Intrinsically Elastic Robots: Safety, Optimal Control, & Cyclic Motion

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Introduction

Common reasons for intrinsic elasticity:

- Better safety
- Better energy efficiency
- Better robustness

None of these arguments can be answered uniquely with *yes* or *no* (except maybe robustness, but this still has to prove in the full context of applications, reliability,...). It depends on the task.

Problems we investigate

At DLR we investigate following problems:

- Safety for VIA: injury analysis & collision detection and reaction
- Optimal control for VIA: performance increase through elastic energy storage and release
- Motion and interaction control: vibration damping, impedance control
- Elasticity for cyclic manipulation motions
- Learning impedances based on human motor control insights (together with Imperial College)

Problems we investigate

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Safety for VIA

Collision experiments

Momentum based detection

Rigid body dynamics

$$M(\mathbf{q})\ddot{\mathbf{q}} + C(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + \mathbf{g}(\mathbf{q}) = \boldsymbol{\tau}_J + \boldsymbol{\tau}_{\mathbf{ext}} \tag{1}$$

$$\mathbf{p} = M(\mathbf{q})\dot{\mathbf{q}}, \tag{2}$$

Reformulated dynamics

$$\dot{\mathbf{p}} = \boldsymbol{\tau}_J - \beta(\mathbf{q},\dot{\mathbf{q}}) - \boldsymbol{\tau}_{\mathbf{ext}} \tag{3}$$

where

$$\beta(\mathbf{q},\dot{\mathbf{q}}) = \mathbf{n}(\mathbf{q},\dot{\mathbf{q}}) - \dot{M}(\mathbf{q})\dot{\mathbf{q}} = C(\mathbf{q},\dot{\mathbf{q}}) + \mathbf{g}(\mathbf{q}) - \dot{M}(\mathbf{q})\dot{\mathbf{q}} \tag{4}$$

Momentum based detection

It can be shown that the observed disturbance $\hat{\mathbf{r}}$ is a component-wise filtered version of the real external torque $\boldsymbol{\tau}_{\mathrm{ext}}$:

$$\hat{r}^i = \frac{1}{sT_O^i + 1}\tau_{\mathrm{ext}}^i = \frac{K_O^i}{s + K_O^i}\tau_{\mathrm{ext}}^i \approx \tau_{\mathrm{ext}}^i \quad \forall i \in \{1, ..., n\} \quad (5)$$

$$\hat{\mathbf{r}} = (\hat{r}^1 \cdots \hat{r}^n). \quad (6)$$

The dynamics of $\hat{\mathbf{r}}$ is

$$\dot{\hat{\mathbf{r}}} = -K_O\hat{\mathbf{r}} + K_O\boldsymbol{\tau}_{\mathrm{ext}}. \quad (7)$$

Collision detection: soft-tissue injury

VIA impact cases

There are **two** important impact cases.

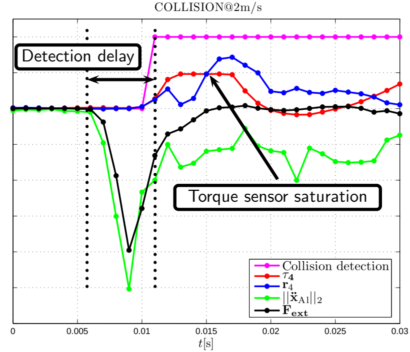
1. collisions **without** preceding elastic energy storage and release
2. collisions **with** preceding elastic energy storage and release

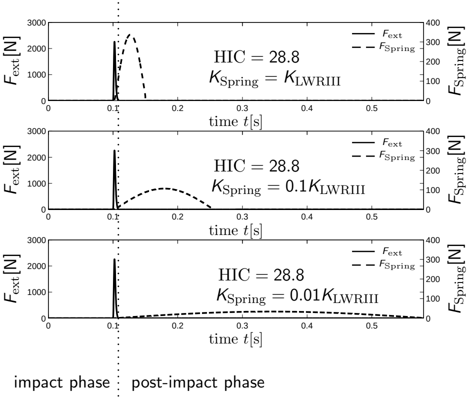
Up to now:

- motor and link collide **at the same** velocity (e.g. original work by Bicchi, Khatib)
- $\rightarrow$ decoupling improves the impact characteristics (however only for certain conditions, see next sllide)
- speed gain was not considered at all (case 2)

However, it is well known that velocity influences HIC (Head Injury Criterion) more than quadratically, whereas inertia shows a saturation effect.

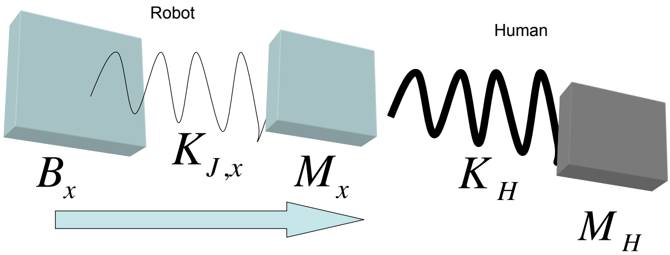
COLLISION LWR-HUMAN HEAD





→ Joint stiffness reduction does not help for the full manipulator LWR-III. **It is already decoupled!**

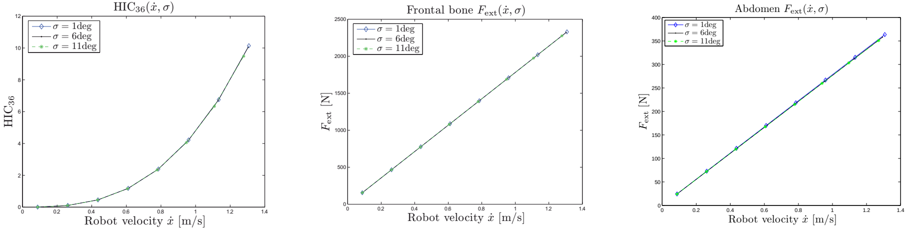
Collision LWR-human head



$$B_x > M_x \quad \boxed{M_x \approx M_H} \quad K_{J,x} << K_H \tag{8}$$

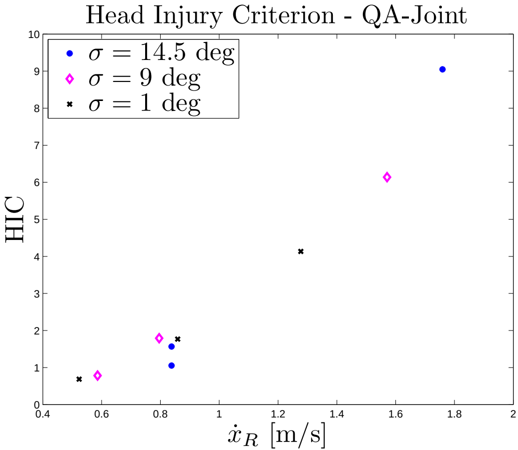
$M_x = 4.0$ kg, $K_H = 10^3$ kN/m
→ Decoupling already present for realistic link inertia and moderate (non-desired) joint stiffness!
→ **These are conditions of a full scale robot!**

VSA: Case 1



Simulation analysis for the DLR QA-Joint.

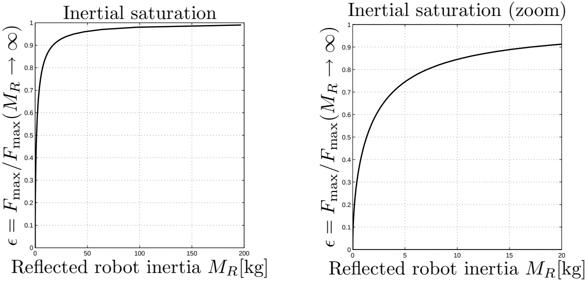
VSA: HIC experiment: case 1



Low values due to suppression of elastic shifts by vibration damping.

Case 1

$$\mathrm{HIC} = 2\left(\frac{M_x}{(M_x+M_H)g}\right)^{\frac{5}{2}} \alpha^{-\frac{3}{2}} (\sin\alpha)^{-\frac{5}{2}} \left(\frac{M_x+M_H}{M_x M_H}\right)^{\frac{3}{4}} K_H^{\frac{3}{4}} ||\dot{\mathbf{x}}_0||^{\frac{5}{2}}$$



$$\mathrm{HIC} = 2g^{-\frac{5}{2}} \alpha^{-\frac{3}{2}} (\sin\alpha)^{-\frac{5}{2}} M_H^{-\frac{3}{4}} K_H^{\frac{3}{4}} ||\dot{\mathbf{x}}_0||^{\frac{5}{2}}$$

$\rightarrow$ Impact velocity is the most important factor determining HIC!!!

Maximum velocity for n switchings

Simple optimal control problem: maximize $\dot{q}(T)$

$$\dot{\theta}(t) = u(t), \quad |u(t)| \leq u_{\max} \tag{9}$$

$$\ddot{q}(t) = \frac{K_J}{B}(\theta - q) \tag{10}$$

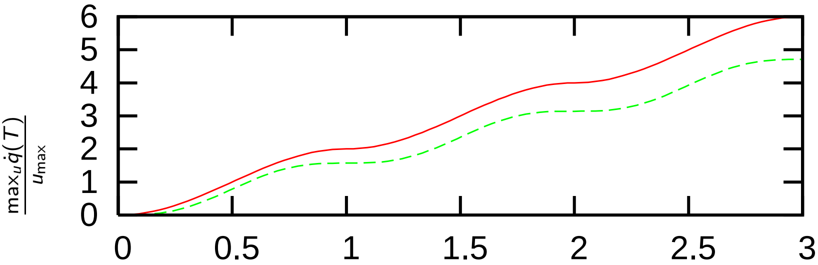
$$q(0) = \dot{q}(0) = \theta(0) = \dot{\theta}(0) = 0 \tag{11}$$

Solution:

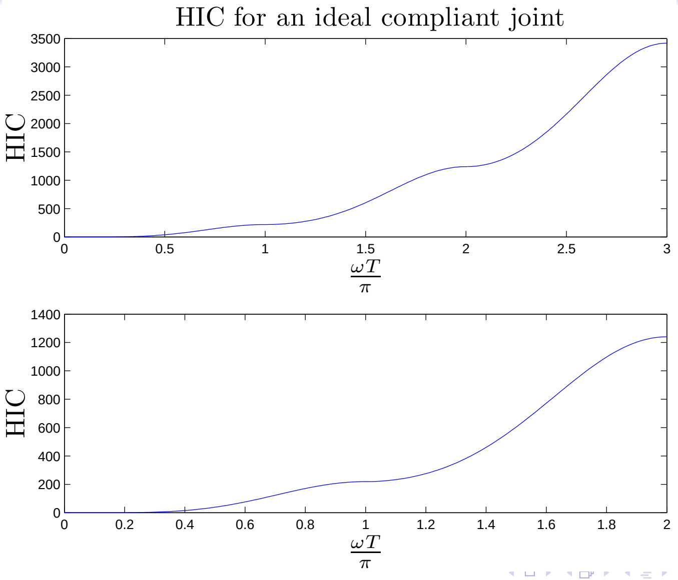
$$\max_u \dot{q}(T) = u_{\max}\big(2n + 1 - \cos(\omega T - n\pi)\big), \tag{12}$$

with $n = \lfloor \frac{\omega T}{\pi} \rfloor$ and $u = \dot{\theta}$.

Theoretical velocity gain: linear unbounded



Theoretical HIC



Realistic speed gain

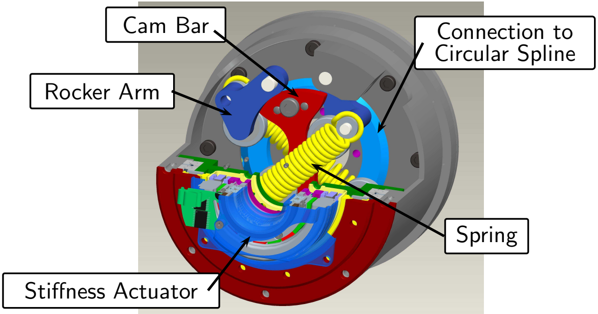
→ speed gain for a real joint (constrained deflection)

$$\dot{q}_{\max} = \dot{\theta}_{\max} + \boxed{\Delta \dot{q}_{\max}}$$

$$\dot{q}_{\max} = \dot{\theta}_{\max} + \sqrt{\frac{2}{M} E_{\max}(\varphi, \sigma^*)}$$

σ^* is the constant stiffness actuator preset (no variation through motion).

Speed gain QA-Joint



$$M_x = 3.1 \text{ kg} \qquad \dot{q}_{\max} = 2.9 \times 80 \text{ deg/s}$$

$$\dot{\theta}_{\max} = 80 \text{ deg/s} \longrightarrow HIC_{VSA} = \mathbf{14.1} \times HIC_{stiff}$$

Collision detection: QA-Joint

Conclusion VSA I

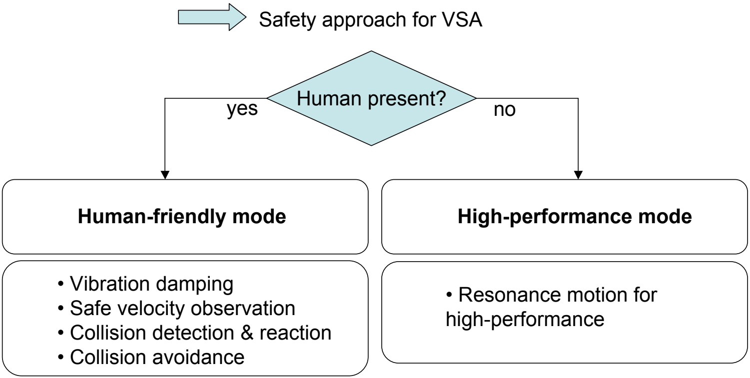
Active compliance (software)

- Decoupled for **high** contact stiffness
- Coupling for **low** contact stiffness
  - Software →
  - Decoupled for **low** contact stiffness

Intrinsic compliance (mechanical)

- Decoupled for **every** contact stiffness
- **High** velocities due to dynamic energy storage and release
  - Software →
  - Ensure **low** velocities by effective vibration damping and speed limitation

Conclusion VSA II



Literature: safety for VIA

- [Zinn et al., 2004]
- [Bicchi and Tonietti, 2004]
- [Haddadin et al., 2007a]
- [Van Damme et al., 2009]
- [Haddadin et al., 2007b]
- [De Luca et al., 2006]
- [Haddadin et al., 2008a]
- [Haddadin et al., 2010b]
- [Albu-Schäffer et al., 2008]
- [Haddadin et al., 2009a]
- [Haddadin et al., 2009b]

Literature: safety for VIA

- [Shin et al., 2008]
- [Bicchi et al., 2008]
- [Haddadin et al., 2008b]
- [Haddadin et al., 2009c]
- [Haddadin et al., 2010a]
- [Eiberger et al., 2010]
- [D.Gao and Wampler, 2009]
- [Ikuta et al., 2003]
- [Lim and Tanie, 2000]
- [Park et al., 2009]
- [Haddadin, 2011]

Optimal control for VIA

Child vs. KR500

Instep-kick with the DLR-LWRIII

Typical ball speed	27m/s
Needed speed with LWRIII	20.25m/s
Real speed with LWRIII	2.7m/s
Deficit	$\times 8$

$\longrightarrow$ Huge deficits!

How can we optimally utilize joint elasticity for highly dynamic (explosive) motions?

Optimal control for VIA

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t), \mathbf{u}(t)), \tag{13}$$

with $\mathbf{x}$ and $\mathbf{u}$ being the state vector and control input, respectively.

Optimality?
Integral cost functional is a reasonable choice, as it weights the final state with the function h and the timely evolution of the state and control input with integrating the function g.

$$J = h(\mathbf{x}(t_f), t_f) + \int_0^{t_f} g(\mathbf{x}(t), \mathbf{u}(t), t)\, \mathrm{d}t \tag{14}$$

Optimal control for VIA

Together with the Hamiltonian

$$H(\mathbf{x}(t), \boldsymbol{\lambda}(t), \mathbf{u}(t), t) = -g(\mathbf{x}(t), \mathbf{u}(t), t) + \boldsymbol{\lambda}^T f(\mathbf{x}(t), \mathbf{u}(t), t) \quad (15)$$

the constrained optimization problem is transformed into a problem without constraints. However, in order to maximize the link side velocity at a certain time instant t_f only, (14) reduces to:

$$J = h(\mathbf{x}(t_f), t_f)) = \dot{q}(t_f) \quad (16)$$

Since no other constraints are taken into consideration (15) reduces to

$$H(\mathbf{x}, \boldsymbol{\lambda}, u, t) = \boldsymbol{\lambda}^T f(\mathbf{x}(t), u(t), t). \quad (17)$$

Optimal control for VIA

Boundary conditions of the adjoint equations result from the transversal condition

$$\boldsymbol{\lambda}(t_f) = \frac{\partial h(t_f)}{\partial \mathbf{x}}. \quad (18)$$

This leads to a two point boundary problem (canonical system).

$$\dot{\mathbf{x}} = \frac{\partial H}{\partial \boldsymbol{\lambda}} \quad (19)$$

$$\dot{\boldsymbol{\lambda}} = -\frac{\partial H}{\partial \mathbf{x}} \quad (20)$$

Optimal control for VIA

case	model	solution	achieved insights
A	Velocity source + SEA	analytical	principal effect of significant joint elasticity
B	PT1 + SEA	analytical	influence of constrained motor dynamics, 1st order
C	PT2 + SEA	analytical	influence of constrained motor dynamics, 2nd order
D	PT2 + SEA + JTF	numerical	influence of joint torque feedback on motor inertia
E	PT2 + SEA + JTF + CD	numerical	influence of deflection constraints
F	Velocity source + VS	analytical	principle effect of stiffness adjustment
G	Velocity source + VS + CD	numerical	influence of stiffness adjustment and constrained deflection
H	PT2 + VS + CMT	numerical	real VIA design behavior and constrained motor torque

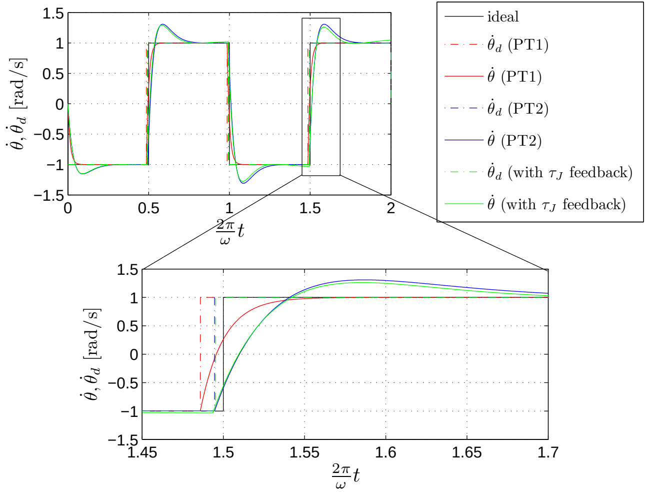
Optimal control for VIA

	Vel. source (A)	PT1 (B)	PT2 (C)	PT2+τ_J (D)
1	$\theta = \int_0^{t_f} \dot{\theta}_d \, dt$ $M\ddot{q} = K_J(\theta - q)$	$\tau_m = K_P(\dot{\theta}_d - \dot{\theta})$ $\tau_m = B\ddot{\theta}$ $M\ddot{q} = K_J(\theta - q)$	$\tau_m = K_D(\dot{\theta}_d - \dot{\theta}) + K_P(\theta_d - \theta)$ $\tau_m = B\ddot{\theta}$ $M\ddot{q} = K_J(\theta - q)$	$\tau_m = K_D(\dot{\theta}_d - \dot{\theta}) + K_P(\theta_d - \theta)$ $\tau_m = B\ddot{\theta} + K_J(\theta - q)$ $M\ddot{q} = K_J(\theta - q)$
2	$\mathbf{x}^T = [\theta \; q \; \dot{q}]$ $u = \dot{\theta}_d$	$\mathbf{x}^T = [\theta \; \dot{\theta} \; q \; \dot{q}]$ $u = \dot{\theta}_d$	$\mathbf{x}^T = [\theta_d \; \theta \; \dot{\theta} \; q \; \dot{q}]$ $u = \dot{\theta}_d$	$\mathbf{x}^T = [\theta_d \; \theta \; \dot{\theta} \; q \; \dot{q}]$ $u = \dot{\theta}_d$
3	$\dot{x}_1 = u$ $\dot{x}_2 = x_3$ $\dot{x}_3 = \omega^2(x_1 - x_2)$	$\dot{x}_1 = x_2$ $\dot{x}_2 = \frac{K_P}{B}(u - x_2)$ $\dot{x}_3 = x_4$ $\dot{x}_4 = \omega^2(x_1 - x_3)$	$\dot{x}_1 = u$ $\dot{x}_2 = x_3$ $\dot{x}_3 = \frac{1}{B}(K_D(u - x_3) +$ $+K_P(x_1 - x_2))$ $\dot{x}_4 = x_5$ $\dot{x}_5 = \omega^2(x_2 - x_4)$	$\dot{x}_1 = u$ $\dot{x}_2 = x_3$ $\dot{x}_3 = \frac{1}{B}(K_D(u - x_3) +$ $+K_P(x_1 - x_2) - K_J(x_2 - x_4))$ $\dot{x}_4 = x_5$ $\dot{x}_5 = \omega^2(x_2 - x_4)$

Optimal control for VIA

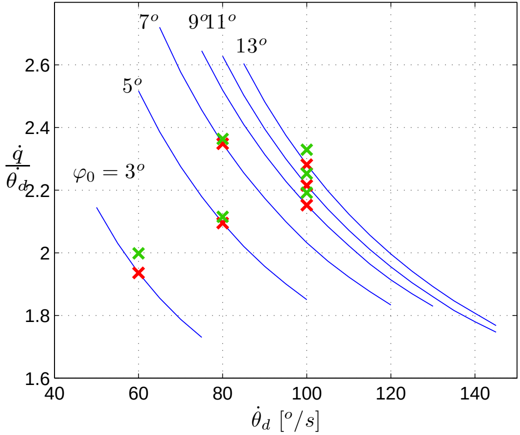
	Vel. source (A)	PT1 (B)	PT2 (C)	PT2+τ_J (D)
4	$H(\mathbf{x}(t),\boldsymbol{\lambda}(t),u(t),t)=$ $\lambda_1 u+\lambda_2 x_3+\lambda_3\omega^2(x_1-x_2)$	$H(\mathbf{x}(t),\boldsymbol{\lambda}(t),u(t),t)=\lambda_1 x_2+$ $+\lambda_2\frac{K_P}{B}(u-x_2)+\lambda_3 x_4+\lambda_4\omega^2(x_1-x_3)$	$H(\mathbf{x}(t),\lambda(t),u(t))=\lambda_1 u+\lambda_2 x_3$ $+\lambda_3\frac{1}{B}(K_D(u-x_3)+K_P(x_1-x_2))+$ $+\lambda_4 x_5+\lambda_5\omega^2(x_2-x_4)$	$H(\mathbf{x}(t),\lambda(t),u(t))=\lambda_1 u+\lambda_2 x_3$ $+\lambda_3\frac{1}{B}(K_D(u-x_3)+$ $+K_P(x_1-x_2)-K_J(x_2-x_4))+$ $+\lambda_4 x_5+\lambda_5\omega^2(x_2-x_4)$
5	$\dot\lambda_1=-\lambda_3\omega^2$ $\dot\lambda_2=\lambda_3\omega^2$ $\dot\lambda_3=-\lambda_2$	$\dot\lambda_1=-\lambda_4\omega^2$ $\dot\lambda_2=-\lambda_1+\frac{K_P}{B}\lambda_2$ $\dot\lambda_3=\lambda_4\omega^2$ $\dot\lambda_4=-\lambda_3$	$\dot\lambda_1=-\lambda_3\frac{K_P}{B}$ $\dot\lambda_2=\lambda_3\frac{K_P}{B}-\lambda_5\omega^2$ $\dot\lambda_3=-\lambda_2+\lambda_3\frac{K_D}{B}$ $\dot\lambda_4=\lambda_5\omega^2$ $\dot\lambda_5=-\lambda_4$	$\dot\lambda_1=-\lambda_3\frac{K_P}{B}$ $\dot\lambda_2=\lambda_3\left(\frac{K_P}{B}+\frac{K_J}{B}\right)-\lambda_5\omega^2$ $\dot\lambda_3=-\lambda_2+\lambda_3\frac{K_D}{B}$ $\dot\lambda_4=-\lambda_3\frac{K_J}{B}+\lambda_5\omega^2$ $\dot\lambda_5=-\lambda_4$
6	$\boldsymbol{\lambda}^T(t_f)=[0\ 0\ 1]$ $\mathbf{x}^T(0)=[0\ 0\ 0]$	$\boldsymbol{\lambda}^T(t_f)=[0\ 0\ 0\ 1]$ $\mathbf{x}^T(0)=[0\ 0\ 0\ 0]$	$\boldsymbol{\lambda}^T(t_f)=[0\ 0\ 0\ 0\ 1]$ $\mathbf{x}^T(0)=[0\ 0\ 0\ 0\ 0]$	$\boldsymbol{\lambda}^T(t_f)=[0\ 0\ 0\ 0\ 1]$ $\mathbf{x}^T(0)=[0\ 0\ 0\ 0\ 0]$
7	$\dot\theta_d^*=\begin{cases}\dot\theta_{\max}, & \lambda_1>0\\ \dot\theta_{\min}, & \lambda_1<0\\ \text{singular}, & \lambda_1=0\end{cases}$	$\dot\theta_d^*=\begin{cases}\dot\theta_{\max}, & \lambda_2>0\\ \dot\theta_{\min}, & \lambda_2<0\\ \text{singular}, & \lambda_2=0\end{cases}$	$\dot\theta_d^*=\begin{cases}\dot\theta_{\max}, & \lambda_1+\frac{K_D}{B}\lambda_3>0\\ \dot\theta_{\min}, & \lambda_1+\frac{K_D}{B}\lambda_3<0\\ \text{singular}, & \lambda_1+\frac{K_D}{B}\lambda_3=0\end{cases}$	$\dot\theta_d^*=\begin{cases}\dot\theta_{\max}, & \lambda_1+\frac{K_D}{B}\lambda_3>0\\ \dot\theta_{\min}, & \lambda_1+\frac{K_D}{B}\lambda_3<0\\ \text{singular}, & \lambda_1+\frac{K_D}{B}\lambda_3=0\end{cases}$

Optimal control for VIA

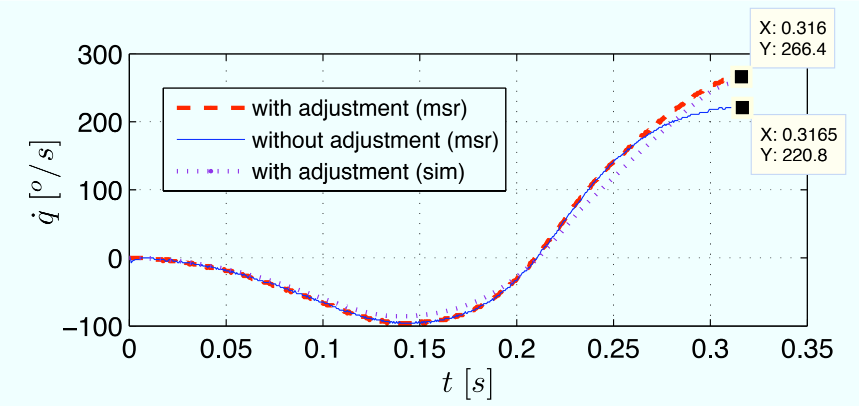


Optimal control: linear case

Relative maximum link vs. motor velocity



Optimal control problem solved for the 1DoF QA-Joint.


X: 0.316
Y: 266.4
X: 0.3165
Y: 220.8
300
200
100
0
−100
$\dot{q}\ [^o/s]$
with adjustment (msr)
without adjustment (msr)
with adjustment (sim)
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
$t\ [s]$

Throwing a ball with the DLR VS-joint

Throwing

2 DOF throwing

2DOF throwing

Literature: optimal control for VIA

- [Haddadin et al., 2011c]
- [Garabini et al., 2011]
- [Bryson and Ho, 1975]
- [Papageorgiou, 1996]
- [Kirk, 1970]
- [Pontrjagin, 1967]
- [Hermann, 2004]
- [Haddadin, 2011]

Elasticity for cyclic manipulation tasks

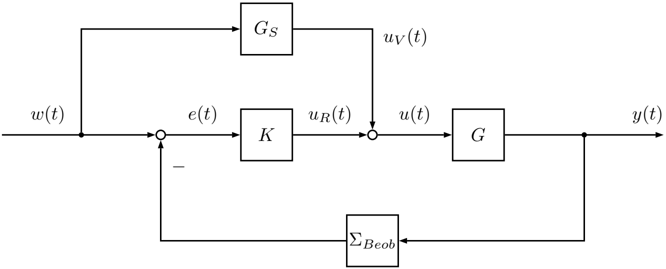
MOTIVATION

Humans are able to use their elasticities for performing dynamic cyclic manipulation motions, which are hybrid by nature.

GOALS

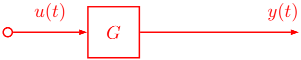
- dribbling by **proprioceptive feedback only!**, no vision feedback
- utilizing **intrinsically compliant fingers** for
  1. protecting the robot
  2. enlarging the contact time
  3. utilizing dynamic elastic energy storage and release

CONTENT

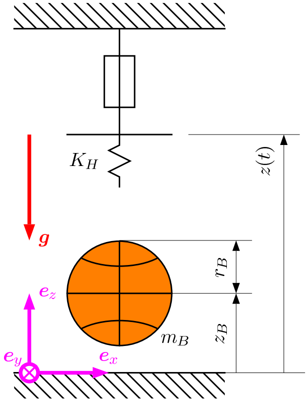


1. Modeling
2. Feedforward control and stability
3. Observer
4. Feedback control
5. Simulations and experiments

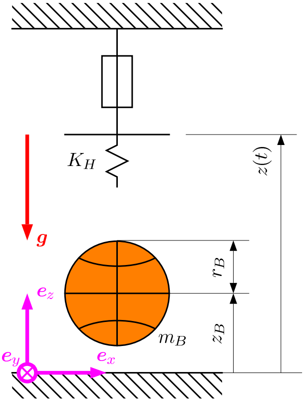
1. Modeling

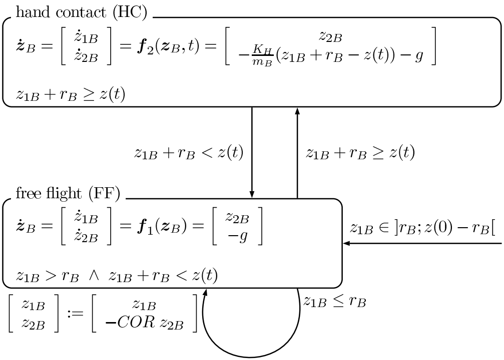


1 DoF model



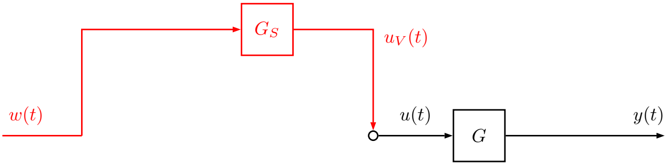
1 DoF model





with $\mathbf{z}_B = [z_B \ \dot{z}_B]^T = [z_{1B} \ z_{2B}]^T$

2. Feedforward control and stability



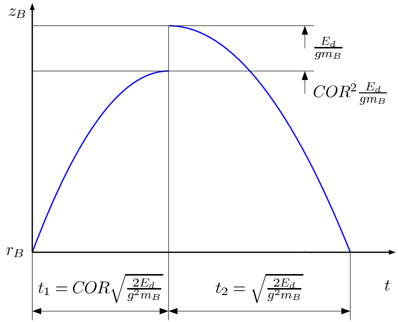
HAND TRAJECTORY

using a sine as reference trajectory

- classical problem of robot juggling $\rightarrow$ negative accelerations
- natural choice for stimulating a spring system

$$z(t) = \begin{cases} A \sin\left(\frac{5\pi}{4T} t\right) + z_0 & \text{for } t \in \left[0; \frac{4}{5} T\right] \\ -\frac{1}{4} A \sin\left(\frac{5\pi}{T} t\right) + z_0 & \text{for } t \in \left]\frac{4}{5} T; T\right[\end{cases}$$

Hand trajectory



desired ball energy E_d as parameterization for the hand trajectory

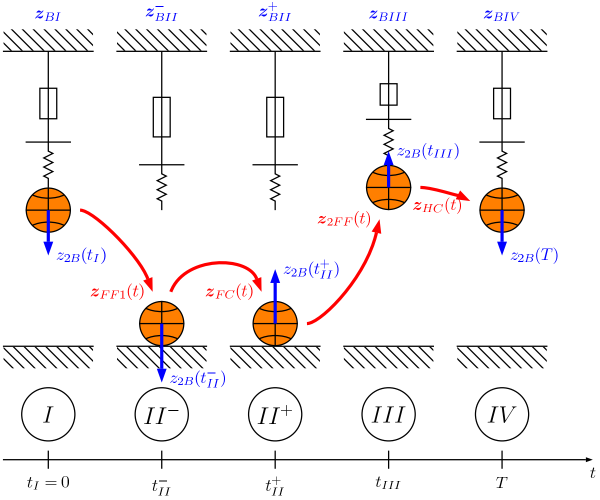
- period time T from t_1 and t_2
- amplitude A and height z_0 are linearly dependent

$$A(E_d) = a_1 + a_2 E_d$$
$$z_0(E_d) = a_3 + a_4 E_d$$

with a_i as parameter from the simulation

- no proof yet, but it is valid $E_H \sim E_d$

Analytic solution 1 DoF



STABILITY

Ansatz:
Investigate the given initial error

$$\mathbf{z}_{BI}^{p} = \mathbf{z}_{BI} + \mathbf{e}_{I}$$

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Investigate the given initial error

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over one cycle by the error mapping

$$\mathbf{e}_{I_{n+1}} =^{IV} M_I \mathbf{e}_{I_n}$$

STABILITY

Ansatz:
Investigate the given initial error

$$\mathbf{z}_{BI}^{p} = \mathbf{z}_{BI} + \mathbf{e}_{I}$$

over one cycle by the error mapping

$$\mathbf{e}_{I_{n+1}} = {}^{IV}M_{I}\mathbf{e}_{I_n}$$

with

$${}^{IV}M_{I} = {}^{IV}M_{III}\ {}^{III}M_{II^+}\ {}^{II^+}M_{II^-}\ {}^{II^-}M_{I}.$$

STABILITY

Ansatz:
Investigate the given initial error

$$\mathbf{z}_{BI}^{p} = \mathbf{z}_{BI} + \mathbf{e}_{I}$$

over one cycle by the error mapping

$$\mathbf{e}_{I_{n+1}} = {}^{IV}M_{I}\mathbf{e}_{I_n}$$

with

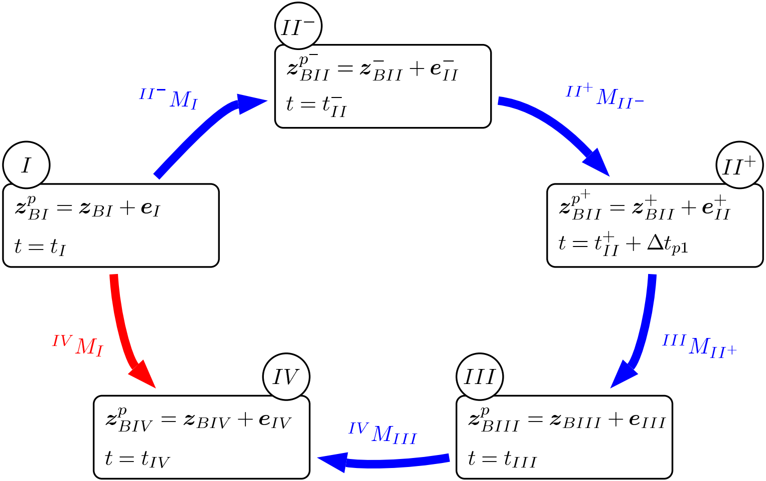
$${}^{IV}M_{I} = {}^{IV}M_{III}\ {}^{III}M_{II^+}\ {}^{II^+}M_{II^-}\ {}^{II^-}M_{I}.$$

The criterion for stability is

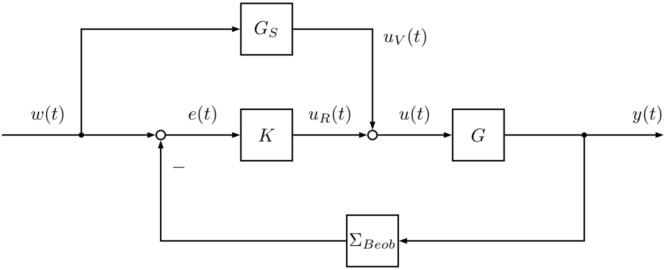
$$\max(||\lambda({}^{IV}M_{I})||) < 1.$$

Interpretation: Poincaré map with error eigenvalue as crossing metric

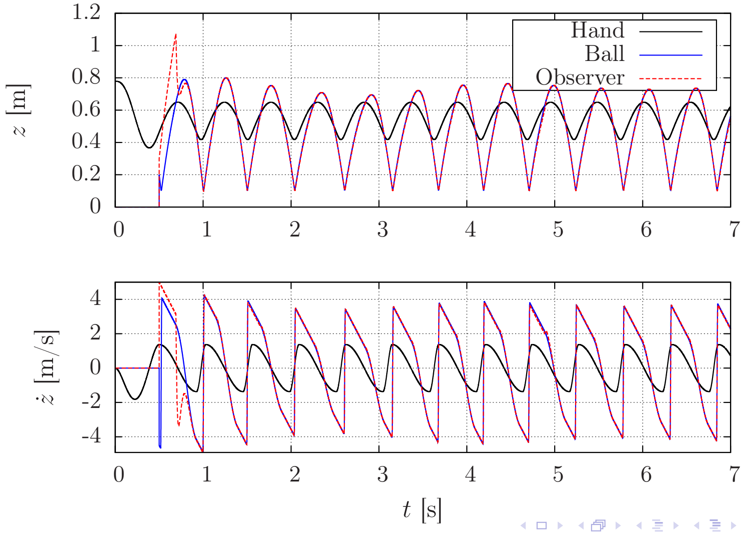
Stability


II^-
$z^{p-}_{BII} = z^-_{BII} + e^-_{II}$
$t = t^-_{II}$
$^{II^-}M_I$
$^{II^+}M_{II^-}$
I
$z^p_{BI} = z_{BI} + e_I$
$t = t_I$
II^+
$z^{p+}_{BII} = z^+_{BII} + e^+_{II}$
$t = t^+_{II} + \Delta t_{p1}$
$^{IV}M_I$
$^{III}M_{II^+}$
IV
$z^p_{BIV} = z_{BIV} + e_{IV}$
$t = t_{IV}$
$^{IV}M_{III}$
III
$z^p_{BIII} = z_{BIII} + e_{III}$
$t = t_{III}$

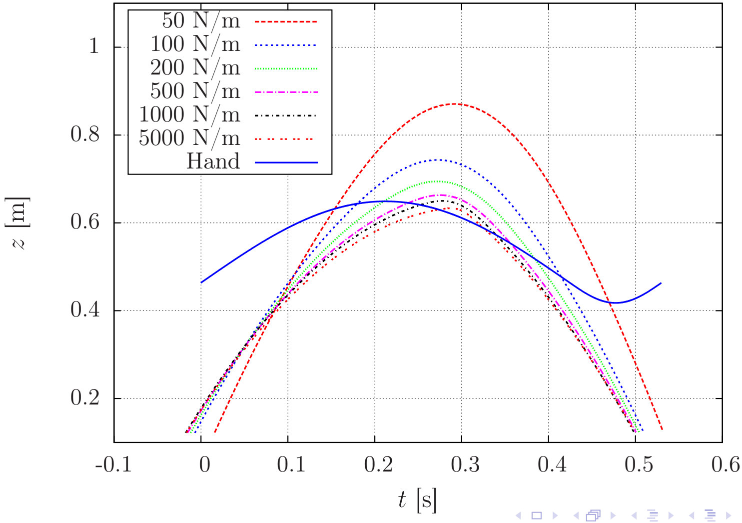
5. Simulations and experiments



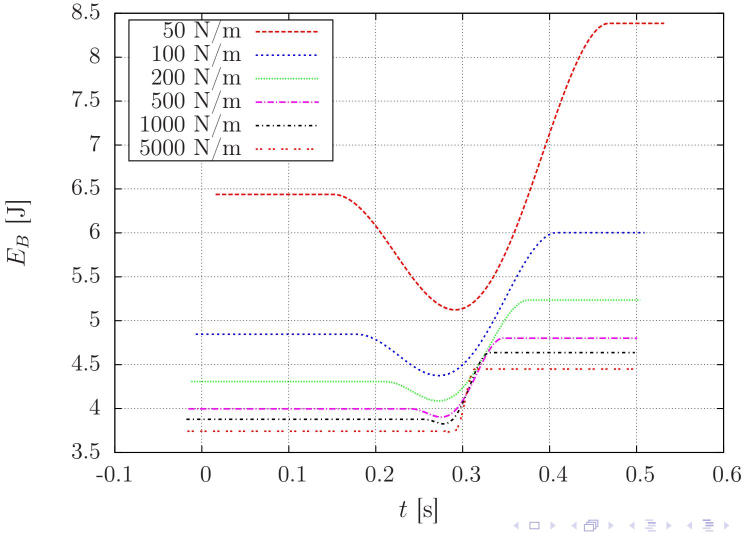
SIMULATION 1 DOF



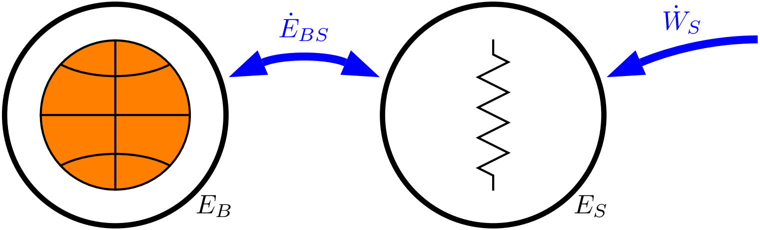
STIFFNESS INVESTIGATION - POSITION



STIFFNESS INVESTIGATION - BALL ENERGY

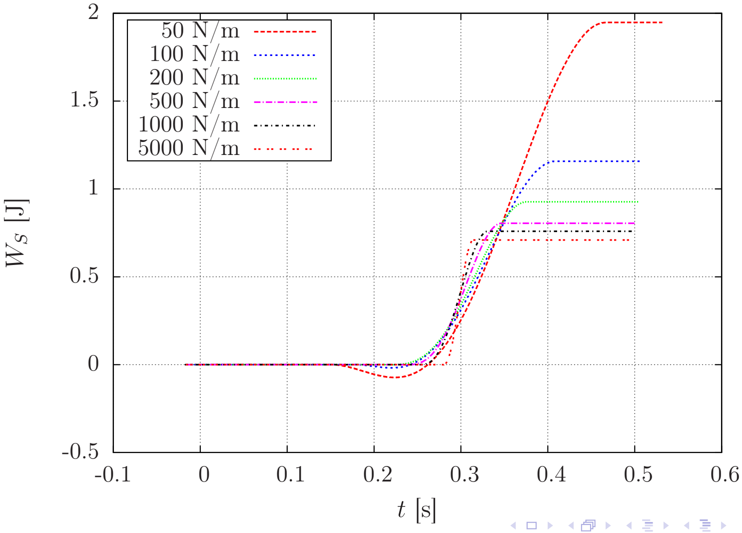


STIFFNESS INVESTIGATION - ENERGY FLOW

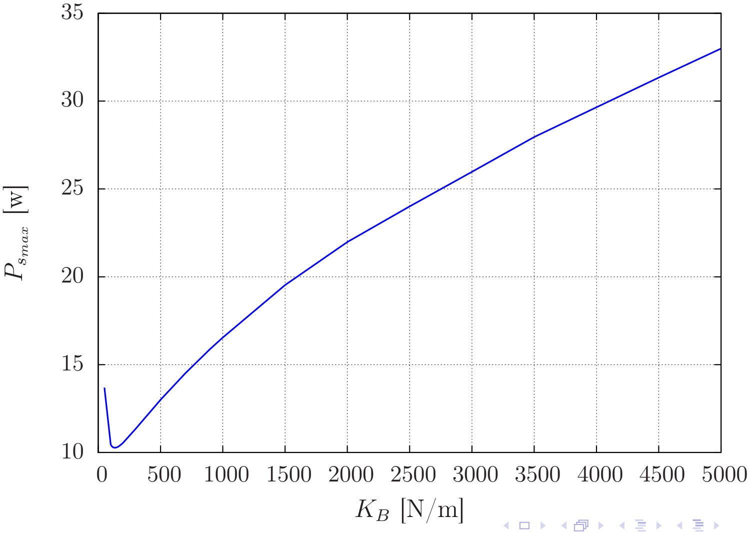


Energy and work considerations

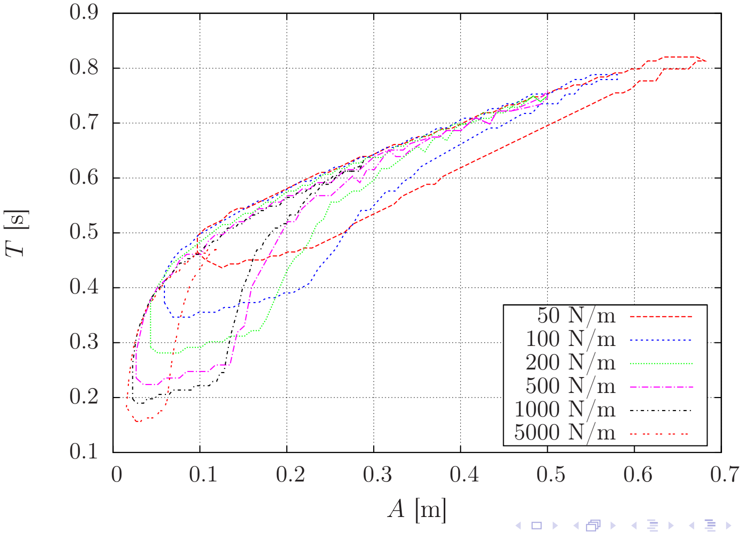
STIFFNESS INVESTIGATION - WORK



STIFFNESS INVESTIGATION - POWER



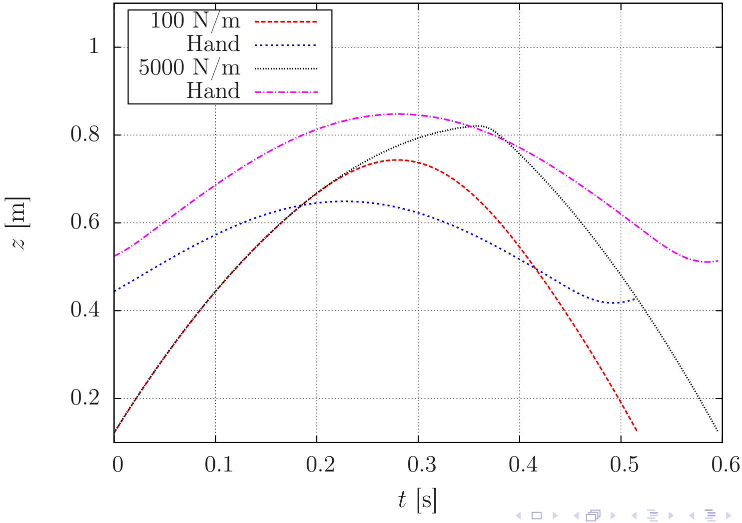
STIFFNESS INVESTIGATION - STABILITY REGIONS



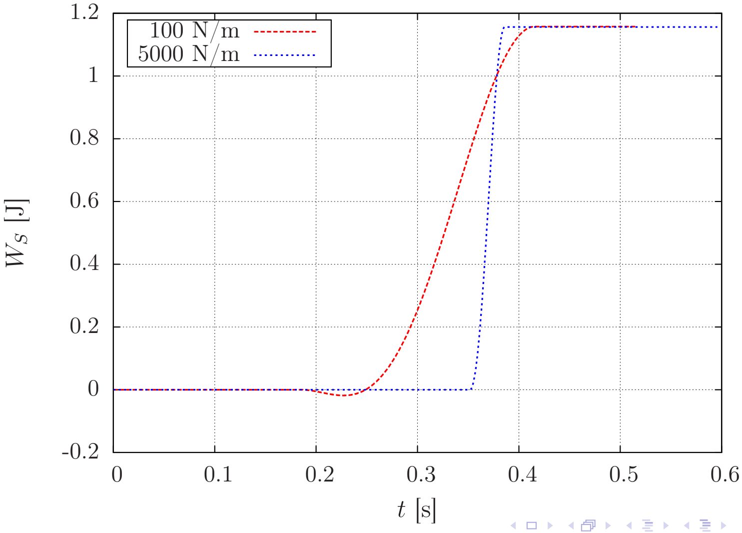
STIFFNESS INVESTIGATION - ENERGY

- **Until now**: z_0 remained the same.
- **Now**: dribbling at a given height (energy level) with different stiffnesses.
- $\rightarrow$ A significantly faster hand trajectory is needed for the high stiffness case

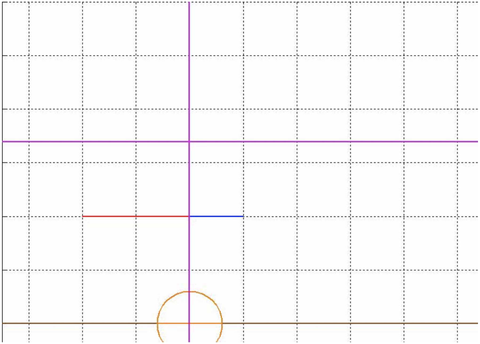
STIFFNESS INVESTIGATION - ENERGY



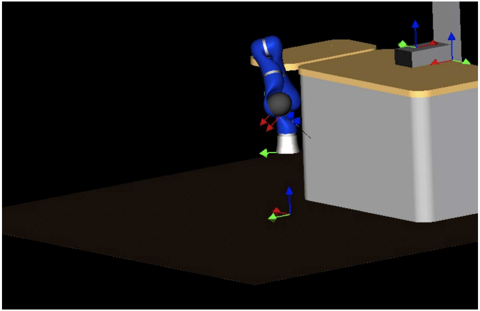
STIFFNESS INVESTIGATION - WORK



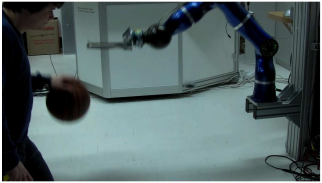
SIMULATION 3 DOF



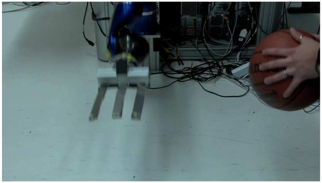
SIMULATION 6 DOF



EXPERIMENT



EXPERIMENT



Literature: cyclic elastic motion for VIA

- [Haddadin et al., 2011a]
- [Haddadin et al., 2011b]
- [Spong, 1987]
- [Albu-Schäffer et al., 2007]
- [Bühler et al., 1988]
- [Bätz et al., 2009]
- [Drakunov, 1992]
- [Mettin et al., 2010]
- [Okada et al., 2002]
- [Reist and D'Andrea, 2009]
- [Khalil, 2002]

Thank you for your attention!

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