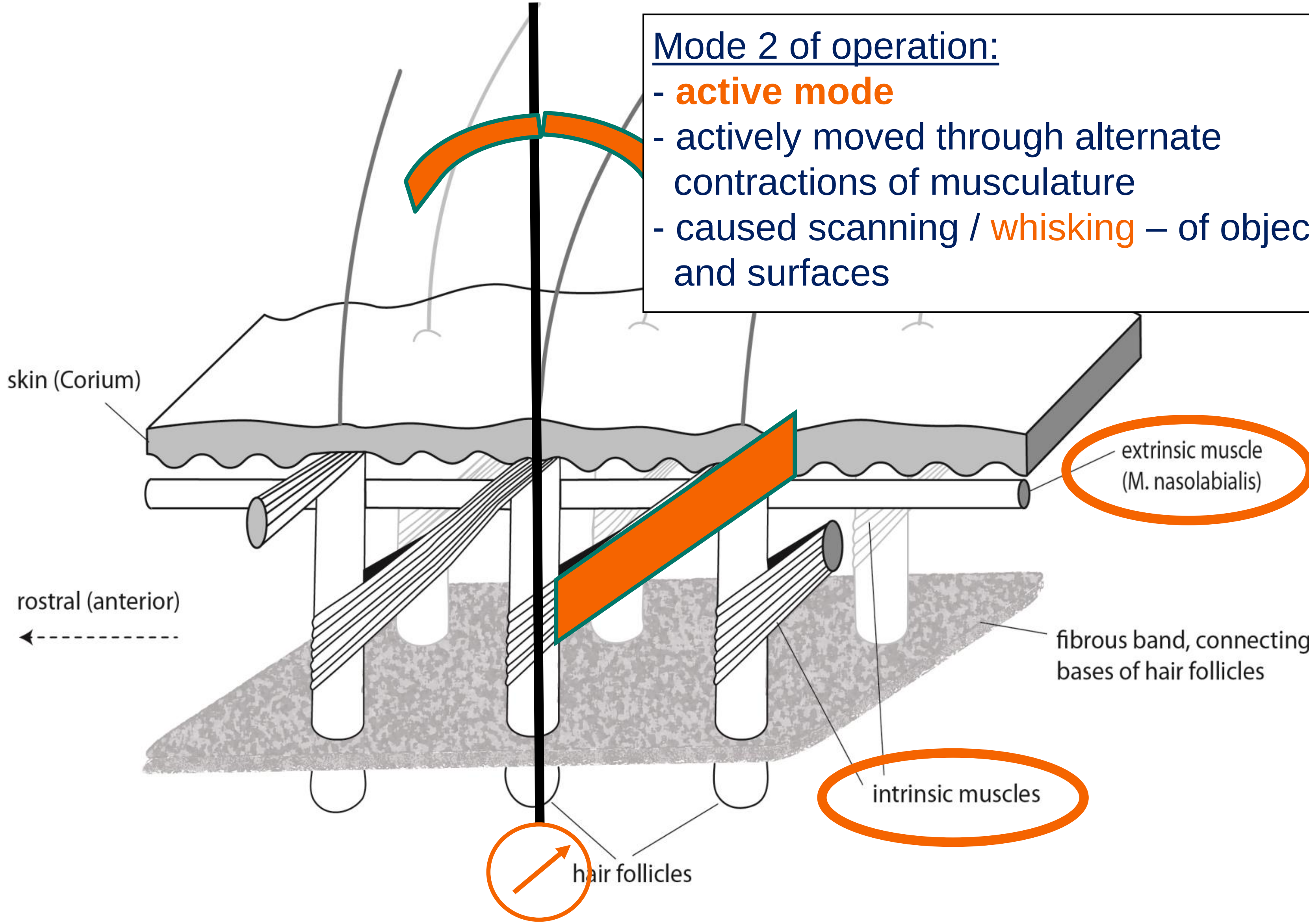
[D. Voges, TUI, 2012]

2. Biology of Vibrissae - Functionality



<u>Mode 1 of operation:</u>
- **passive mode**
- waiting for impulses (caused by wind)
- vibrissa passively returns to rest position

2. Biology of Vibrissae - Functionality



Mode 2 of operation:

- **active mode**
- actively moved through alternate contractions of musculature
- caused scanning / whisking – of objects and surfaces

2. Biology of Vibrissae – Control Strategies

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Offering the ability to adapt its sensitivity to its environment:

- detection of vibrissa displacements by mechanoreceptors in the FSC

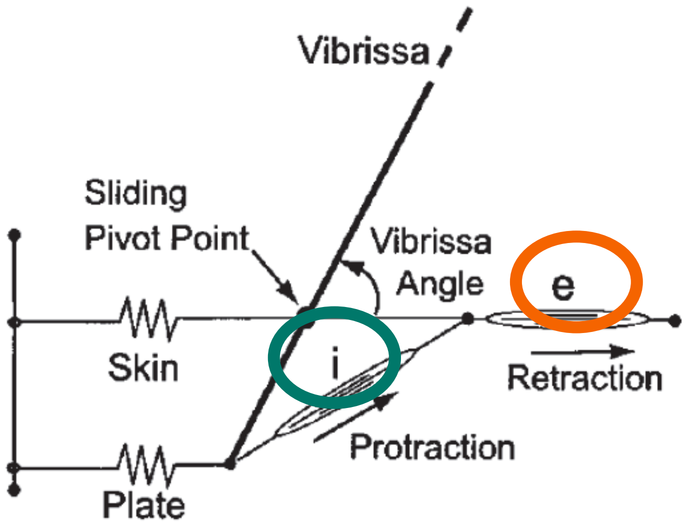
- a feedback loop (closed-loop control system) enables the rodents to immediately react to an object contact: they slow down the vibrissae

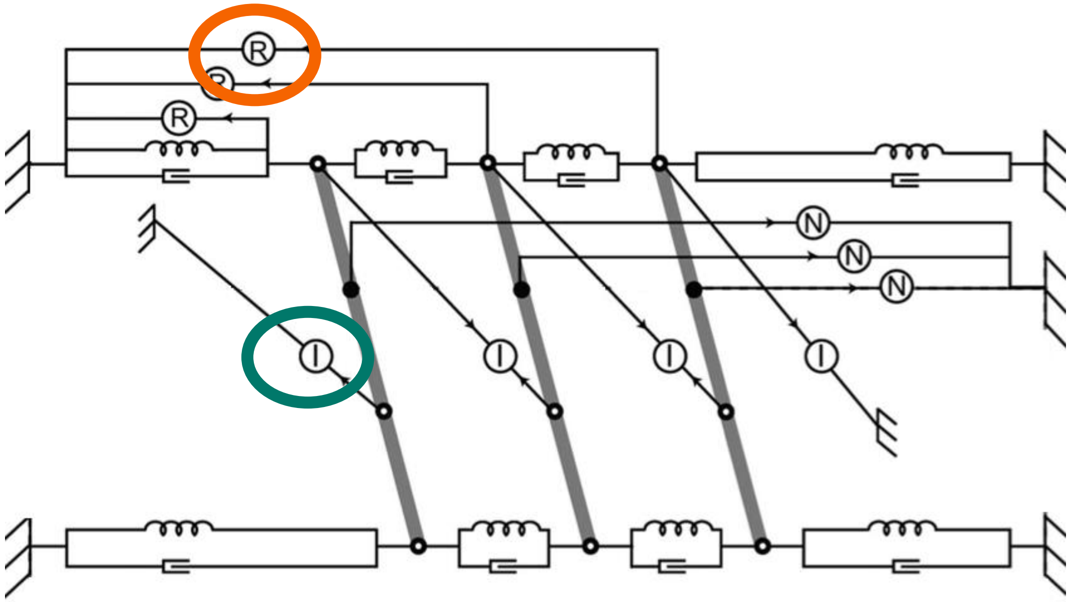
- depending on the mode (passive or active) and the expectations, the neuron's reaction is controlled: is being suppressed, enhanced or left unaltered

- the rodents can *probably* modify the stiffness of the vibrissa support by varying the pressure in the blood-sinus

- active whisking pattern
  a) exploratory whisking: large amplitudes, low frequency (5-15Hz)
  b) foveal whisking: small amplitudes, high frequency (15-25Hz)

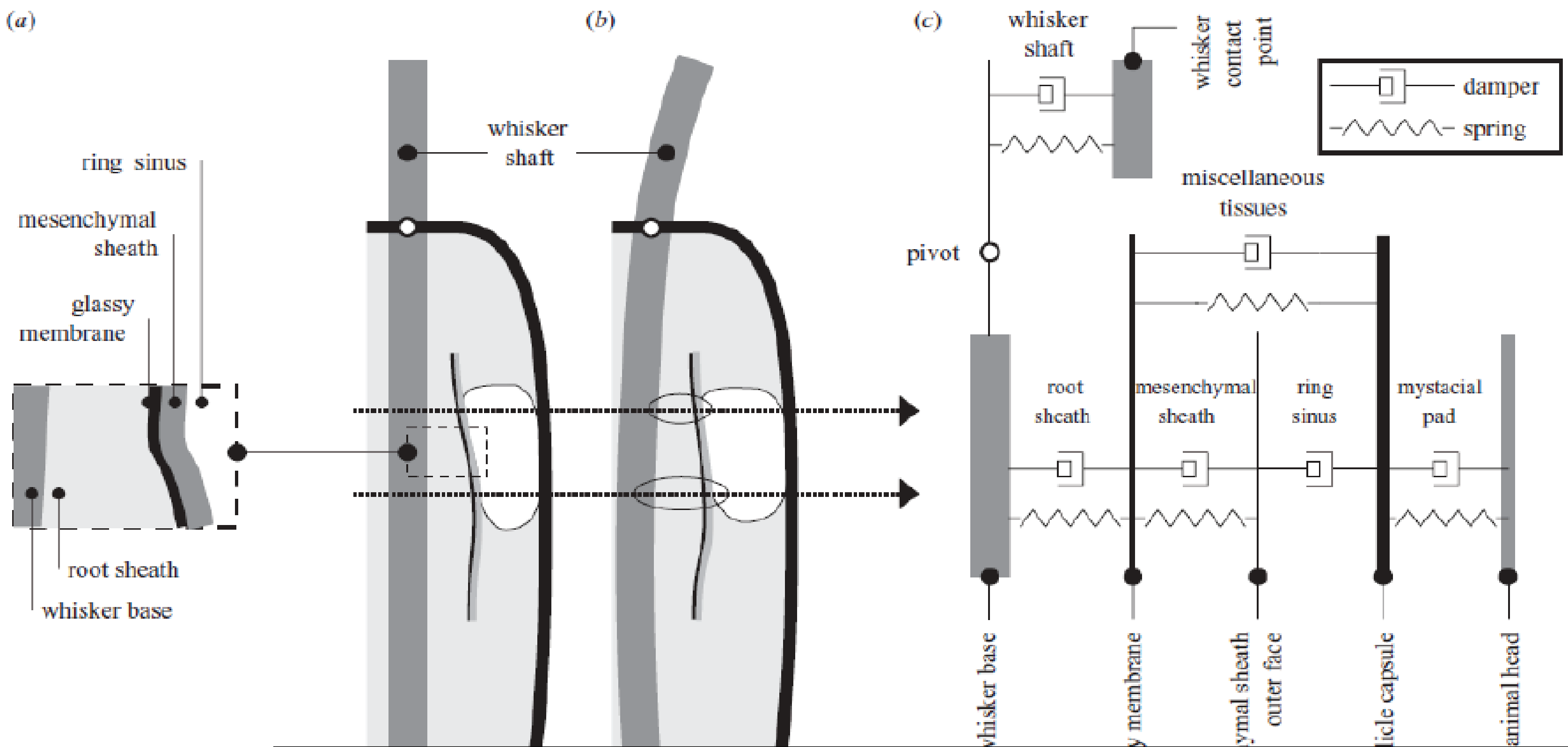
Rigid body model of a vibrissa / vibrissa row with musculature
in **[Berg, Kleinfeld 2003]** and **[Hill et. al. 2008]**





- ⊕ Implementation of the intrinsic and extrinsic musculature
- ⊕ Simulating the viscoelastic properties of the skin
  - ↪ Determination of spring and damping coefficients for the skin
- ⊖ Neglecting the viscoelastic properties of the FSC
- ⊖ Connection between the follicles
  - ↪ leads to complex control strategy and high control effort

Rigid body model of the vibrissa / Simulating the compliance of the FSC in [Mitchinson et. al. 2004], [Mitchinson et. al. 2007]

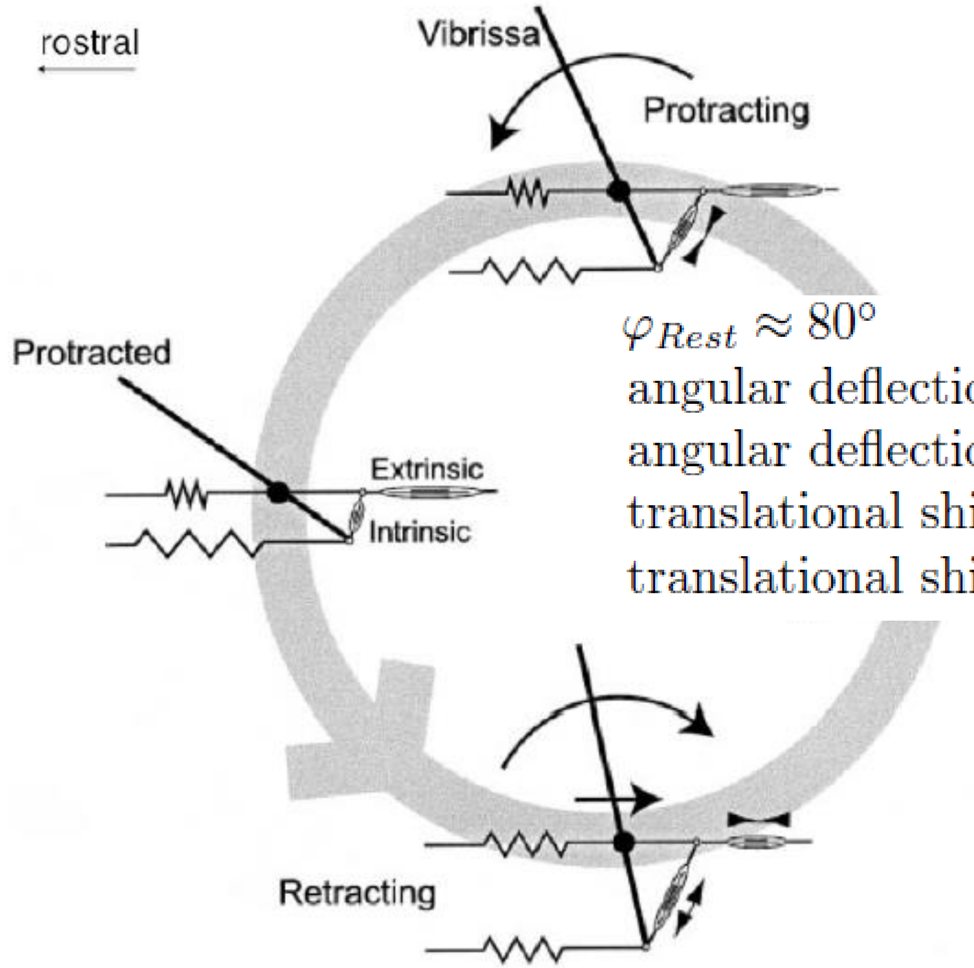


⊖ too complex for a technical implementation

⊕ Determination of spring and damping coefficients for the FSC

3. State of the Art – Mechanical Models

Rigid body model of a vibrissa for determination of the range of movement of the vibrissa in [**Berg, Kleinfeld 2003]**



$\varphi_{Rest} \approx 80^\circ$

angular deflection in rostral direction $\varphi_{rest} + 65^\circ$

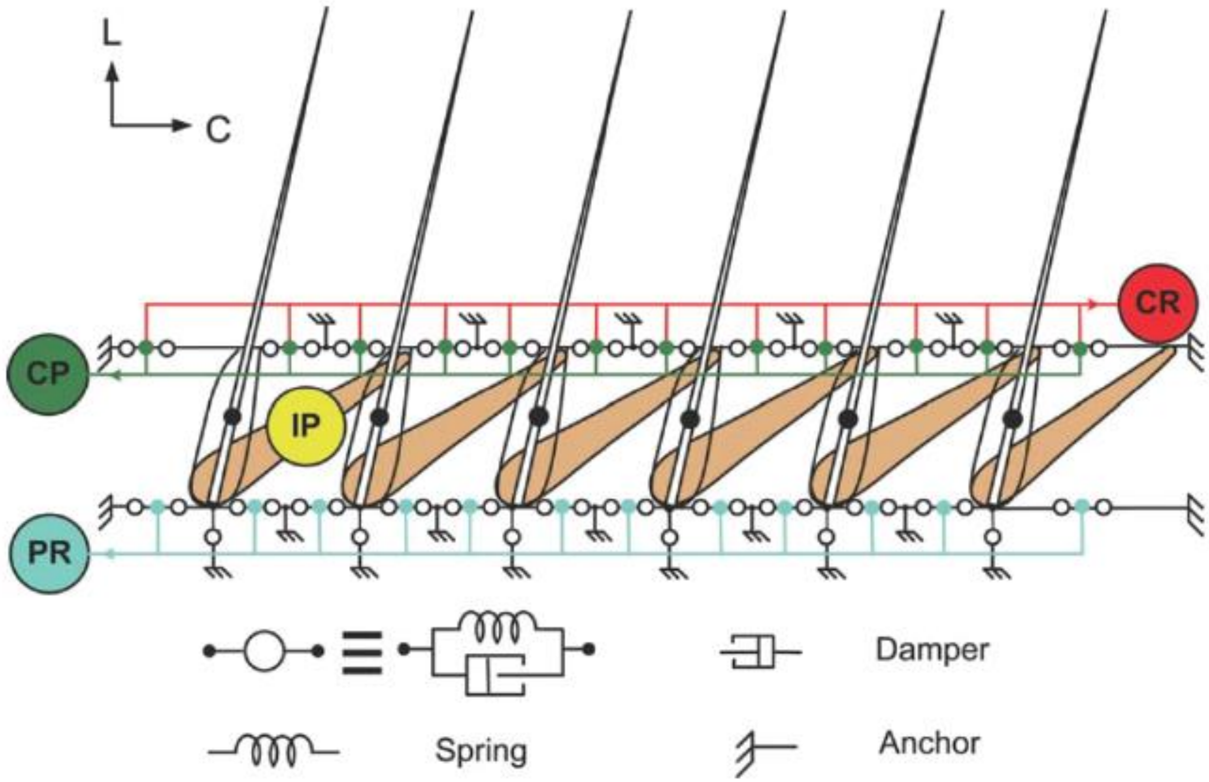
angular deflection in caudal direction $\varphi_{rest} - 35^\circ$

translational shift $\approx 5\,\mathrm{mm}$ in caudal-rostral direction

translational shift $\approx 3\,\mathrm{mm}$ in dorsal-ventral direction

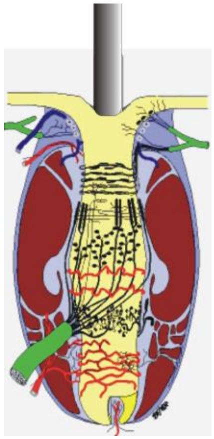
Biomechanical model representing one vibrissal row
in **[Haidarliu et al. 2010]** and **[Haidarliu et al. 2011]**

Goal: modeling the muscle-tissue-system in the mystacial pad

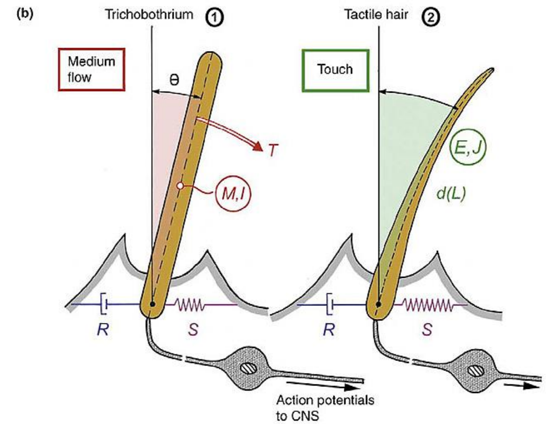


just for illustration, model is too complex to investigate control algorithm, no focus

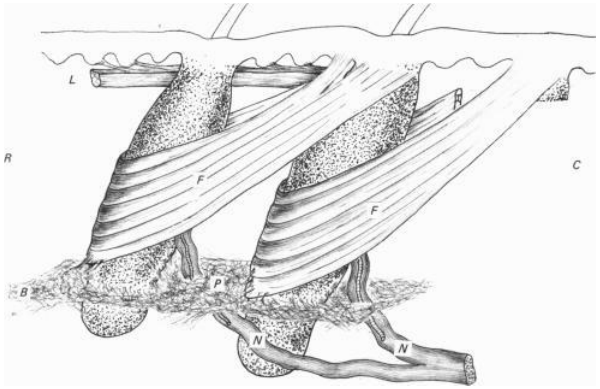
4. Mechanical Vibrissa Model



Follicle sine complex [Rice 86]

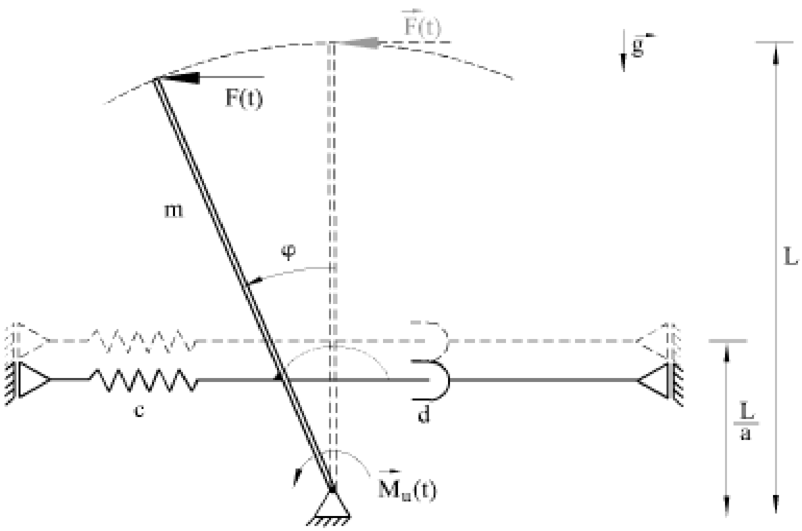


Schema [Barth 04]



FSC & intrinsic musculature [Dörfl 85]

- pendulum-like system
- visco-elastic support
- external excitations (e.g. wind) represented by force
- torque serves as control



5. Control Objectives

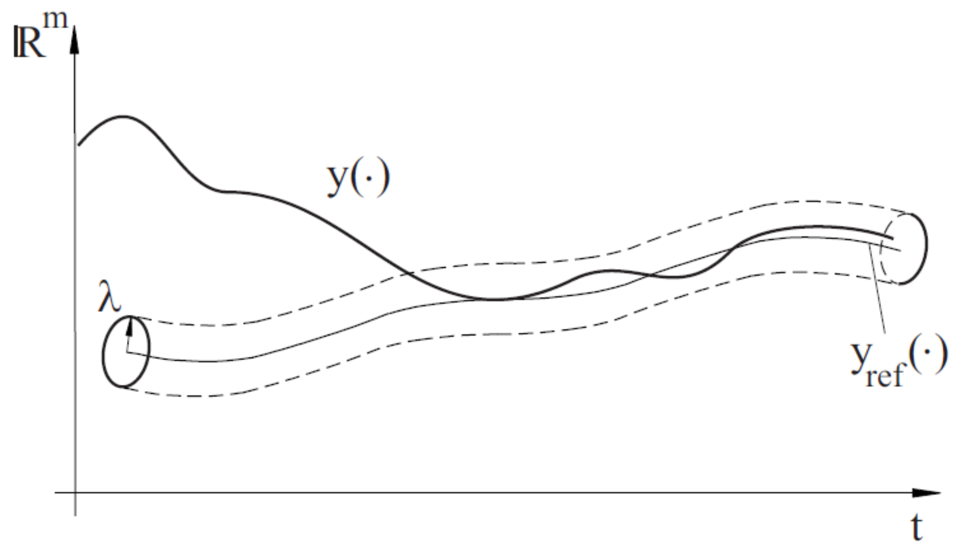
Goal:
Control the vibrissa system in a chosen mode of operation: passive or active

Problem:
- many open-loop and closed-loop controls are based on exactly known parameters
- here: suppose uncertain system (due to biological complexity)
  - unknown system parameters
  - only structural properties known

What to do if the system is not known precisely?

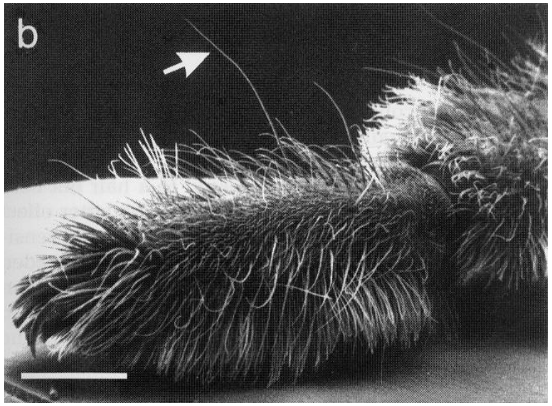
Solution:
Design an adaptive controller, which learns from the behavior of the system, so automatically adjusts its parameters and achieves

λ-tracking



5. Control Objectives

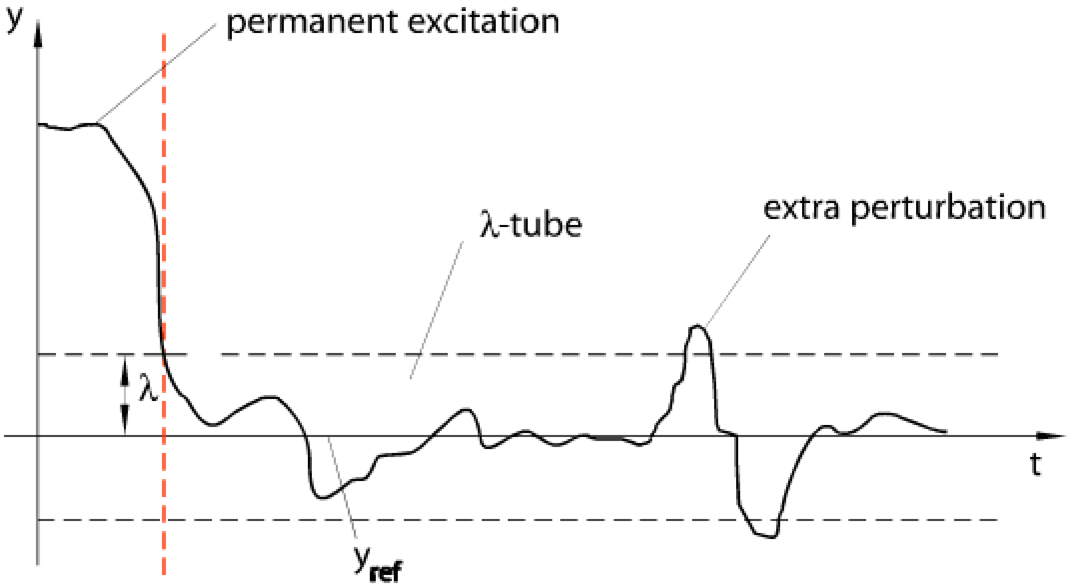
Passive Mode



- stabilize the system under permanent excitation

- while enabling to detect external extra-perturbations (e.g. sensory contact, detect wake of swimming fish)

λ-stabilization

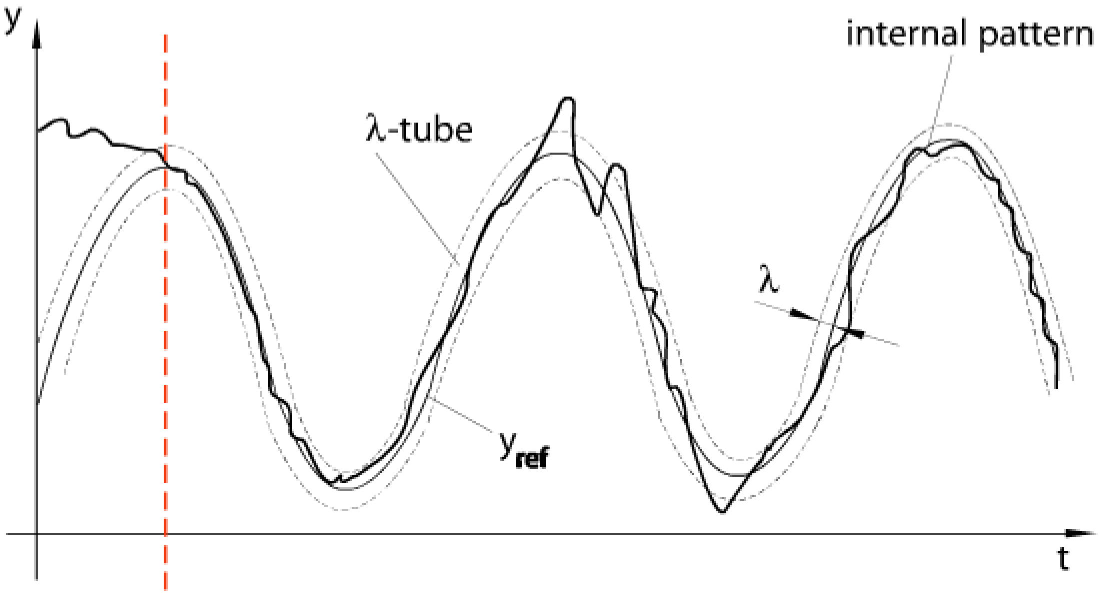


Active Mode

- track an internally generated oscillatory motion pattern

- enable the system to recognize external disturbances of this pattern (caused, e.g., by wind or surface contact scanning of surface texture)

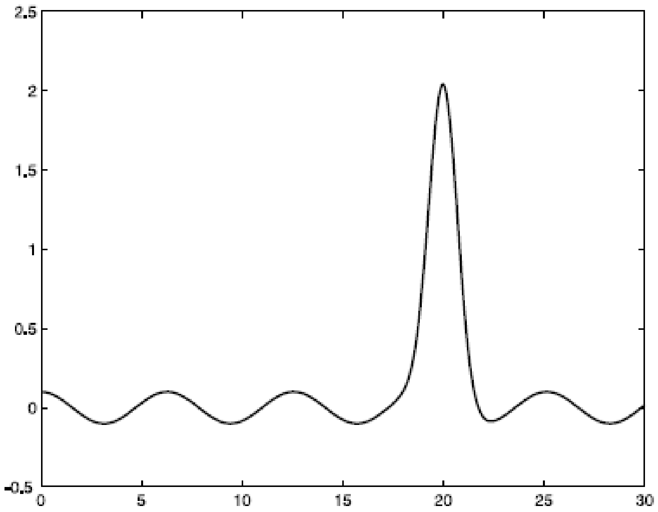
λ-tracking



Simulations

vibrissa: $m = 0.000\,003\,\mathrm{kg},\ c = 5.7\,\frac{\mathrm{N}}{\mathrm{m}},\ d = 0.2\,\frac{\mathrm{Ns}}{\mathrm{m}},\ L = 0.04\,\mathrm{m},\ a = \frac{L}{10} = 0.004\,\mathrm{m}$

environment: $t \mapsto F(t) = 0.1\,\cos(t) + 2\,e^{-(t-20)^2}\,\mathrm{N}$
(small permanent oscillation with a gust of wind)



modes of operation:
passive mode

$$t \mapsto \varphi_{\mathrm{ref0}}(t) = 0\,\mathrm{rad}$$

active mode 1 – exploratory whisking

$$t \mapsto \varphi_{\mathrm{ref1}}(t) = 0.8\,\sin(2\pi\,5\,t)\,\mathrm{rad}$$

active mode 2 – foveal whisking

$$t \mapsto \varphi_{\mathrm{ref2}}(t) = 0.2\,\sin(2\pi\,25\,t)\,\mathrm{rad}$$

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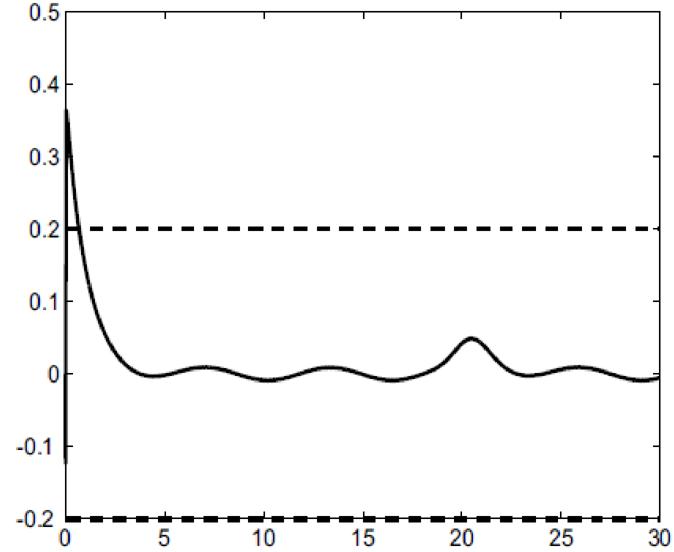
Active Mode 1

$$e(t) := \varphi(t) - \varphi_{\mathrm{ref}}(t)$$

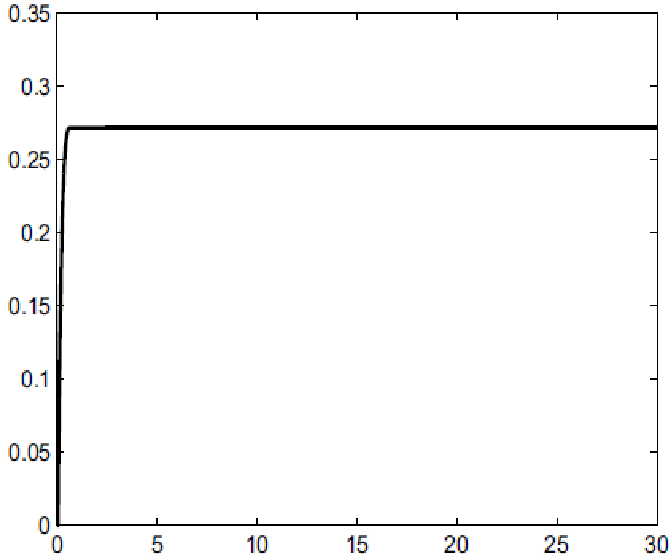
$$M_u(t) = -\left[k(t)\,e(t) + \kappa\,k(t)\,\dot{e}(t)\right]$$

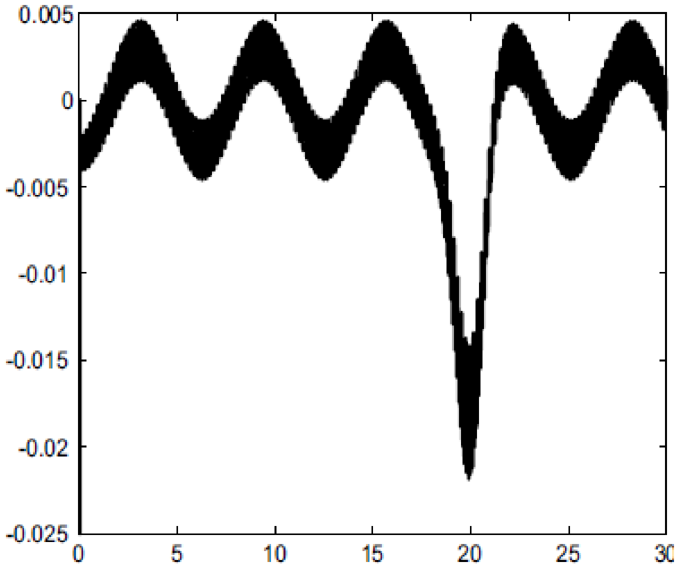
$$\dot{k}(t) = \gamma\Big(\max\big\{0, \|e(t)\| - \lambda\big\}\Big)^2$$



Control torque vs. time

Gain vs. time





- good tracking
- convergence of the gain
- hard to detect the gust in system variables e and k
- control torque reflects peak

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6. Numerical Simulations

Next Attempt:

- make the attraction of the tube stronger

- using different exponents for large/small distance from the tube:

$$e(t) := \varphi(t) - \varphi_{\mathrm{ref}}(t)$$

$$M_u(t) = -\left[k(t)\,e(t) + \kappa\,k(t)\,\dot{e}(t)\right]$$

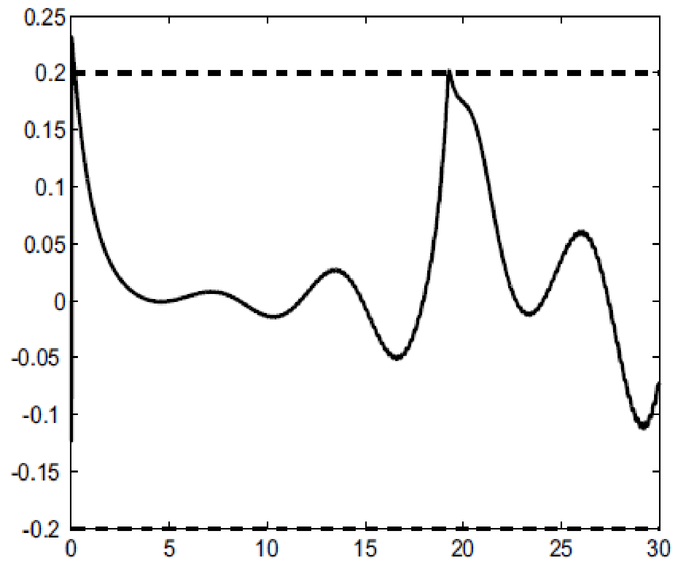
$$\dot{k}(t) = \begin{cases} \gamma\,\left(\|e(t)\| - \lambda\right)^2, & \text{if } \|e(t)\| \geq \lambda + 1 \\ \gamma\,\left(\|e(t)\| - \lambda\right)^{0.5}, & \text{if } (\lambda + 1) > \|e(t)\| \geq \lambda \\ 0\,, & \text{if } \left(\|e(t)\| < \lambda\right) \wedge (t - t_E < t_d) \\ -\sigma\,k(t)\,, & \text{if } \left(\|e(t)\| < \lambda\right) \wedge (t - t_E \geq t_d) \end{cases}$$

(Parameters as before)

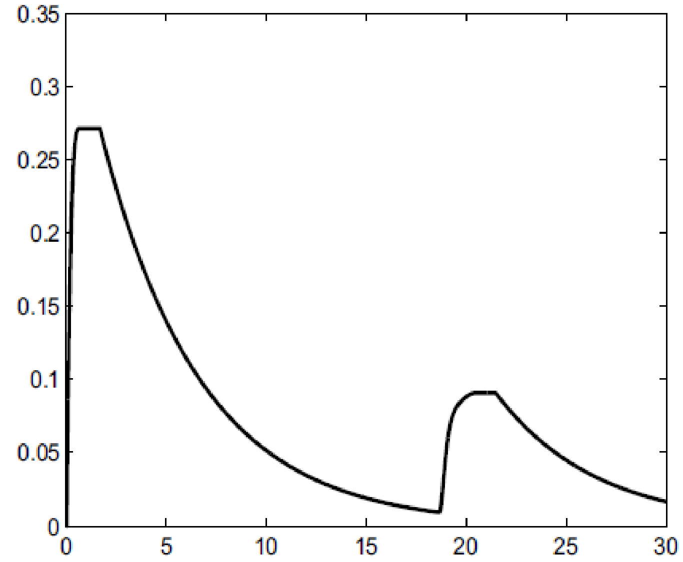
6. Numerical Simulations

Active Mode 1

Error vs. time



Gain vs. time



- good tracking
- advantage of two alternating exponents:
  - *k(.)* increases, *e(.)* forced into the tube
  - *k(.)* decreases, *e(.)* leaves the tube, but forced back into the tube very fast (higher attraction for small deviations)
- interesting: detect superimposed impulse in observing *k(.)*

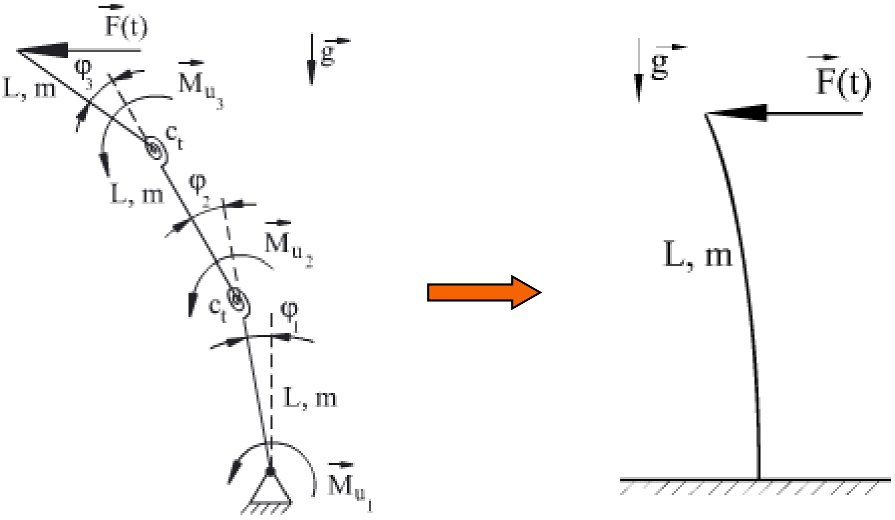
7. Conclusions & Outlook

Conclusions:
- shown: adaptive control is promising in application to vibrissae systems.
- allows to describe two operations of vibrissae: passive and active one
- improved controllers are useful and should be developed further

Current tasks:
- allowing for input and output disturbances
- identification techniques to get knowledge of solitary excitations
- separation of an extra receptor from vibrissa

Future tasks:
- find favourable adaptor data
- replace circular pendulum by spherical or
- hardware experiments

- develop elastic vibrissae models (higher I



Thank you for your attention!

No animals

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neither rats, mice, nor cats

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were harmed !

+ - + - Breaking News - + - + -

Latest biological observations show that animals misuse other body-parts as tactile sensors.