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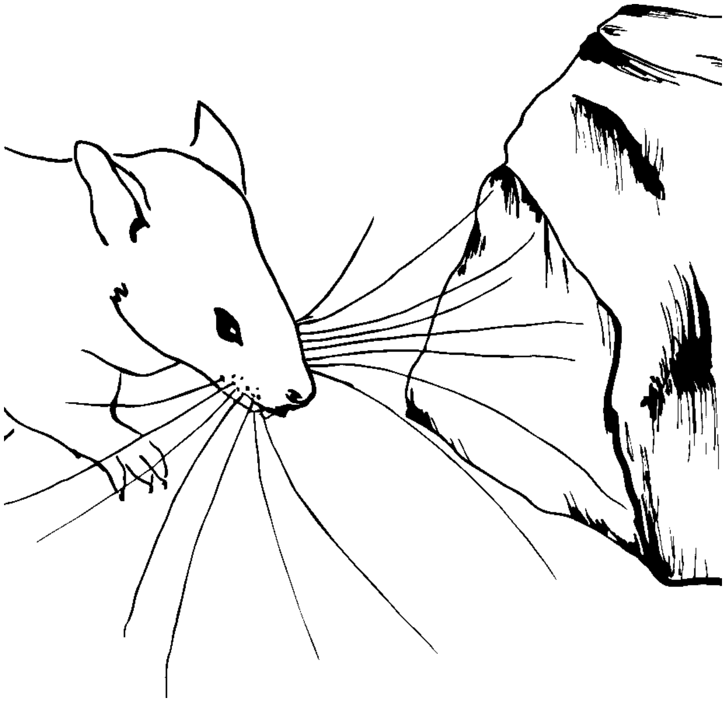
Friction Invariant Object Reconstruction Using a Vibrissa-inspired Tactile Sensor Concept

Lukas Merker [1], Joachim Steigenberger[1], Carsten Behn [2]



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Short Resume of the Presenter

Lukas Merker received the B.Sc. degree (2015) and the M.Sc. degree (2017) in Mechanical Engineering from Technische Universität Ilmenau. Since 2017, he has been working as a Ph.D student at the Department of Mechanical Engineering at Technische Universität Ilmenau. His research interests include the development of biologically inspired tactile sensors for object shape recognition .

Authors of the Paper

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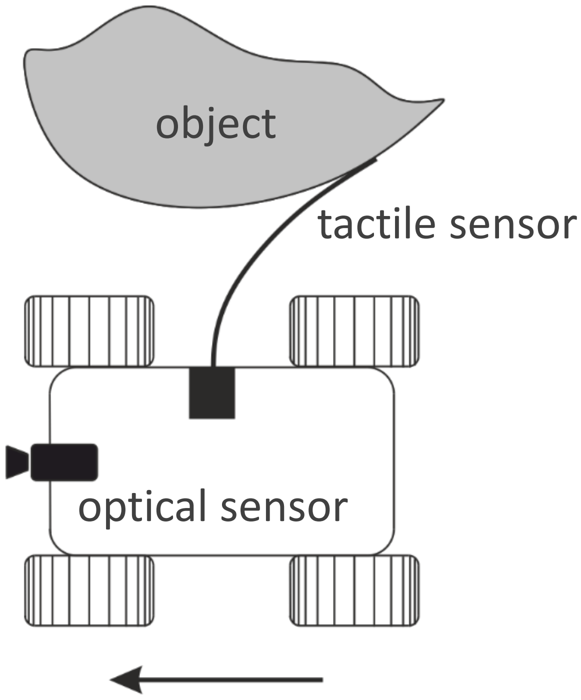
Prof. Carsten Behn

1. Introduction – Future Goal

biological paragon

technical application example



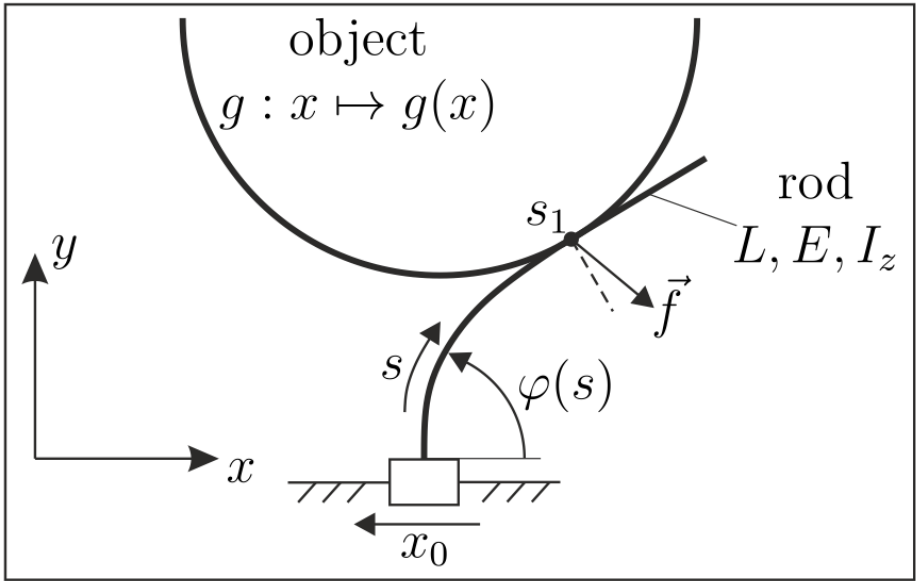
- vibrissae enable animals to determine different object features: size, orientation, shape, surface texture
- sensing information only in follicle/support of each vibrissa

highly flexible tactile sensors (complementing optical sensors)

- for object shape scanning and reconstruction
- path planning for rovers

2. Mechanical Model

biological paragon	mechanical model

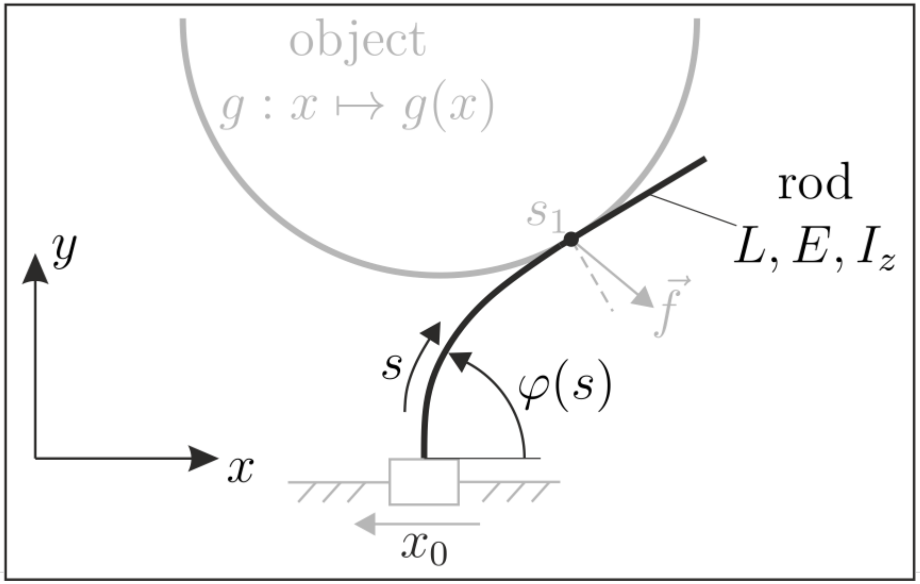


2. Mechanical Model

technical vibrissa (probe)

- nonlinear Euler-Bernoulli bending rod
- length L
- one-sided clamped at x_0
- isotropic, homogeneous Hooke's material
- constant Young's modulus E and second moment of area I_z

mechanical model



dimensionless treatment

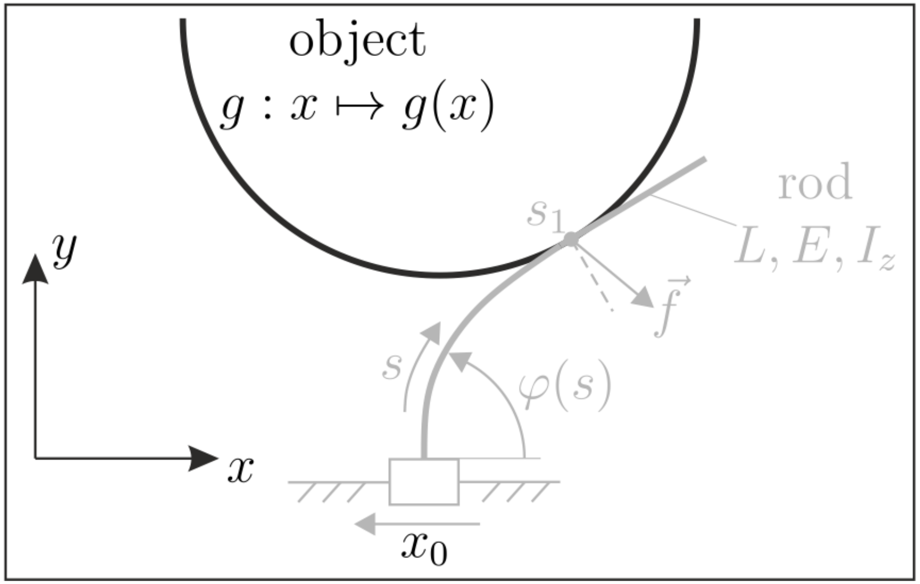
- introducing the following units of measure:
  - $[length] \coloneqq L,$
  - $[force] \coloneqq \frac{EI_z}{L^2},$
  - $[moment] \coloneqq \frac{EI_z}{L}$

2. Mechanical Model

object

- rigid body
- strictly convex profile contour function, parameterized by angle
$$\tilde{\alpha} \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right) \mapsto \left(\xi(\tilde{\alpha}), \eta(\tilde{\alpha})\right)$$
- here: circular object contour (only for example)

mechanical model



contact

- strict convexity ⇒ only one contact point
- Coulomb friction:

$$\vec{f} = \vec{f}_n + \vec{f}_t$$
$$= f \cdot \left[\sin(\alpha)\,\vec{e}_x - \cos(\alpha)\,\vec{e}_y\right]$$

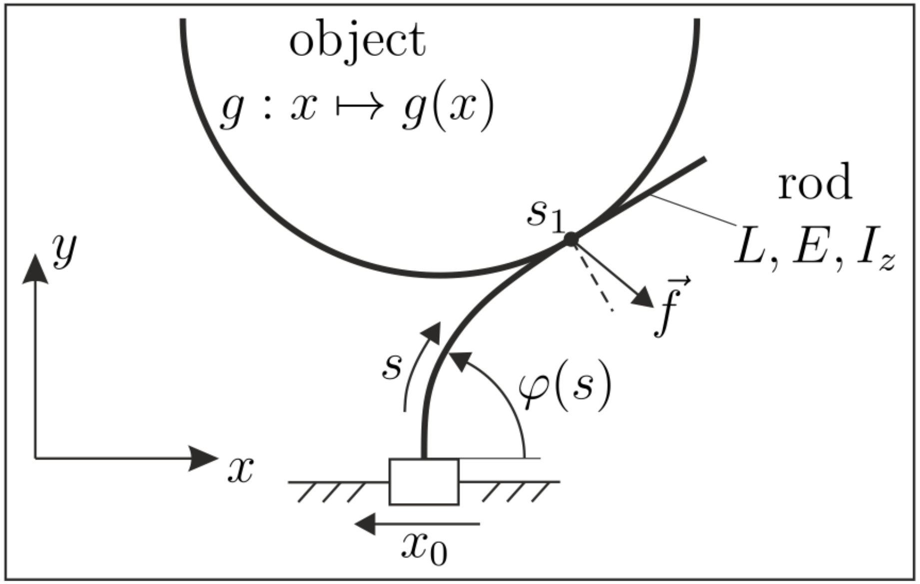
$$\mu = \frac{\left|\vec{f}_t\right|}{\left|\vec{f}_n\right|} = \tan(\zeta)$$

2. Mechanical Model

scanning process

- plane scanning sweep
- quasi-static process
- translational displacement of the clamping position x_0 (input variable)

mechanical model



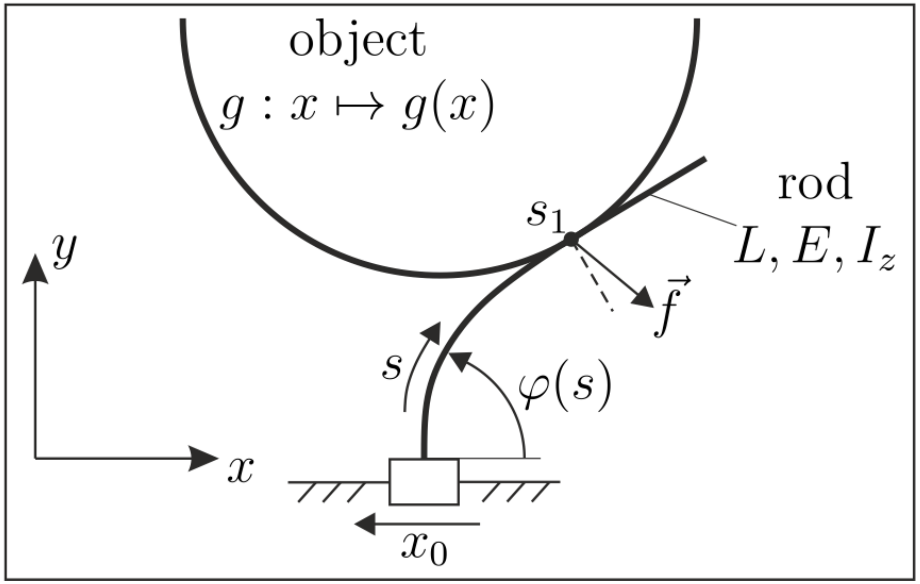
2. Mechanical Model

deformation of the rod

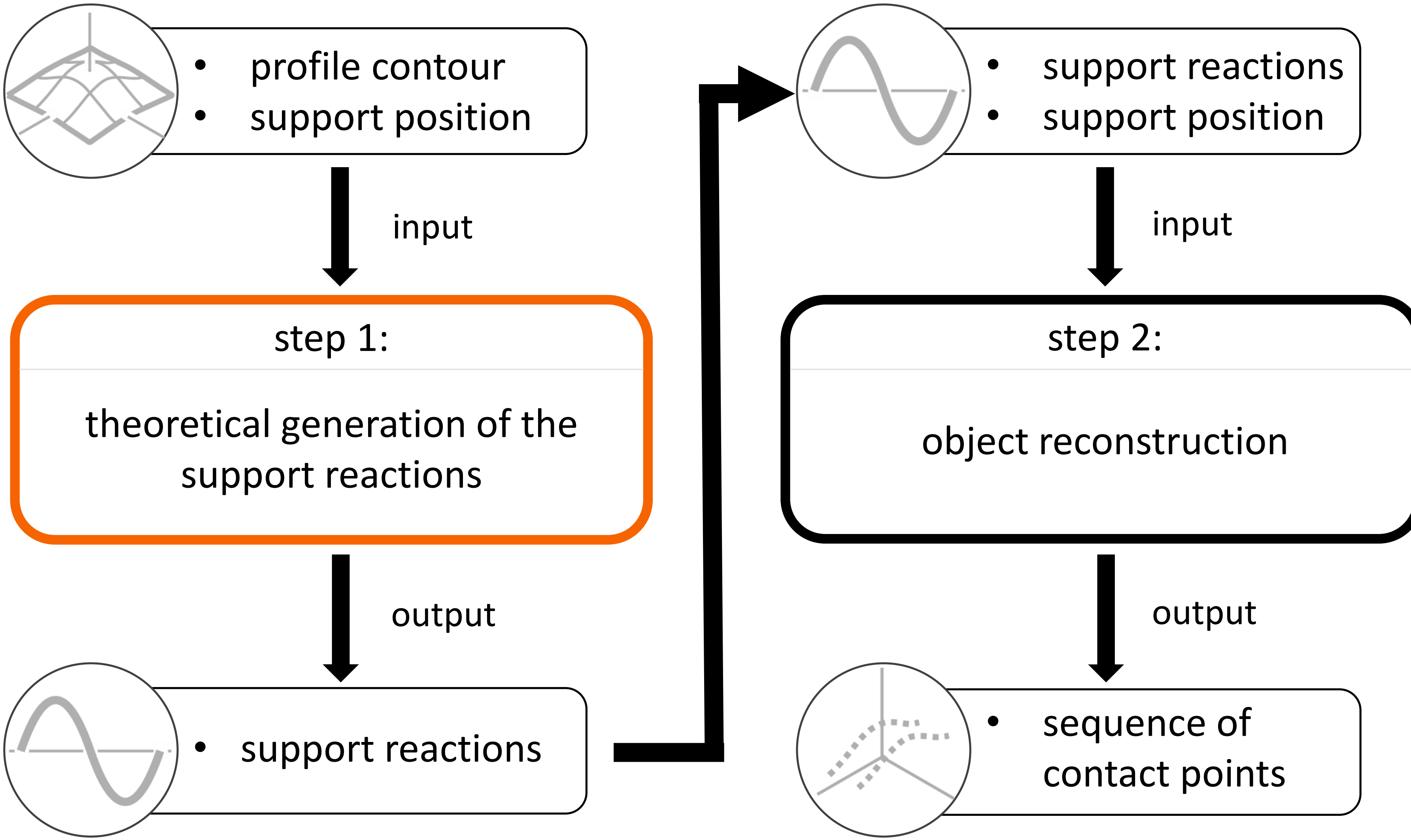
$$x'(s) = \cos(\varphi(s))$$
$$y'(s) = \sin(\varphi(s))$$
$$\varphi'(s) = \kappa(s)$$
$$\kappa'(s) = f \cdot \cos(\varphi(s) - \alpha)$$

- system of nonlinear ordinary differential equations (ODE) of first order
- used in two steps… in the following

mechanical model



2. Mechanical Model – Step 1



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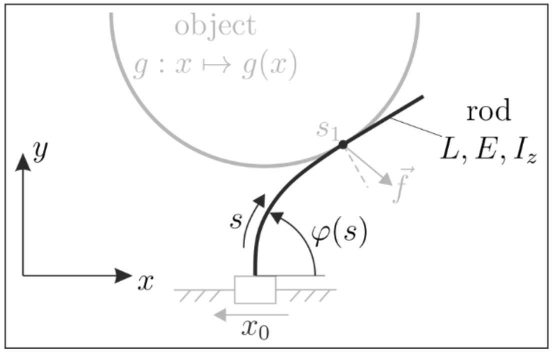
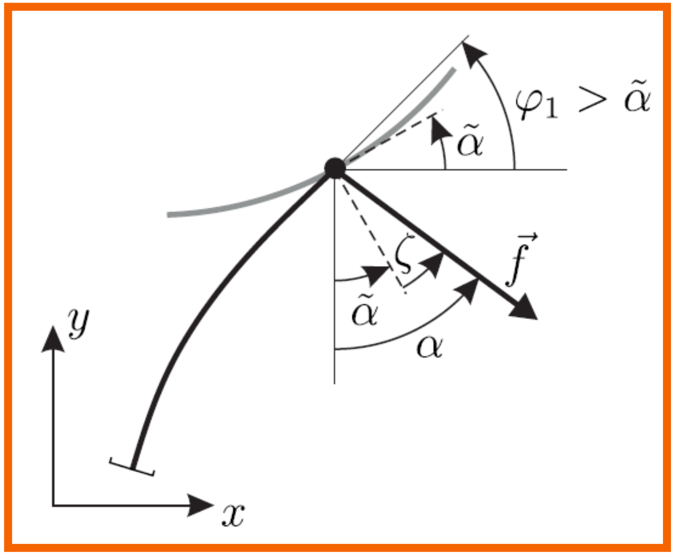
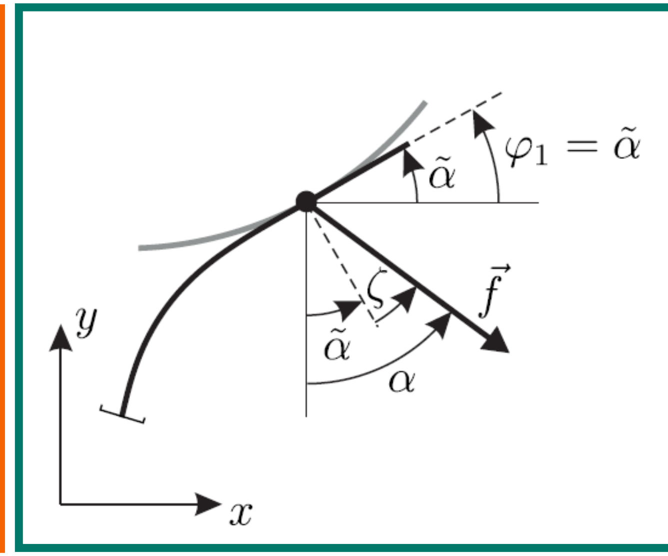






two-point boundary-value problem:

elastic line

$$x'(s) = \cos(\varphi(s))$$
$$y'(s) = \sin(\varphi(s))$$
$$\varphi'(s) = \kappa(s)$$
$$\kappa'(s) = f \cdot \cos(\varphi(s) - \alpha)$$

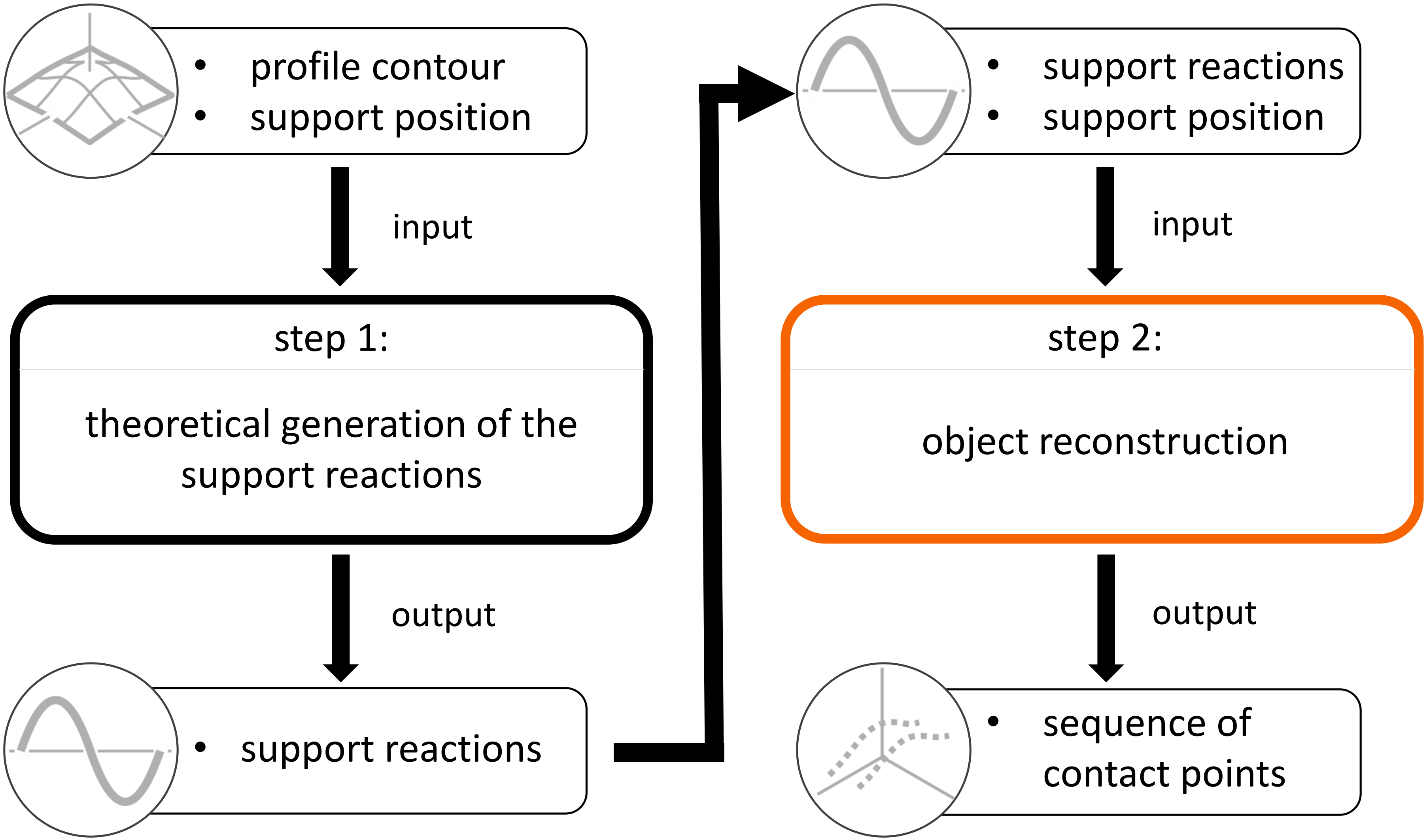
tip contact

$$x(0) = x_0 \qquad x(1) = \xi(\tilde{\alpha})$$
$$y(0) = 0 \qquad y(1) = \eta(\tilde{\alpha})$$
$$\varphi(0) = \frac{\pi}{2}$$
$$\kappa(1) = 0$$

tangential contact

$$x(0) = x_0 \qquad x(s_1) = \xi(\tilde{\alpha})$$
$$y(0) = 0 \qquad y(s_1) = \eta(\tilde{\alpha})$$
$$\varphi(0) = \frac{\pi}{2} \qquad \varphi(0) = \tilde{\alpha}$$
$$\kappa(1) = 0$$

2. Mechanical Model – Step 2



2. Mechanical Model – Step 2

reaction forces
(known from Step 1 or from measurements):

known quantities: $x_0, \varphi_0, f_x, f_y, m_z$

$$f = \sqrt{f_x^2 + f_y^2}, \qquad \alpha = -\arctan\left(\frac{f_x}{f_y}\right)$$

initial-value problem (IVP)

$$\begin{aligned} x'(s) &= \cos(\varphi(s)) & x(0) &= x_0 \\ y'(s) &= \sin(\varphi(s)) & y(0) &= 0 \\ \varphi'(s) &= \kappa(s) & \varphi(0) &= \varphi_0 \\ \kappa'(s) &= f \cdot \cos(\varphi(s) - \alpha) & \kappa(0) &= -m_z \end{aligned}$$

[Scholz and Rahn 2004]:

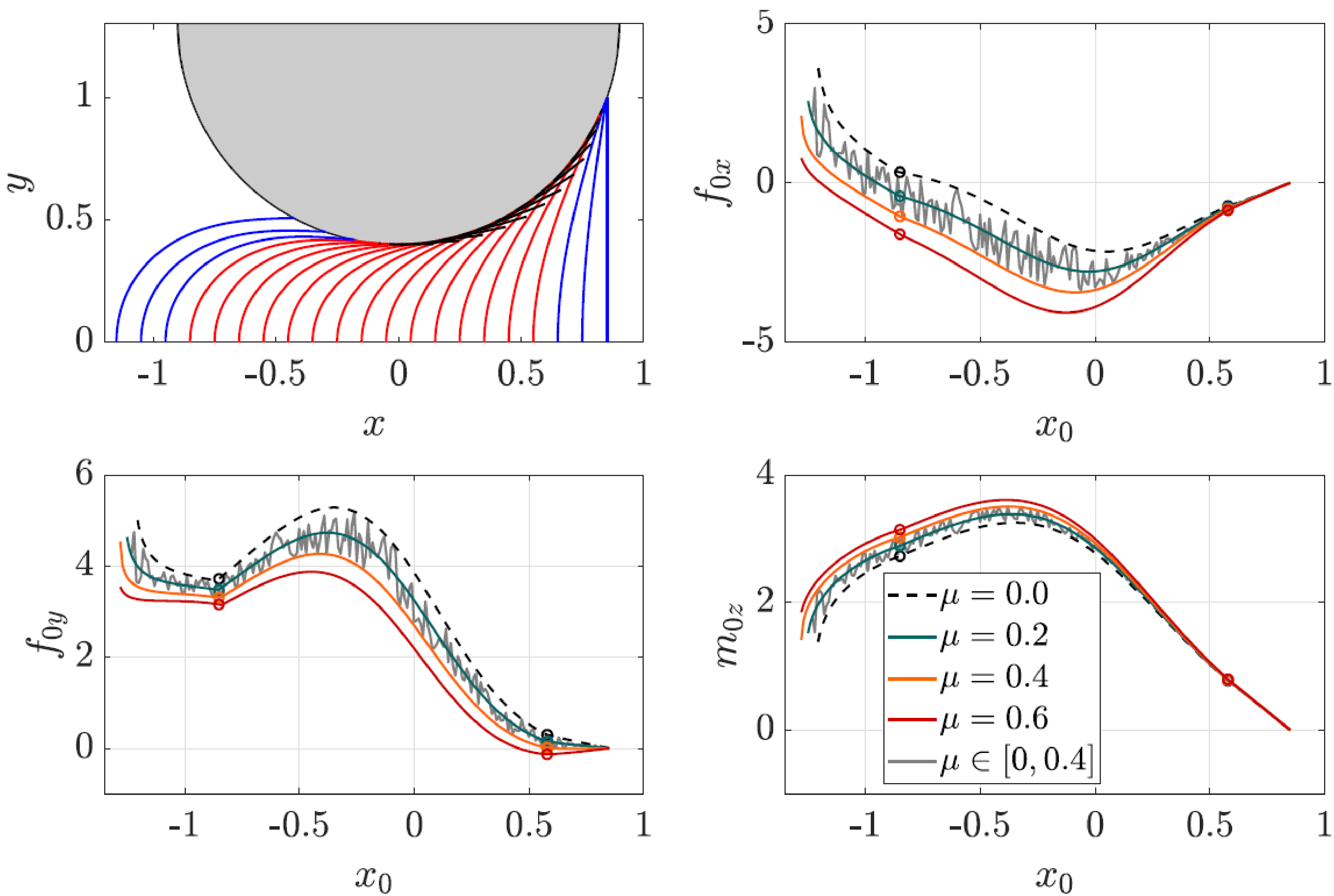
- numerical integration of the IVP
- using an event function
  - cancels further computation if $\kappa(s_1) = 0$ (termination condition)

[Will et. al. 2018]:

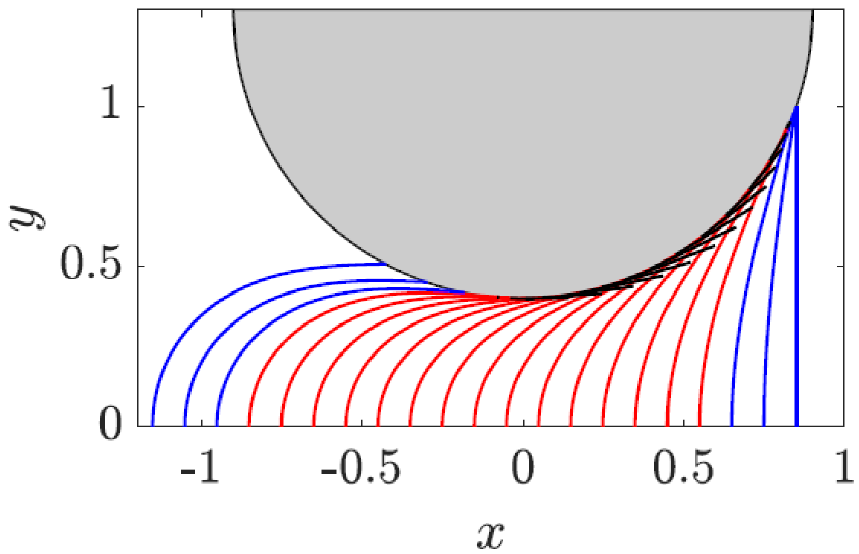
- analytical integration of the IVP
- using an analytic expression

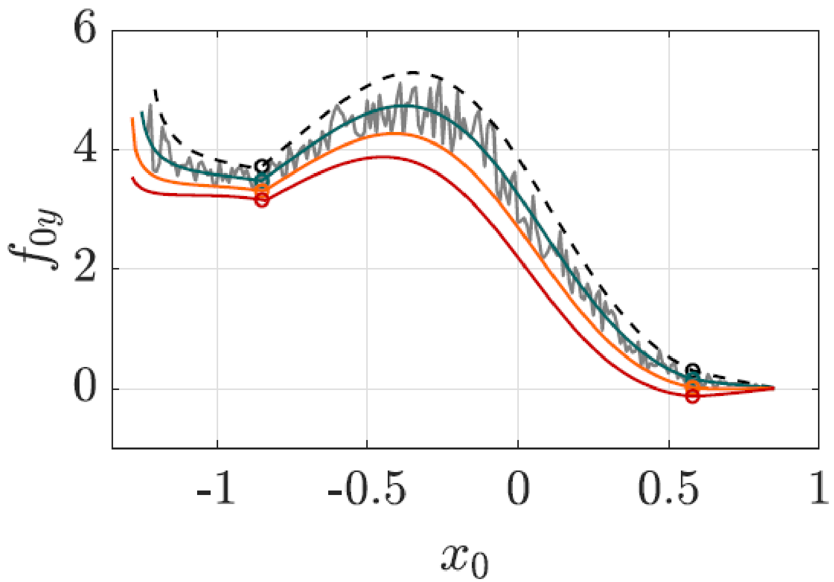
$$s_1 = -\frac{1}{\sqrt{f}} \int_{\frac{\pi}{2}}^{\tilde{\alpha}} \frac{1}{\sqrt{\sin(t - \tilde{\alpha})}} dt$$

3. Simulation Results – Step 1



3. Simulation Results – Step 1

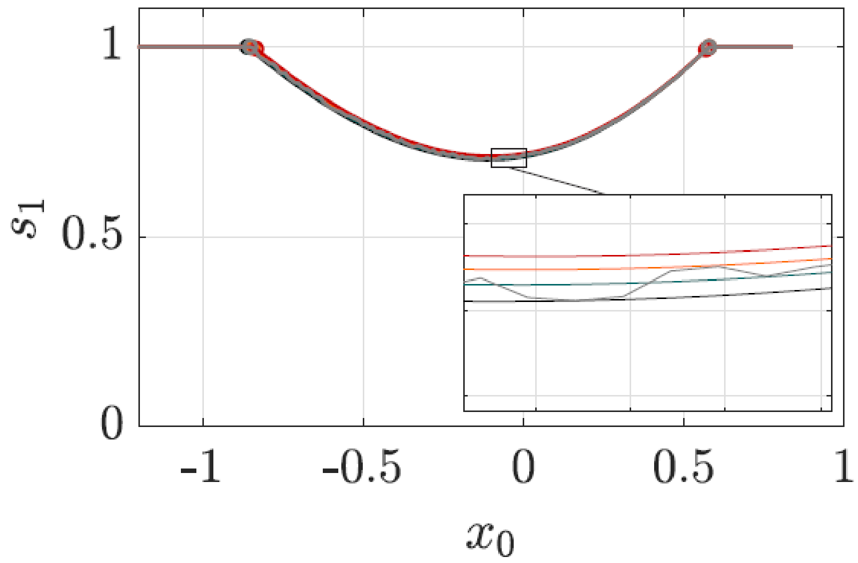


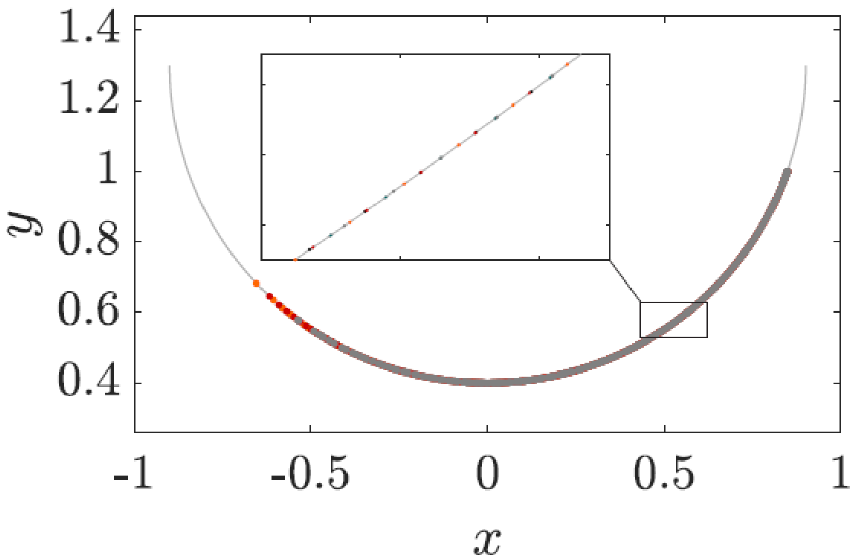


- all support reactions are affected by friction
- increasing friction coeffictient results in a longer contact phase
- the friction coefficient has little impact on the transitions between tip and tangential contacts

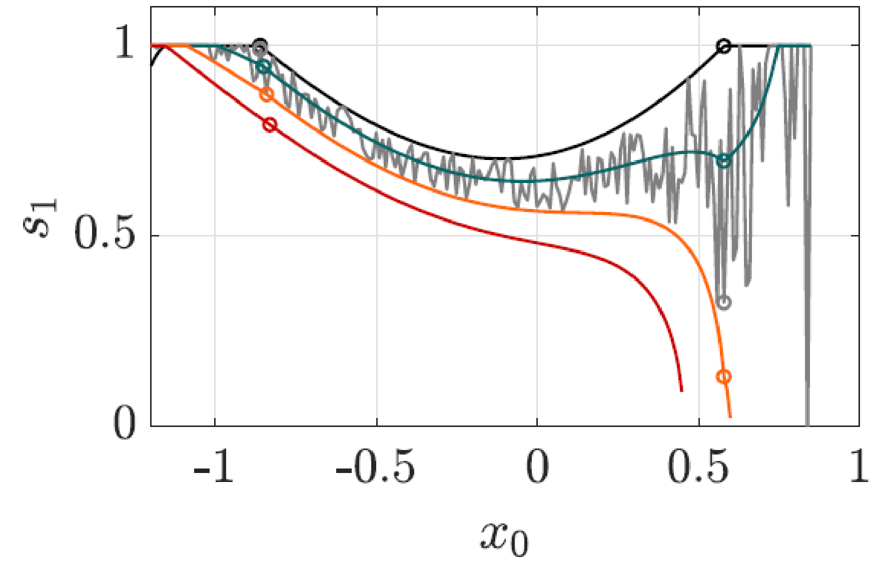
3. Simulation Results – Step 2

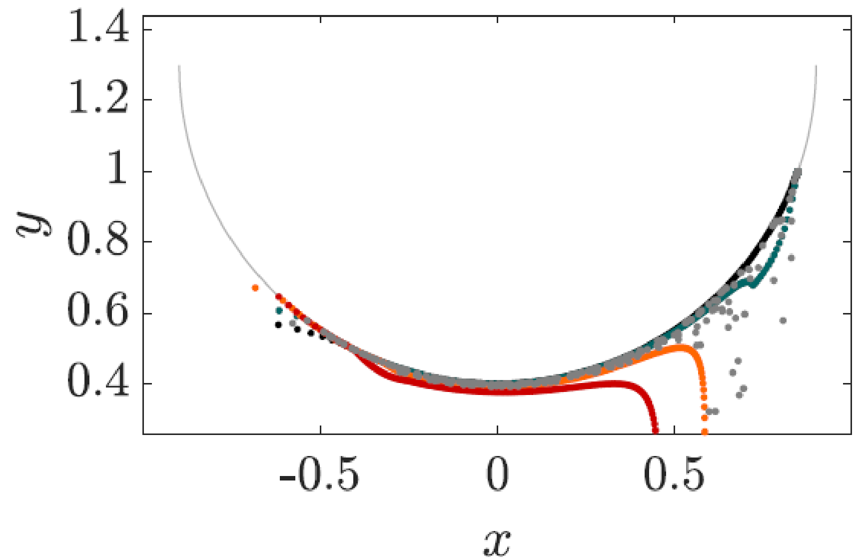
[Scholz and Rahn 2004]:





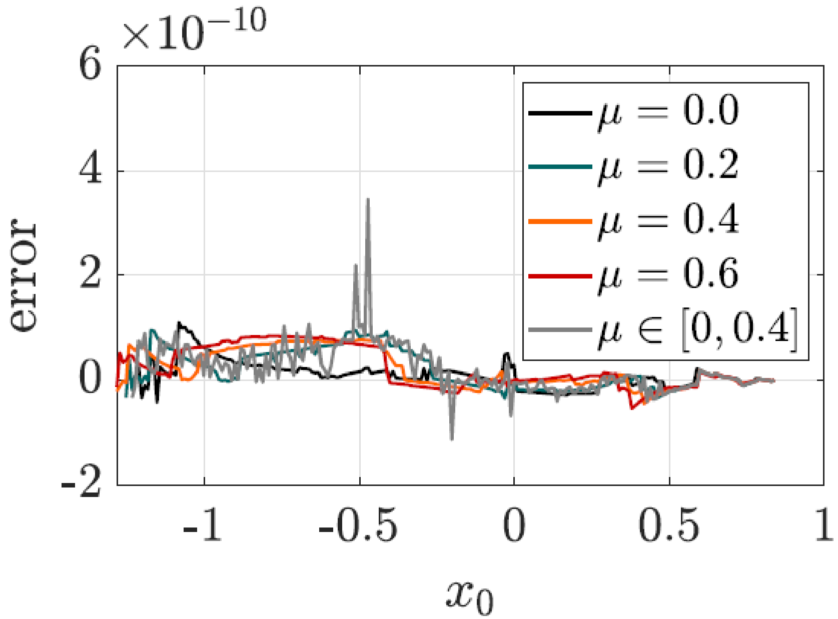
[Will et. al. 2018]:



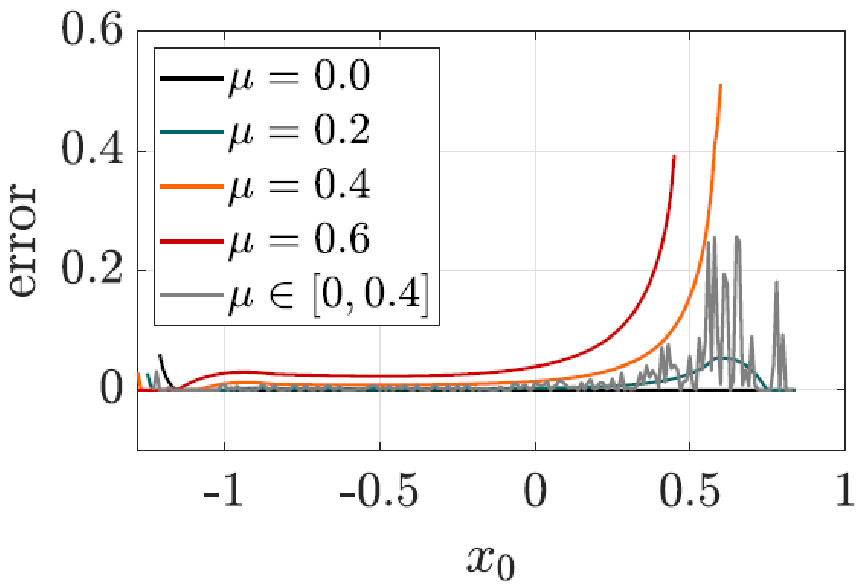


3. Simulation Results – Step 2

[Scholz and Rahn 2004]:

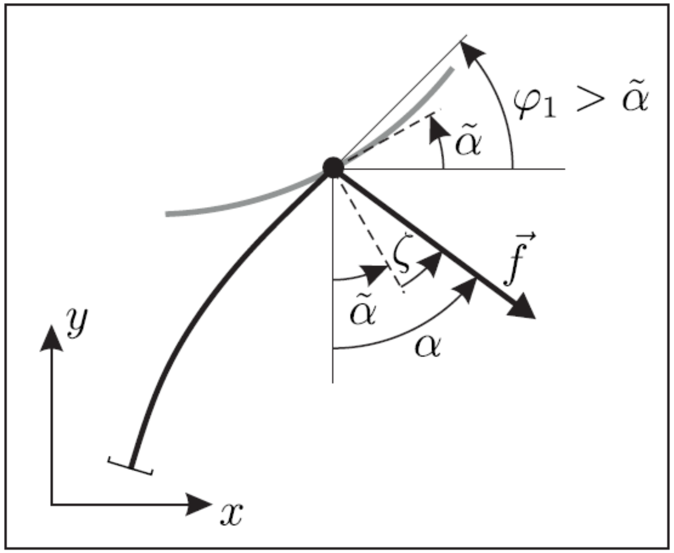


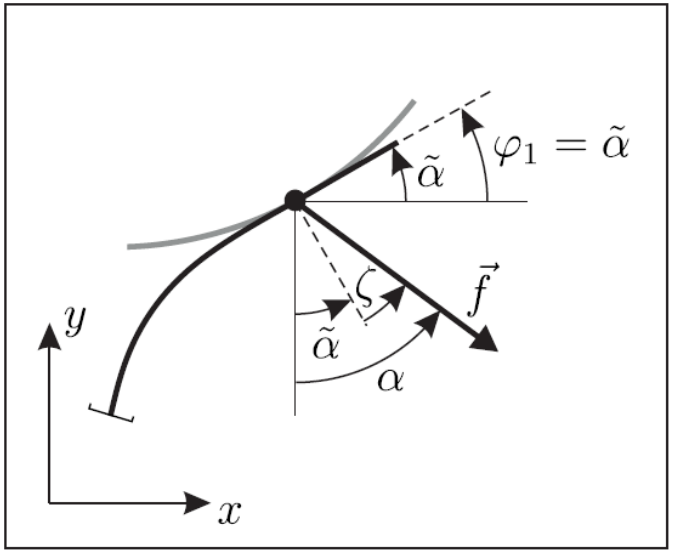
[Will et. al. 2018]:



- regardless of the friction coefficient, the reconstruction error lies within numerical boundaries
- large reconstruction errors, resulting from errors of the contact position s_1

4. Reconstructing Friction Parameters





$$\kappa'(s) = f \cdot \cos(\varphi(s) - \alpha)$$

$$\kappa(0) = -m_{0z}$$

$$\kappa(s_1) = 0$$

$$\varphi(0) = \frac{\pi}{2}$$

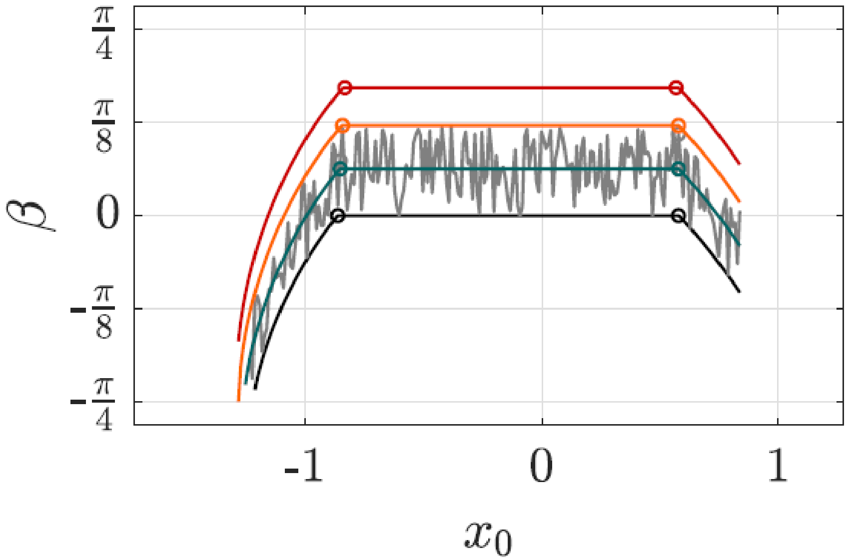
$$\varphi(s_1) = \varphi_1$$

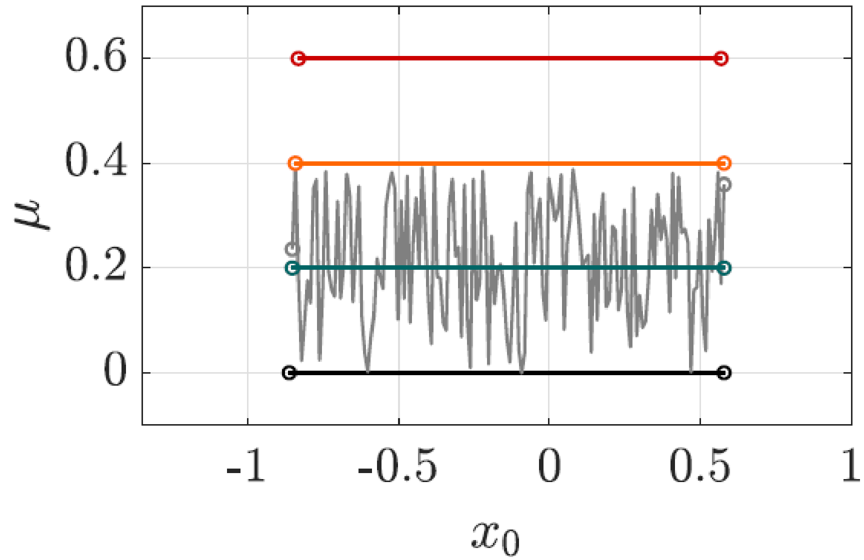
$$\varphi_1 = \alpha - \arcsin\left(\frac{m_{0z}^2 - 2f_{0y}}{2f}\right) = \tilde{\alpha} + \zeta - \beta$$

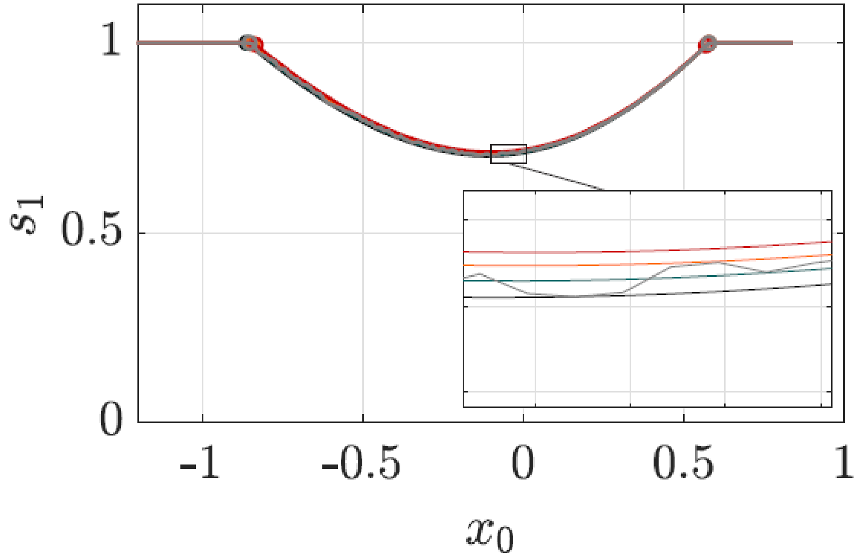
tangential contact:

$$\boxed{\zeta = \beta = \arcsin\left(\frac{m_{0z}^2 - 2f_{0y}}{2f}\right)}$$

4. Reconstructing Friction Parameters







$$\varphi_1 = \alpha - \arcsin\left(\frac{m_{0z}^2 - 2f_{0y}}{2f}\right) = \tilde{\alpha} + \zeta - \beta$$

tangential contact:

$$\boxed{\zeta = \beta = \arcsin\left(\frac{m_{0z}^2 - 2f_{0y}}{2f}\right)}$$

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5. Summary & Outlook

Summary

- adapting a vibrissa-inspired sensor model for object contour scanning and reconstruction including Coulomb‘s friction
- friction affects the support reactions during scanning
- the recontruction error is invariant against friction
- analytical condition: reconstructing friction parameters during tangential contact

Outlook

- using different kinds of objects and distances
- validating the mentioned findings in experiments
- adapting the model for spatial problems
- conical and pre-curved rods

+ - + - Breaking News - + - + -

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

6. References

[1] B. Mitchinson et al., “Active vibrissal sensing in rodents and Marsupials,“ Phil. Trans. R. Soc., vol. 366, pp. 3037 – 3048, 2011.

[2] C. Will, C. Behn, and J. Steigenberger, “Object contour scanning using elastically supported technical vibrissae,” ZAMM J. Appl. Math. Mec., vol. 98, pp. 289-305, 2018.

[3] G. R. Scholz and C. D. Rahn, „Profile sensing with an actuated whisker,“ IEEE Trans. Rob. Autom., vol. 20, pp. 124-127, 2004.

hints for further references:

[4] L. Merker, J. Steigenberger, R. Marangoni, and C. Behn, “A vibrissainspired highly flexible tactile sensor: scanning 3D object surfaces providing tactile images,” Sensors, vol. 21, 2021.

[5] L. Merker, S. J. Fischer Calderon, M. Scharff, J. H. A. Miranda, and C. Behn, “Effects of Multi-Point Contacts during Object Contour Scanning Using a Biologically-Inspired Tactile Sensor,” Sensors, vol. 20, 2020.

[6] T. J. Prescott, B. Mitchinson, and R. A. Grant, “Vibrissal behavior and function,” Scholarpedia, vol. 6, pp. 6642, 2011.