Adaptive Force Control Solutions

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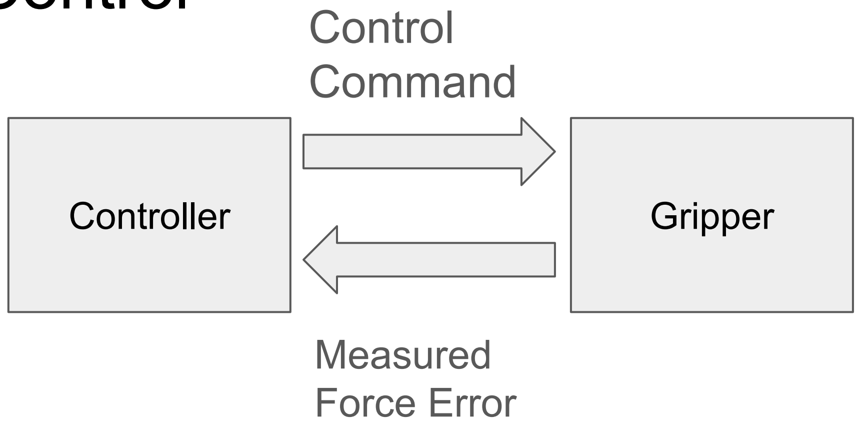
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Motivation - Adaptive Force Control

- Impedance Controller as classical real time Force controller
- Reacts only to measured Values



Idea : Predict parameters parameters

[1] Kevin M Lynch and Frank C Park. Modern robotics. Cambridge University Press, 2017.

Motivation - Problem Overshoot

- All Controllers that are based on measured values can produce overshoot
- Risk of destruction or slippage

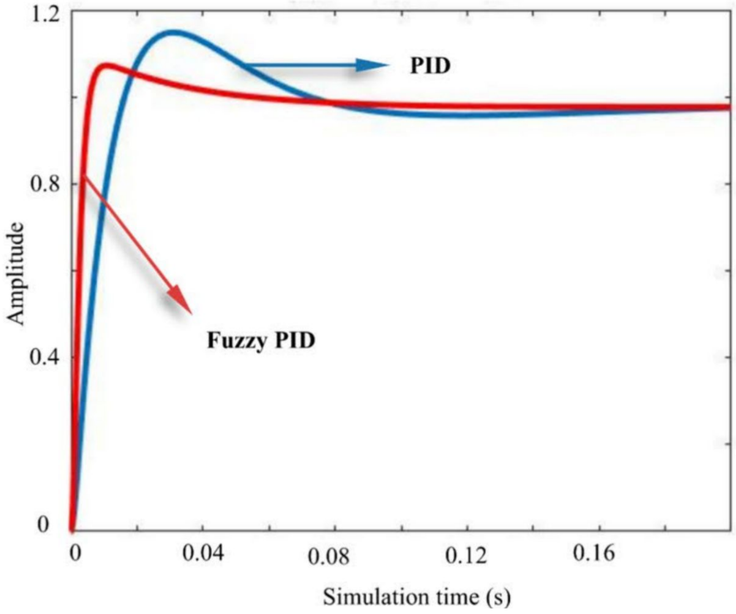


Figure in [2]

→ Idea : Adaptive Force Control to predict future force

[2] Junchang Zhang et al. “Force Sensing and Force Control of Flexible Gripper with Integrated Flexible Strain and Tactile Sensors for Strawberry Non-Destructive Gripping and Freshness Grading”. In: Food and Bioprocess Technology (2025), pp. 1–22

Motivation - Force Oscillation

- Grippers Control Discretized
- Discrete Gripper Configuration Space

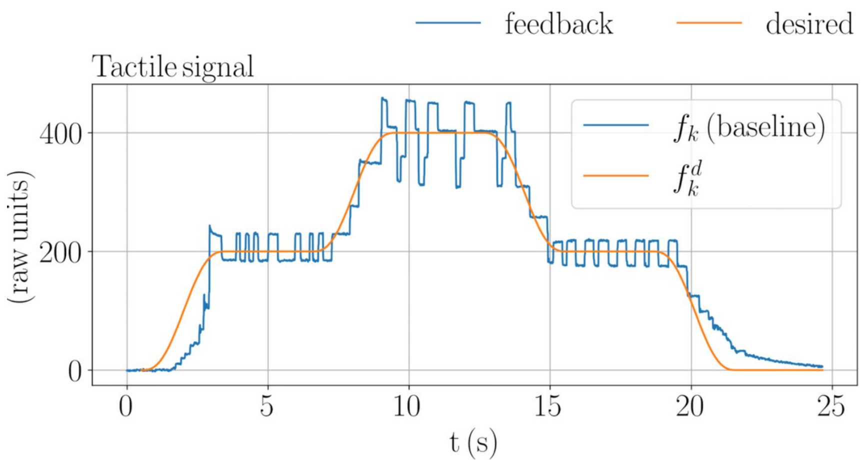


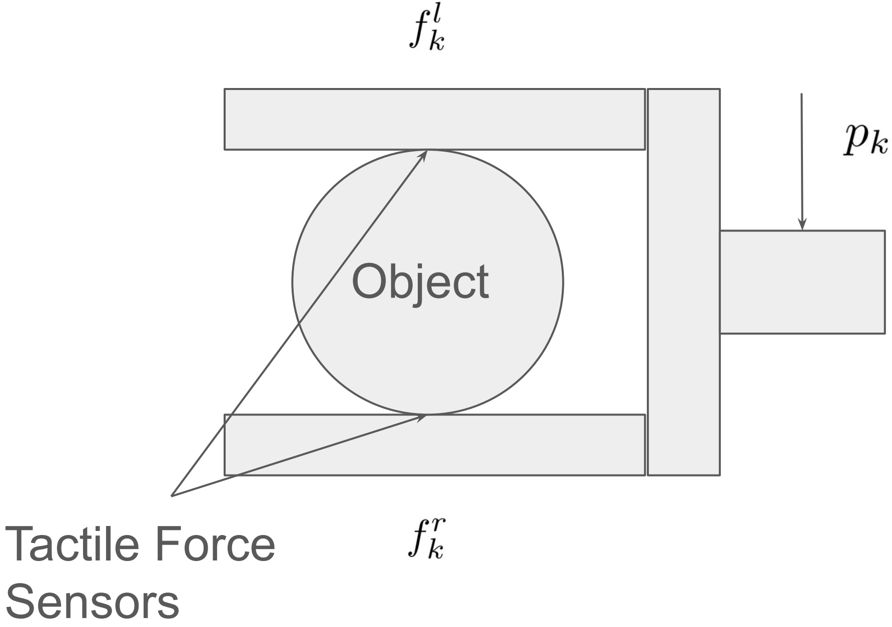
Figure [3]

⇒ Target Forces of Controler may never be reached

[3] Nicola A Piga and Lorenzo Natale. “Adaptive tactile force control in a parallel gripper with low positioning resolution”. In: IEEE Robotics and Automation Letters 8.9 (2023), pp. 5544–5551.

Modeling The Gripper

- 1 Degree of Freedom gripper at time $k \in \mathbb{N}$
- Mean Tactile Force $f_k = \dfrac{f_k^l + f_k^r}{2}$
- Discretized Gripper Aperture $p_k = \left\lfloor \dfrac{u_k}{\delta_p} \right\rfloor \delta_p = N_k \delta_p$
- Desired Continuous Aperture by Controller $u_k \in \mathbb{R}$

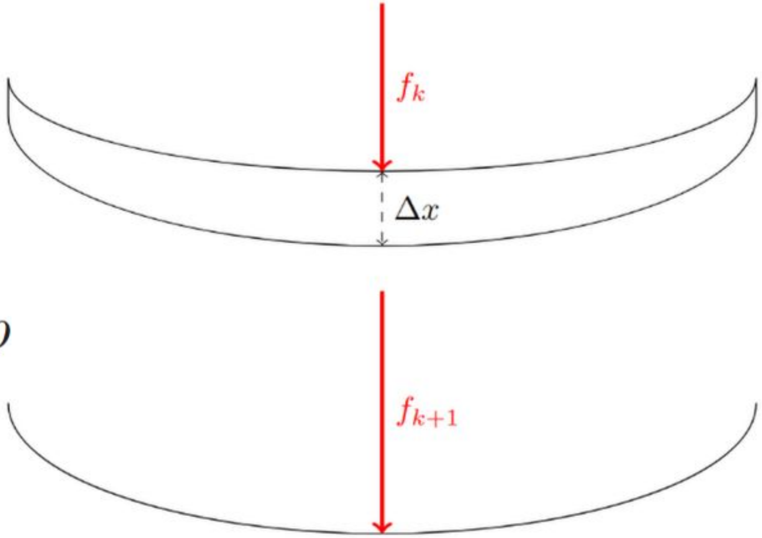


[3] Nicola A Piga and Lorenzo Natale. “Adaptive tactile force control in a parallel gripper with low positioning resolution”. In: IEEE Robotics and Automation Letters 8.9 (2023), pp. 5544–5551.

Stiffness

- How an Object deforms under Force

$$s = \frac{f_{k+1} - f_k}{\Delta x}$$



- Linear Relation: Gripper Position ~ Output Force

$$f(p) = c_0 + c_1 p$$

Relation is Material Dependent!

[4] Zhaoxing Deng, Xutian Deng, and Miao Li. “Learning Based Adaptive Force Control of Robotic Manipulation Based on Real-Time Object Stiffness Detection”. In: arXiv preprint arXiv:2109.06702 (2021)

Modeling the Controller

- Linear Relation $$f(p) = c_0 + c_1 p$$
- Measured Error $$e_k = f_k^d - f_k$$
- Next Controller aperture value $$u_{k+1} = u_k + k_i e_k \Delta_t$$

$$\Rightarrow \quad e_{k+1} = -c_1 \left\lfloor \frac{u_k + k_i e_k \Delta_t}{\delta_p} \right\rfloor \delta_p + f_{k+1}^d - c_0$$

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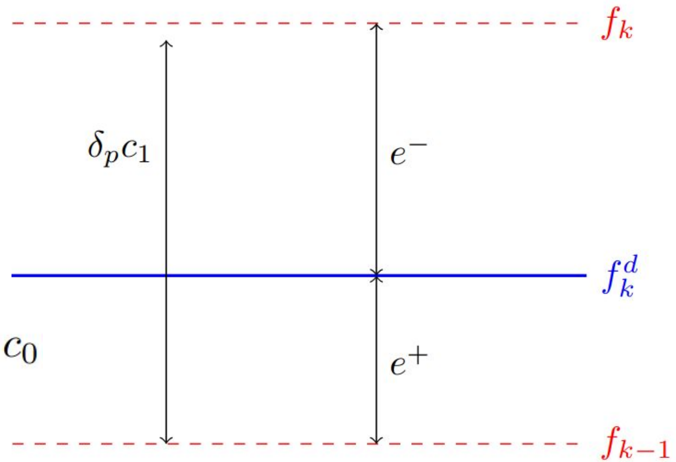
Proof of Oscillation

System at Equilibrium $e_{k+1} = e_k = e_{eq}$

From Controller Model $e_{eq} = -c_1 \left\lfloor \frac{u_{eq} + k_i e_{eq} \Delta_t}{\delta_p} \right\rfloor \delta_p + f_{eq}^d - c_0$



$e_{eq} = 0$ only if $\left| \frac{f_{eq}^d - c_0}{c_1 \delta_p} \right| \in \mathbb{N}.$

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Solution: Adaptive Force Control

Adaptive Controller on Future Error

$$u_{k+1} = u_k + \Delta_u,$$

$$\Delta_u = \begin{cases} k_i e_k \Delta_t & |e^m_{k+1}| < |e_k| \\ 0 & \text{otherwise.} \end{cases}$$

Predict Future Error

$$e^m_{k+1} = f^d_{k+1} - f^m_{k+1}$$

$$f^m_{k+1} = f\left(p_k + \delta(e_k)\right)$$

$$\delta(e_k) = \text{sgn}(e_k) \left\lceil \frac{|e_k|}{c_1 \delta_p} \right\rceil \delta_p$$

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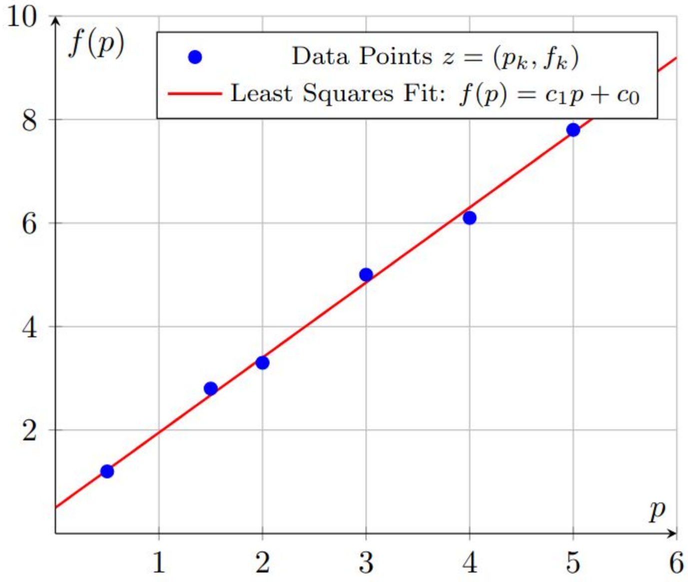
Measurement Prediction

$$f_{k+1}^{m} = f\left(p_k + \delta(e_k)\right)$$

Requires Knowledge of Function f

Linear Regression with Least Squares Error

$$z = (p_k, f_k)$$



$$f(p) = \sum_{i=0}^{N} c_i p^i$$

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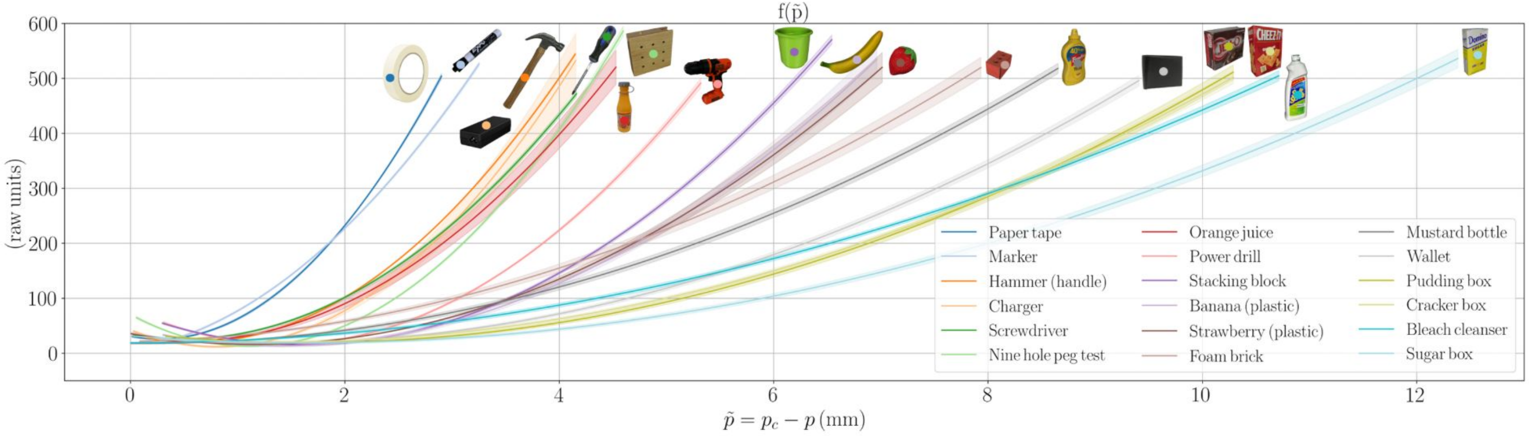
Material Experiments



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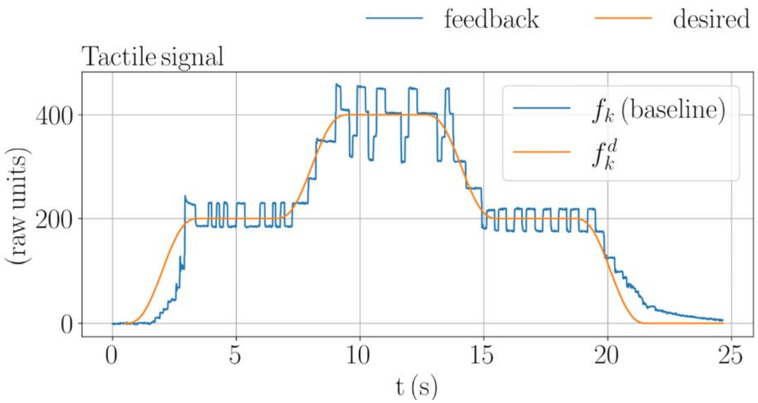
Results



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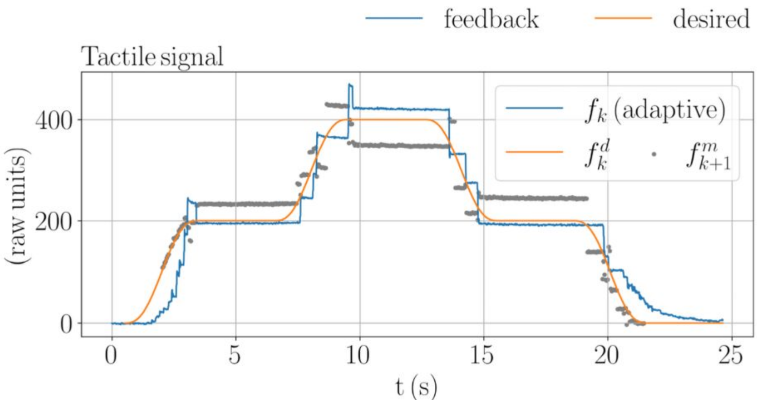

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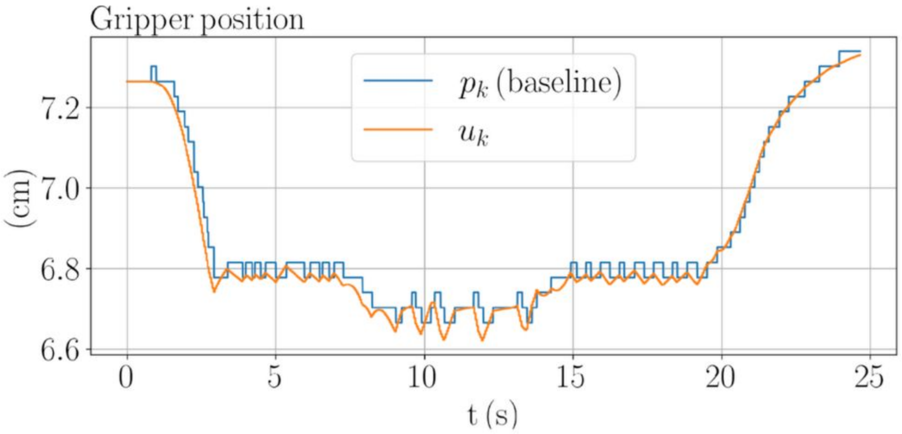

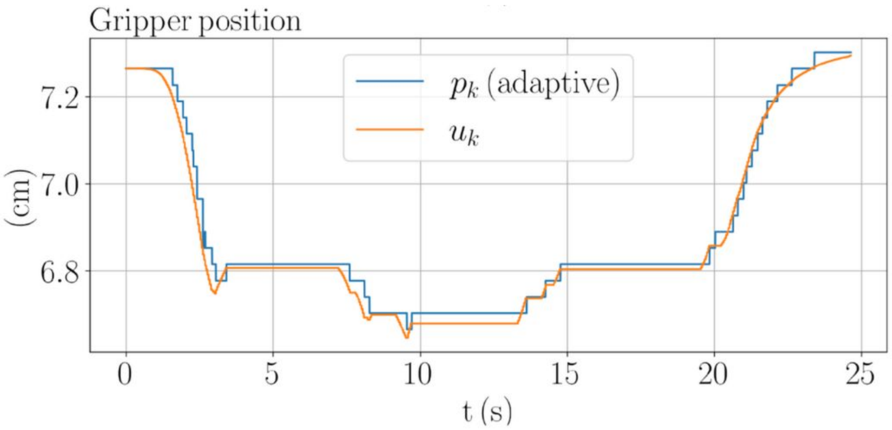

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Conclusion

- Output Force Oscillation can be prevented
- Prediction of Future Error can prevent Overshoot

Problems:

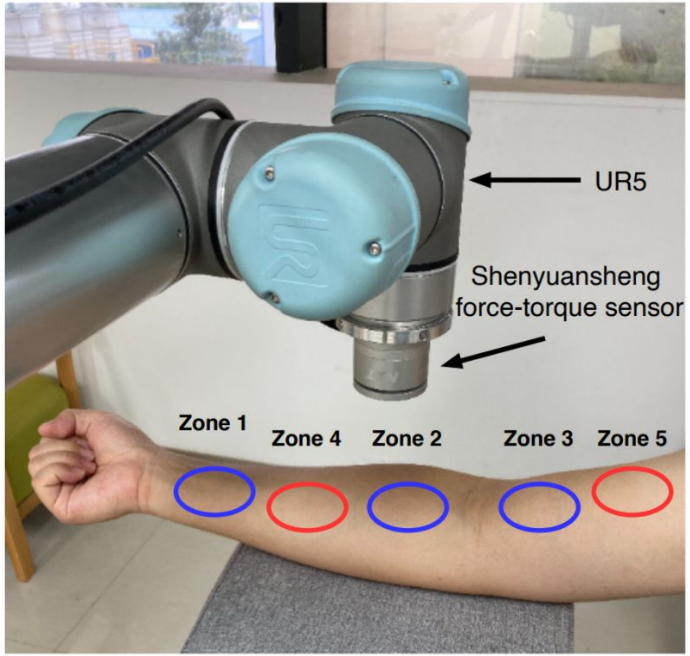
- Wrong Predictions can result in wrong Force Control
- The Selection of the Gain is Material Dependent

Questions?

Changing Environments

- Force Control on Medical Robot critical
- No simple model for all regions of the human body

⇨ Adaptive Force Control



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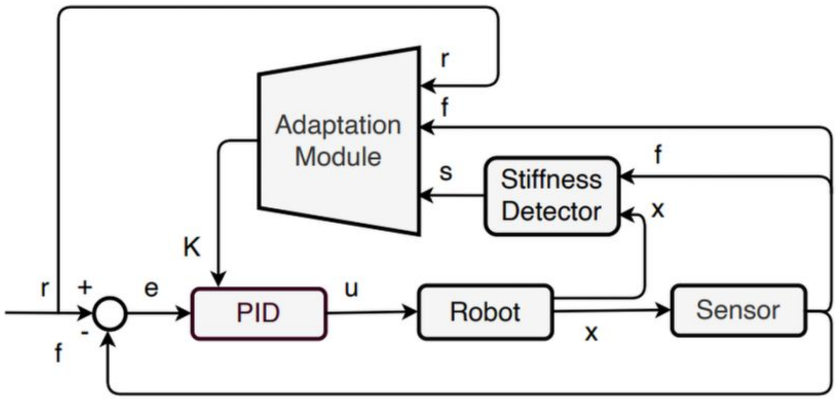
Proposed Controller

- Basis is a PID controller
- PID controller parameters are set by Adaptation Modul
- Modul is a NN



PID Force Controller:

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