Bridging the gap between interaction control and programming models

Sami Haddadin

Robotics and Mechatronics Center

German Aerospace Center

DLR

Robots in Human Spaces

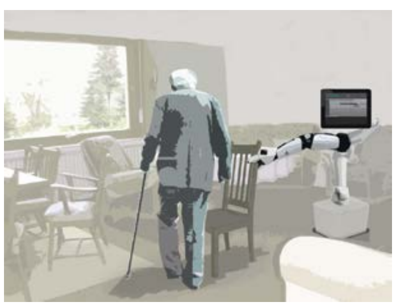
Ten years ago human-friendly robots were still a vision only

Industry & SMEs

Micro enterprises

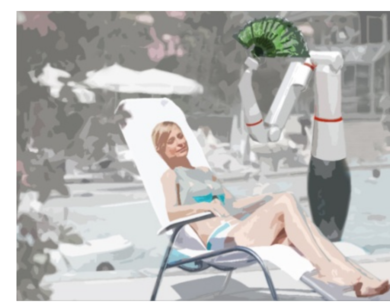
Medicine

Assistive care



Elderly Care

Service robotics

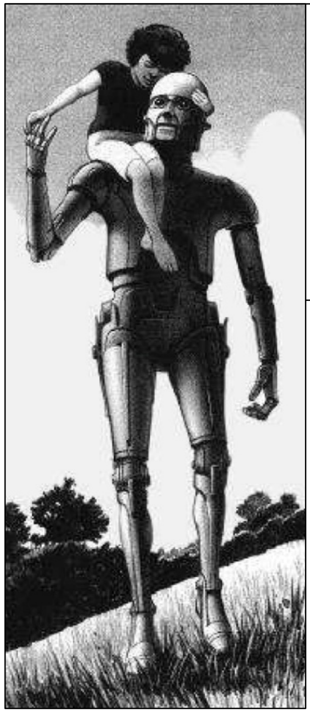


Lifestyle & Games

DLR

The Optimal Robot

Dynamic



Sensitive

Safe

Concept Study „Co-Worker“

DLR

Paradigm Shift: New Generation of Robots

DLR

This also led to a paradigm shift in control

Classical view:

- Position based tracking
  - Motion planning → interpolation → trajectory tracking law → motor control

Now:

- Tracking (still the fall back baseline)
- Soft robotics
  - Interaction control (force control, impedance control,…)
  - Reflex control (collision detection & reaction patterns)
  - Task + kinematic constraints
  - Multi-priority control
  - …

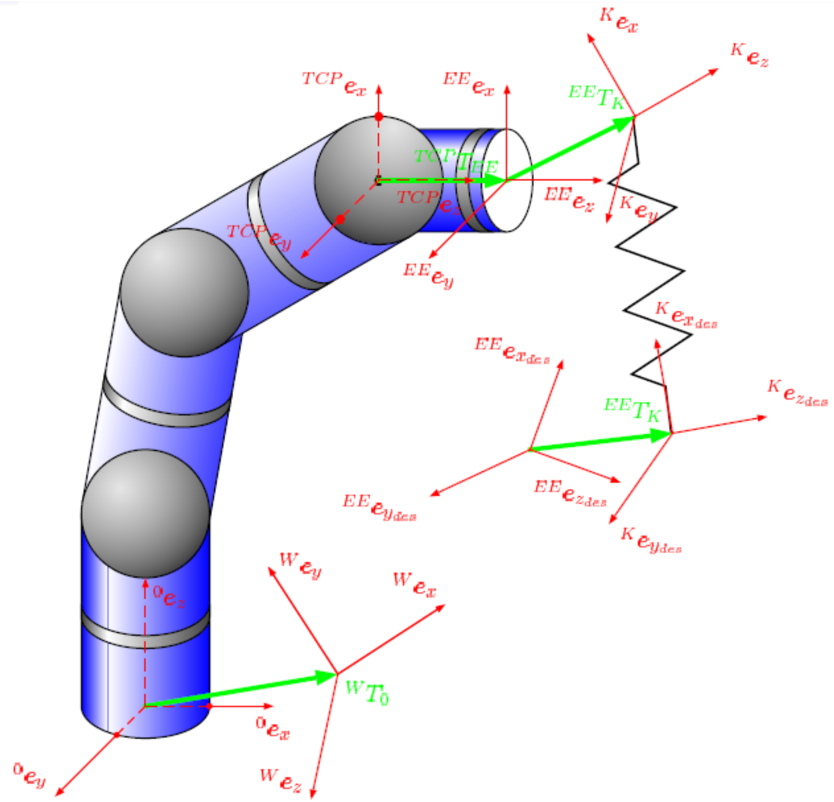
→ Significant increase in complexity
Planning needs to consider physical contact,… and thus takes probably an entirely different form

Brain controlled LWR

together with Brown University

Interaction control

Cartesian Impedance Control



$$M_{x,d}\ddot{\tilde{\mathbf{x}}} + D_{x,d}\dot{\tilde{\mathbf{x}}} + K_{x,d}\tilde{\mathbf{x}} = \mathcal{F}_{\mathrm{ext}}$$

Cartesian impedance control & nullspace behavior

Impedance control

Torque control with gravity compensation

Robust Grasping

Adaptive Impedance Control

Adaptive Controller:

$$\boldsymbol{\tau}_d(t) = \boldsymbol{\tau}_{ff} - K(t)\mathbf{e}(t) - D(t)\dot{\mathbf{e}}(t) - L(t)\epsilon(t) + \boldsymbol{\tau}_r(t)$$

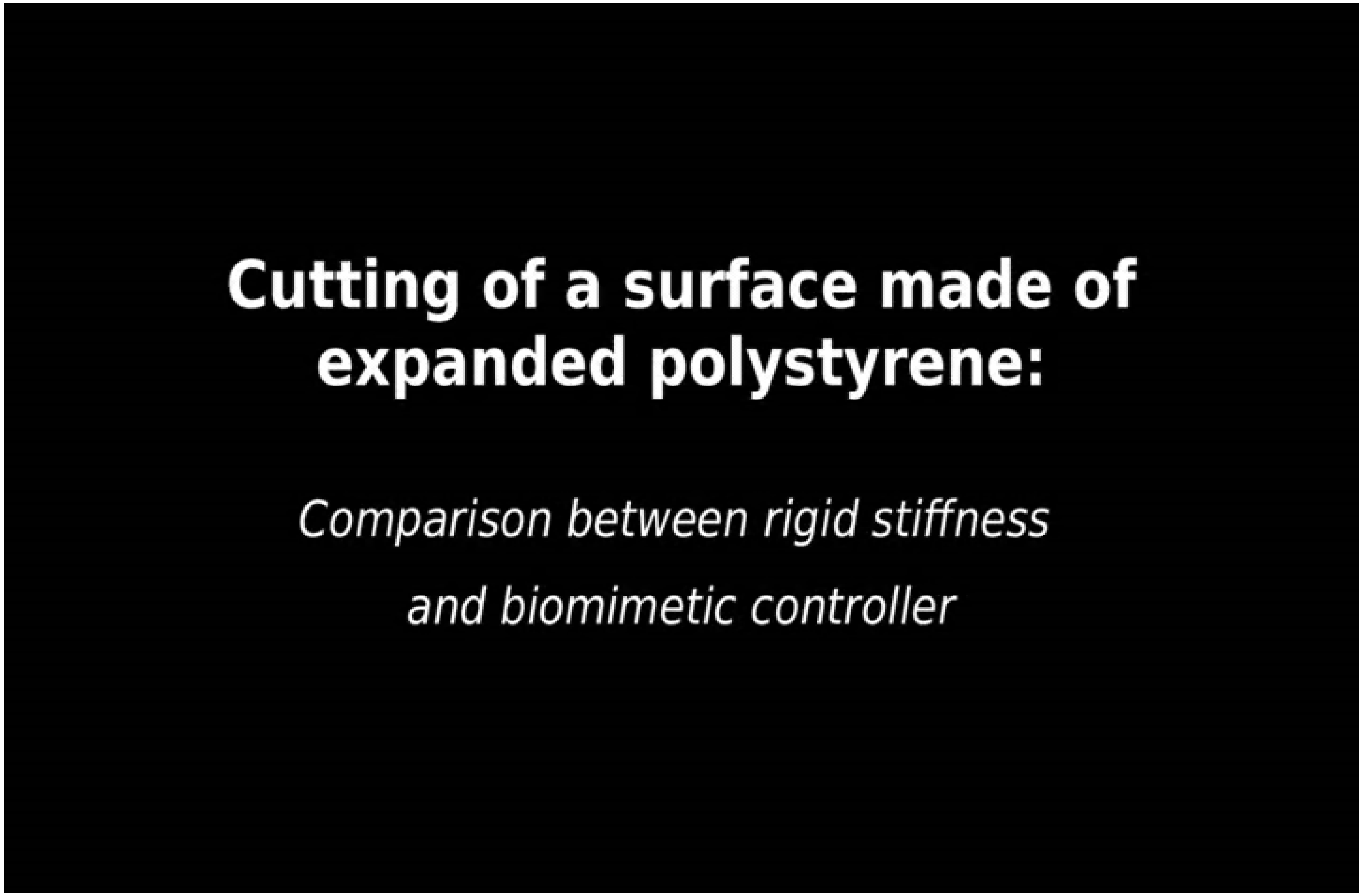
$$\epsilon = \dot{\mathbf{e}}(t) + \kappa\mathbf{e}(t).$$

Human: minimization of metabolic cost and motion error

Impedance and feed-forward torque adaptation law:

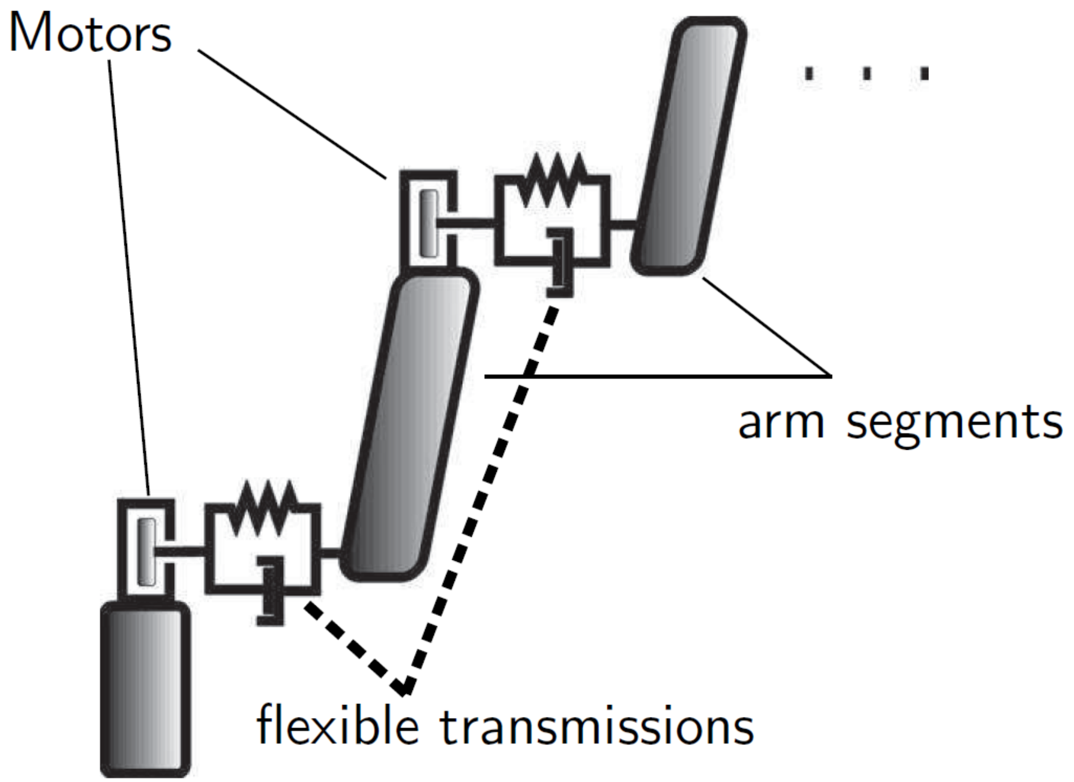
$$\begin{aligned} \delta\boldsymbol{\tau}_{ff}(t) &= Q_\tau(\epsilon(t) - \gamma(t)\boldsymbol{\tau}_{ff}) \\ \delta K(t) &= Q_K(\epsilon(t)\mathbf{e}^T(t) - \gamma(t)K(t)) \\ \delta D(t) &= Q_D(\epsilon(t)\dot{\mathbf{e}}^T(t) - \gamma(t)D(t)) \end{aligned}$$

Automatic Impedance Adaptation

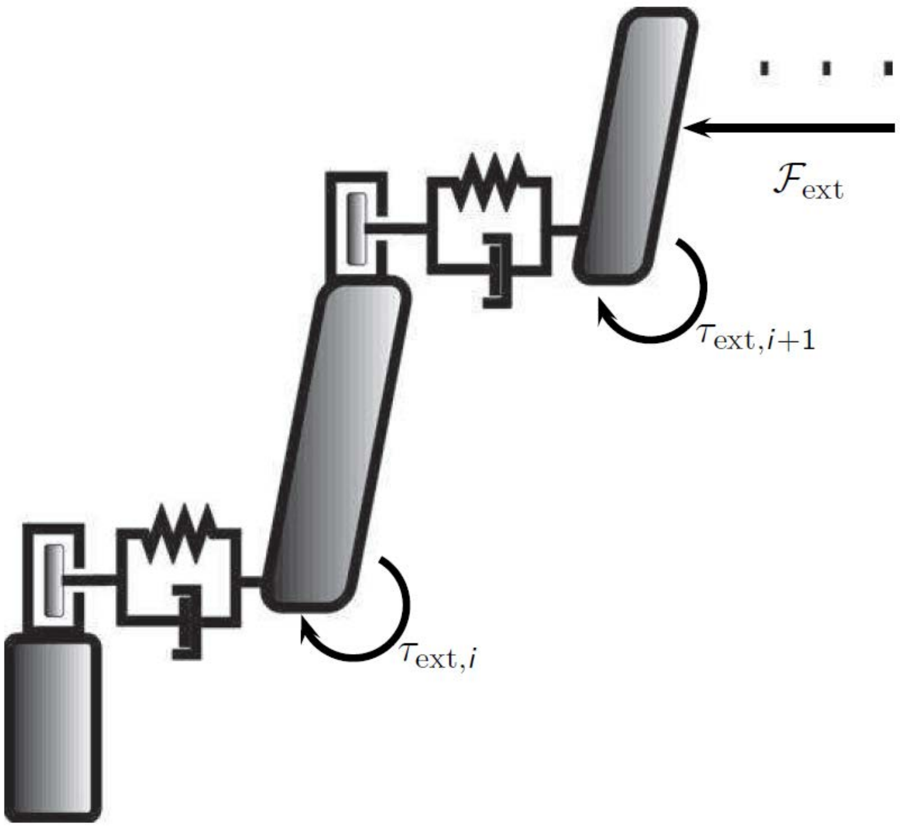


Collision detection & reflex reaction

Flexible Robots



Flexible Robots

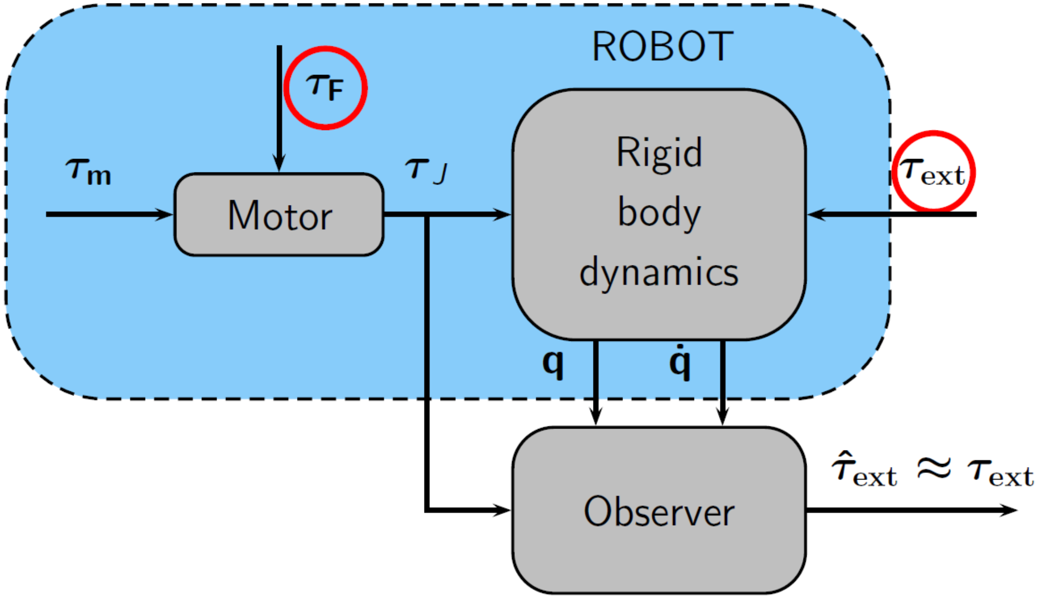


Collision Detection and Estimation

Flexible Joint Dynamics:

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

$$B\ddot{\boldsymbol{\theta}} + \boldsymbol{\tau}_J = \boldsymbol{\tau}_m$$



Observer Design

Idea: Observe generalized momentum

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

Reformulated dynamics:

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

Residual model:

$$\hat{\mathbf{r}} = \hat{\boldsymbol{\tau}}_{\mathrm{ext}} \qquad \dot{\hat{\mathbf{r}}} = \mathbf{0}$$

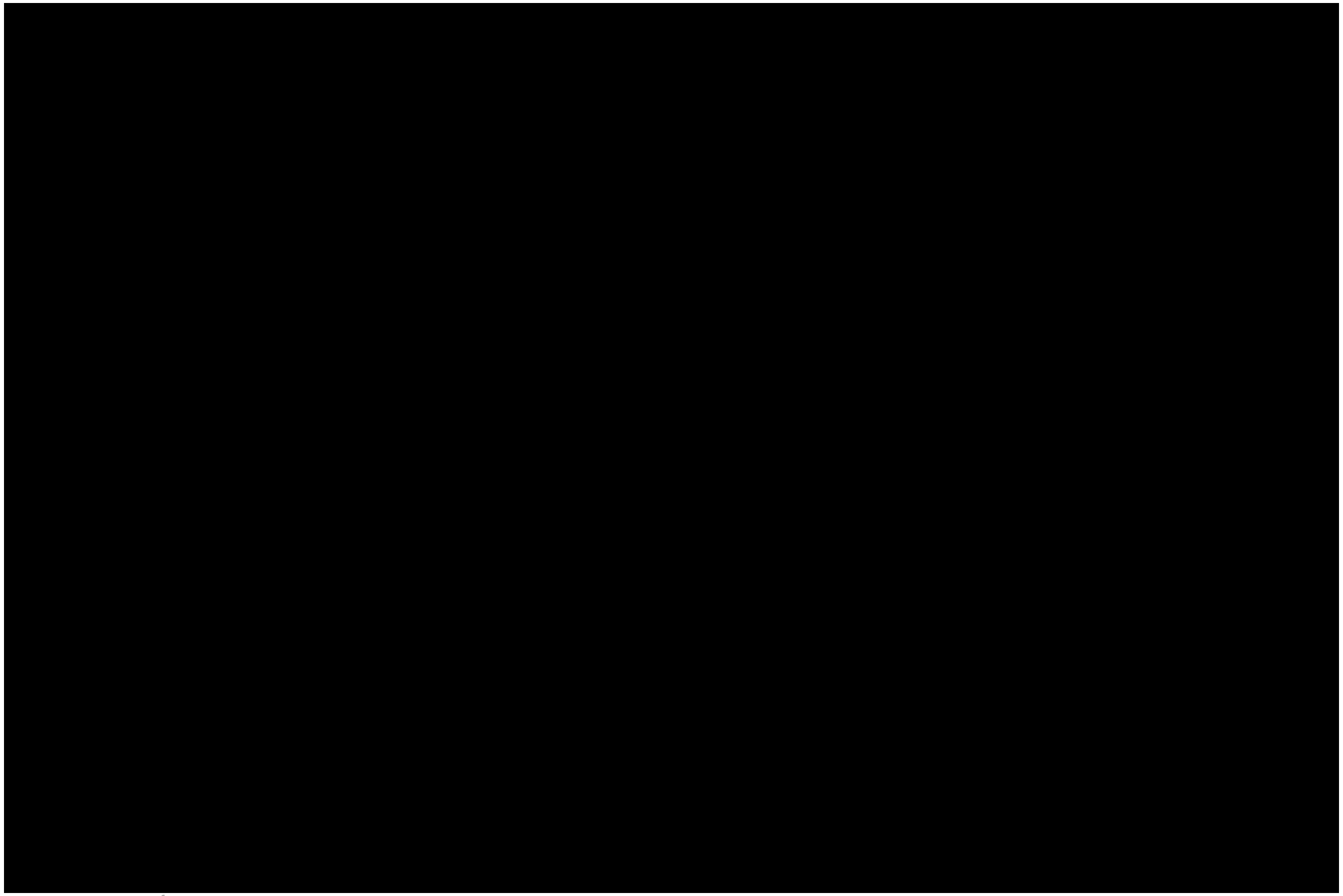
Observer design:

$$\hat{\mathbf{r}} = K_O \left(\int_0^T \left[\boldsymbol{\tau}_J - \boldsymbol{\beta}(\mathbf{q}, \dot{\mathbf{q}}) - \hat{\mathbf{r}} \right] \mathrm{d}t - M(\mathbf{q})\dot{\mathbf{q}} \right)$$

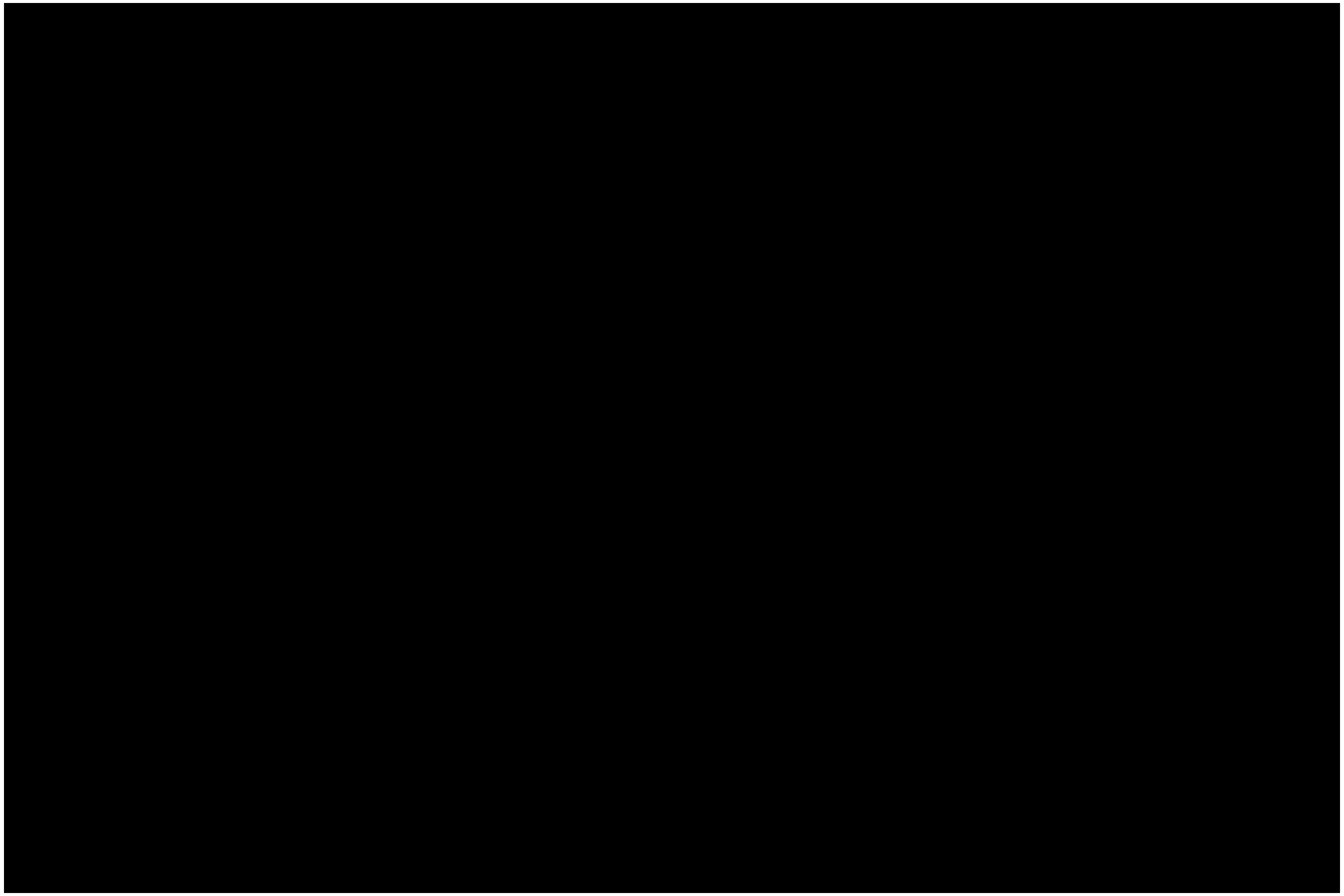
Decoupled Estimation of External Torques

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

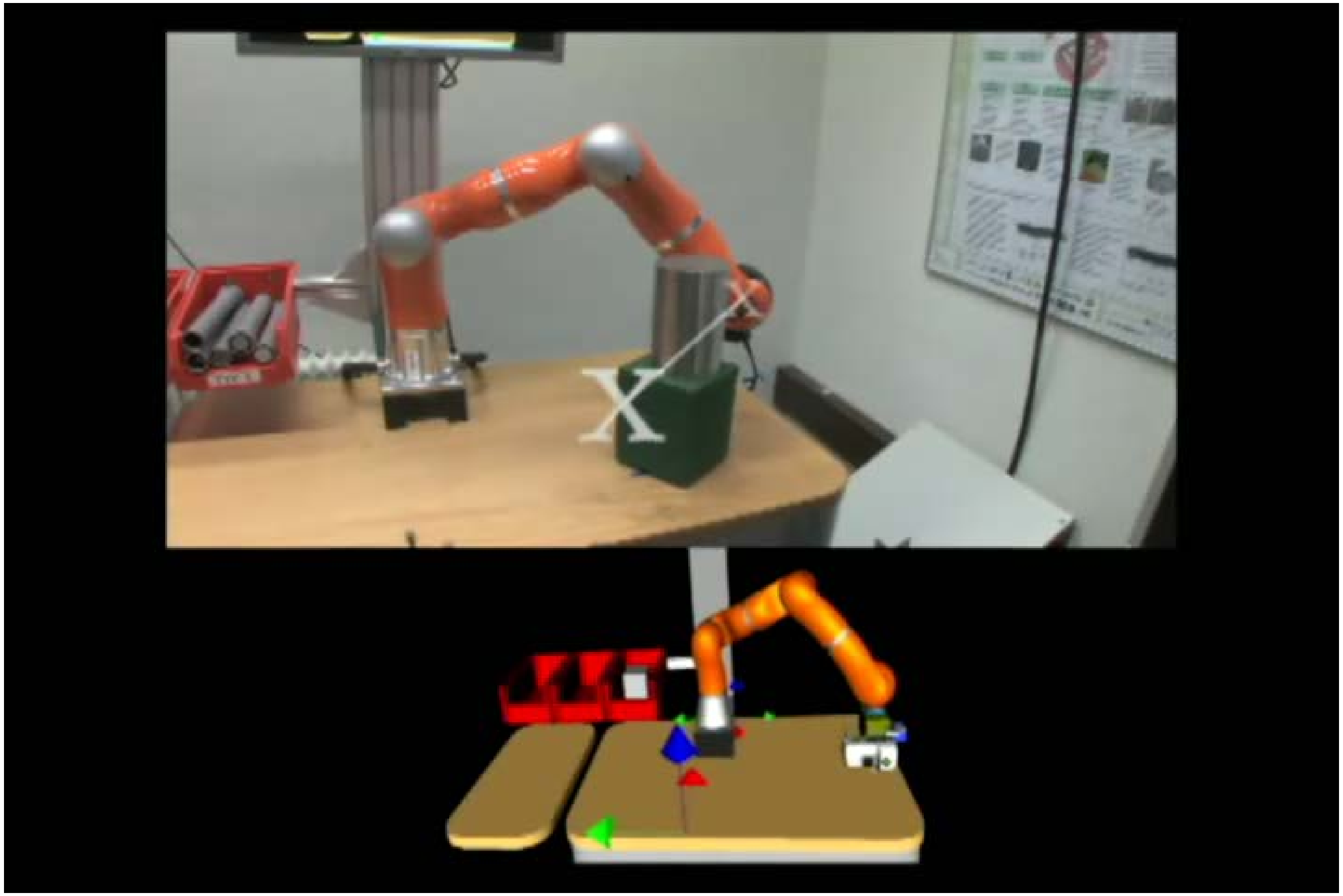
Collision detection and reaction



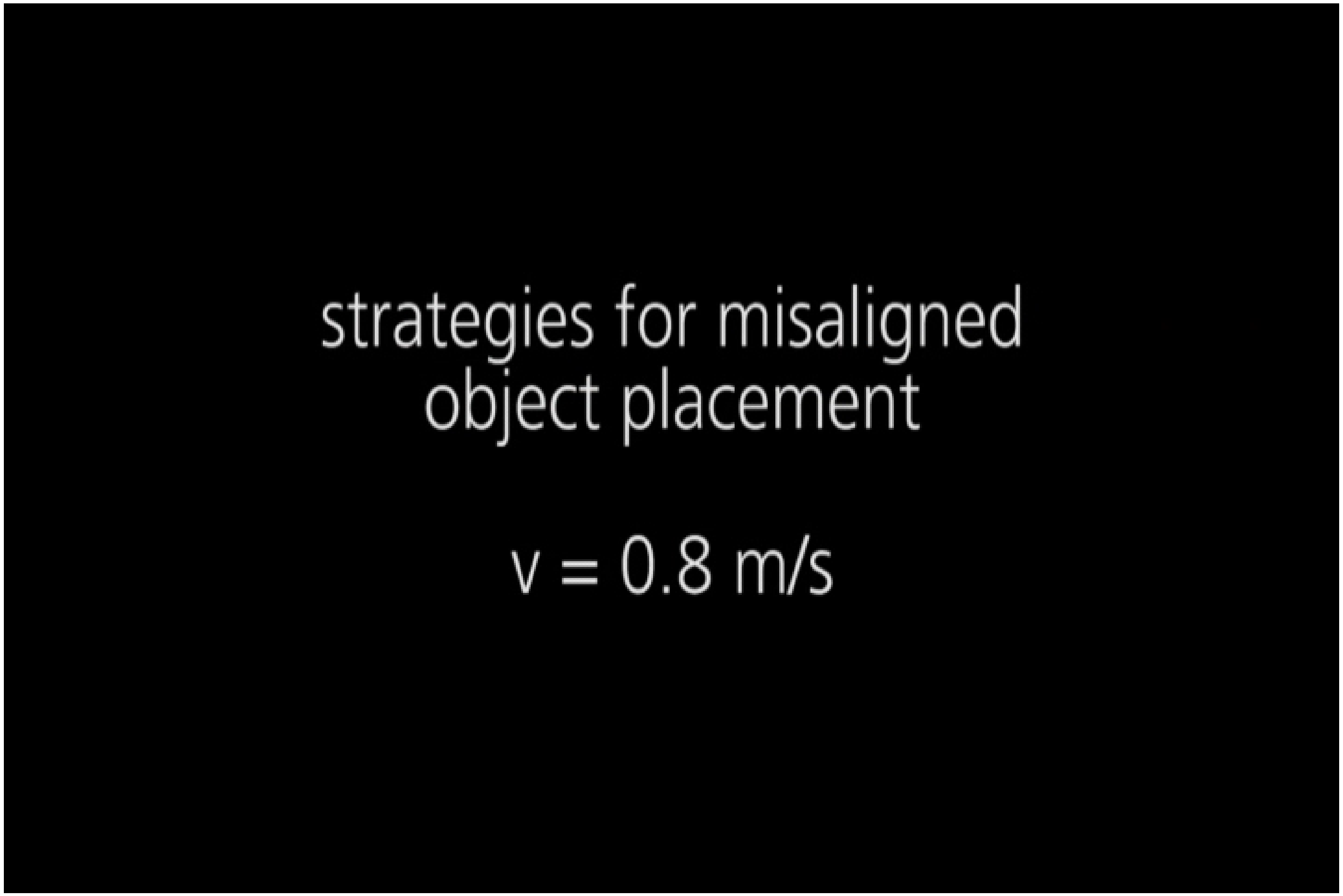
Collision detection and reaction



Another use: Tactile Exploration



Compliant Strategies for Placing

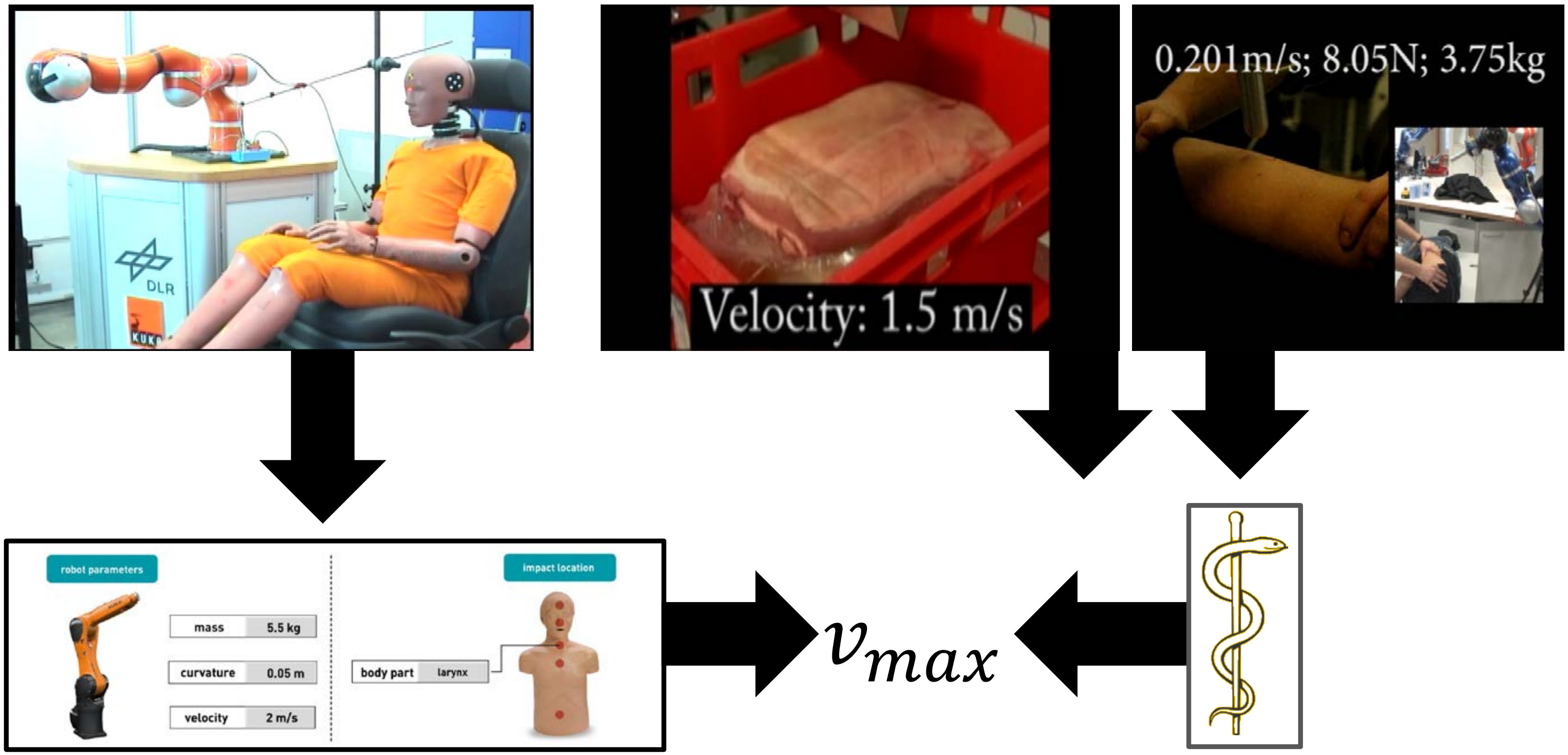


Safe velocity

How fast can a robot move without hurting you?

DLR

Fundamental approach

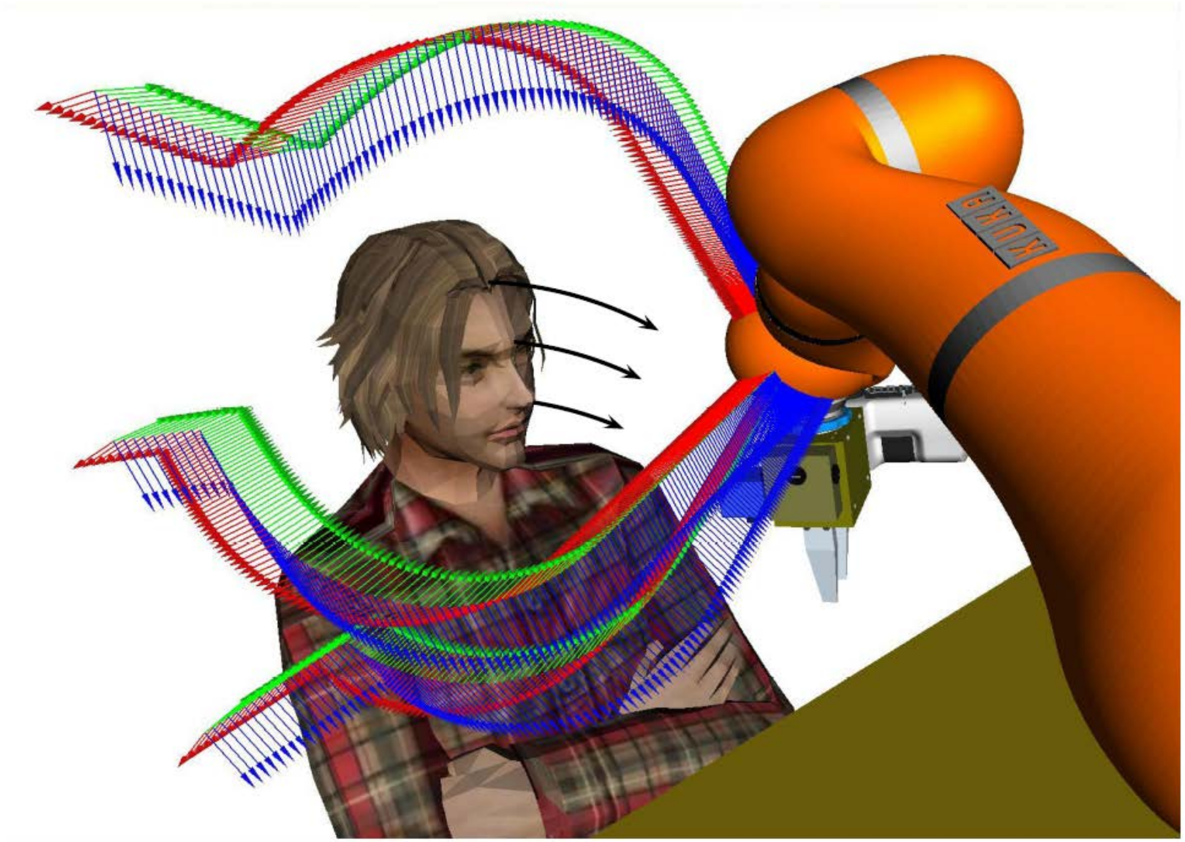


Human-robot collaboration in automobile industry

Human-Robot Interaction in Car Assembly

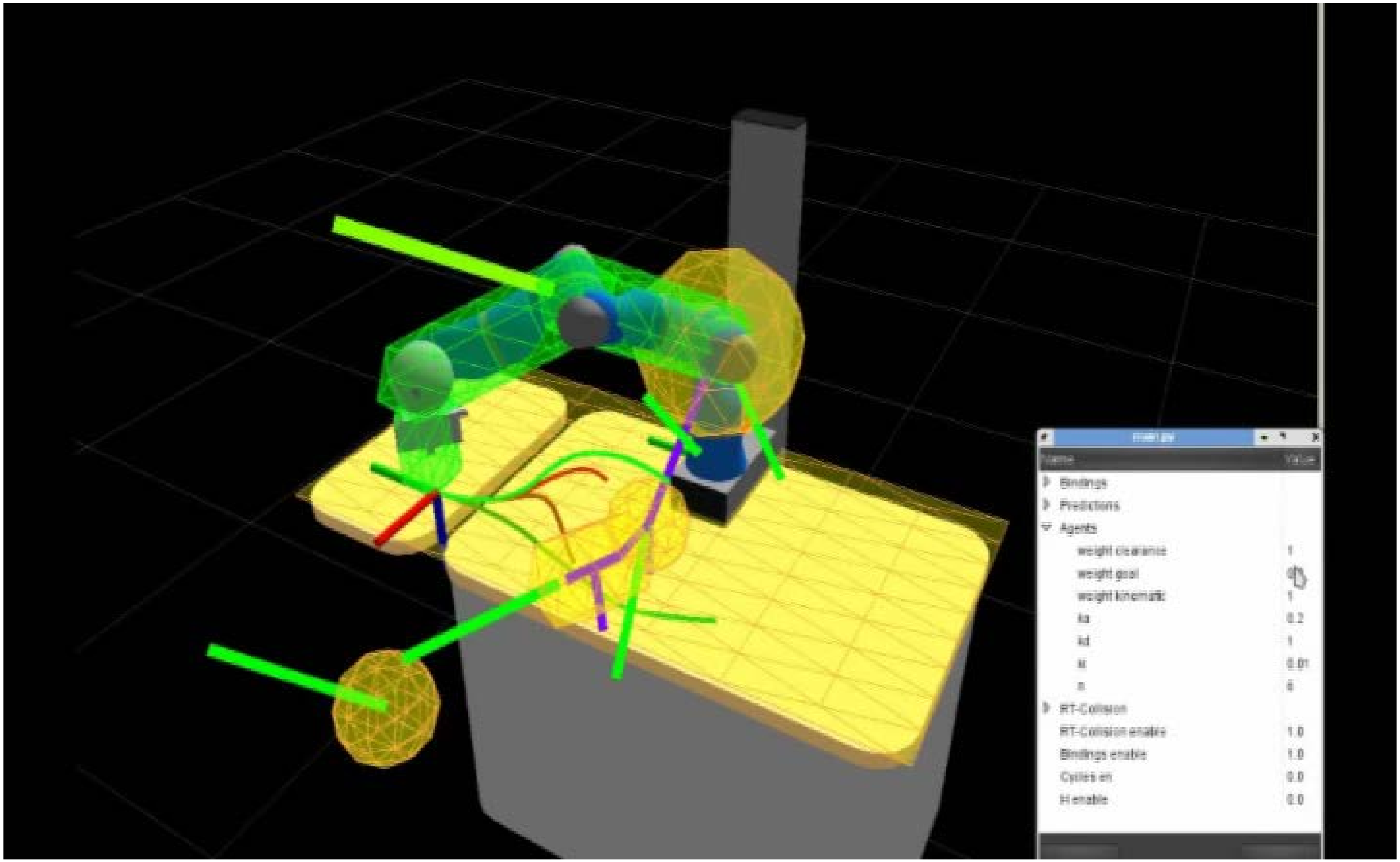
Real-time motion planning and collision avoidance

Real-Time Planning



Collision Avoidance

Cost Based Multi-Agents + Dynamical Systems



What I omitted

- Various types of trajectory generation schemes
- Force profiles
- Virtual walls
- Self-collision avoidance
- Visual servo control
- Complex reflexes
- Emergency patterns

Extremely large set of associated methods & algorithms with according constraints that might be

- hard,
- not so hard,
- fuzzy,
- I have no idea what exactly the constraint actually is,
- …

DLR

General observations

Experience from **real-world** problems:

- automatic planning cannot solve most **real-world** problems due to lacking expert knowledge (where should that come from anyway), limitations in modeling, simulation of the real-world + curse of dimensionality
- FDI is doable, but fault reaction is really hard for non-trivial problems
- Related question: Where do the constraints come from? Also mostly coming from human expertise
- Basically:
  - Expert skills that encapsulate a task invariant, however, parameterizable logical structure including constraints (explicite and/or implicit)
  - Repertoire of skills on which one might plan or program again
- Need: Programming of expert nodes (substitute your favorite synonym here) + planning on top of this
- Automatic planning problem would be significantly simplified

Programming models

Requirements

- Representation needed for encapsulating Soft-robots‘ behaviors and actions

Definition

Behavior:
6-tuple
$b = (m, p_m, c, p_c, pr, s) \in \mathcal{B} = (M \times P_M \times C \times P_C \times PR \times S)$

Definition

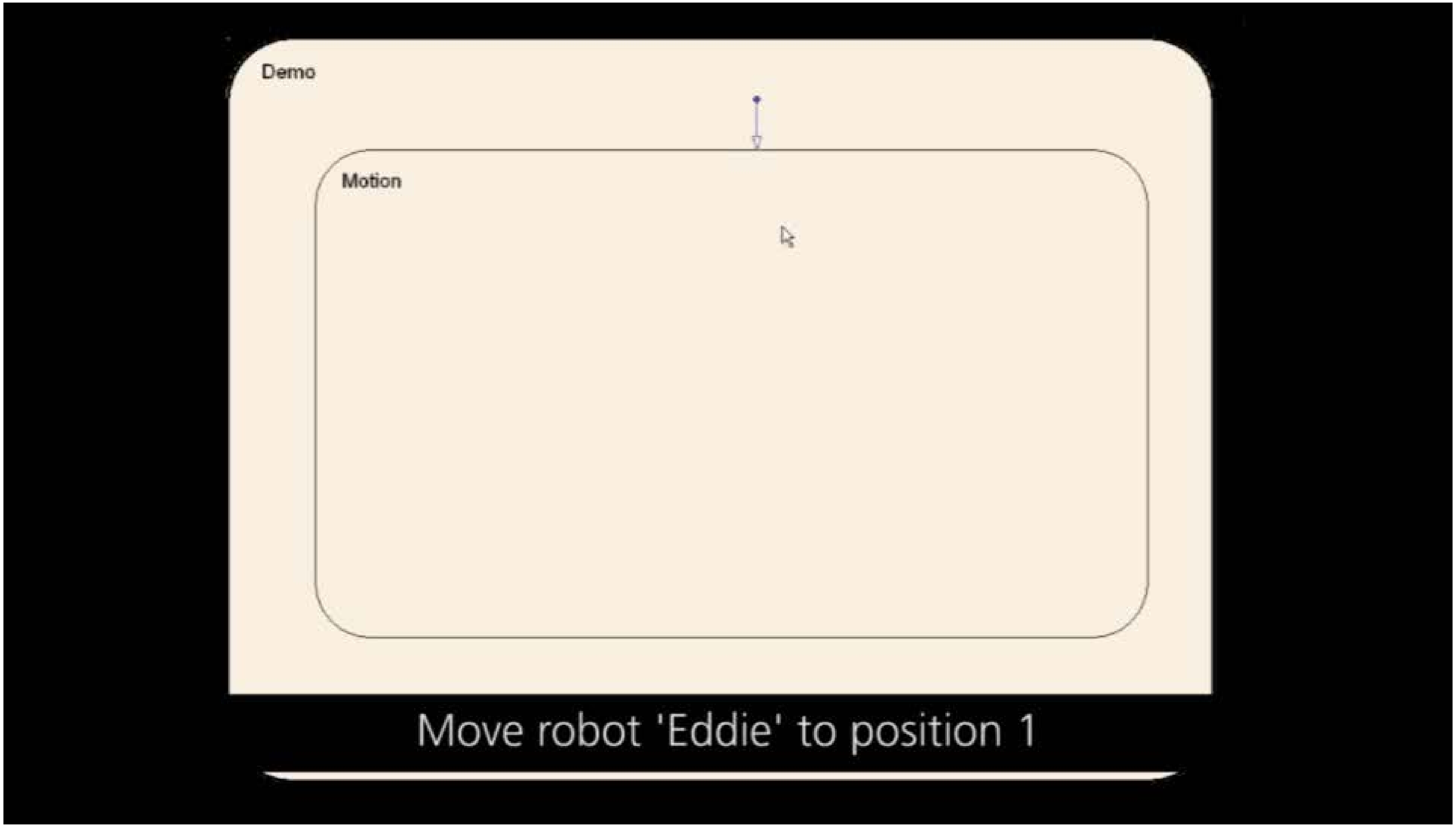
Sets:

- M a set of trajectory generation (motion) modes with P_M as its respective parameter set
- C denotes a set of control modes with P_C as its respective parameter set
- PR a set of priorities
- S a set of safety configurations

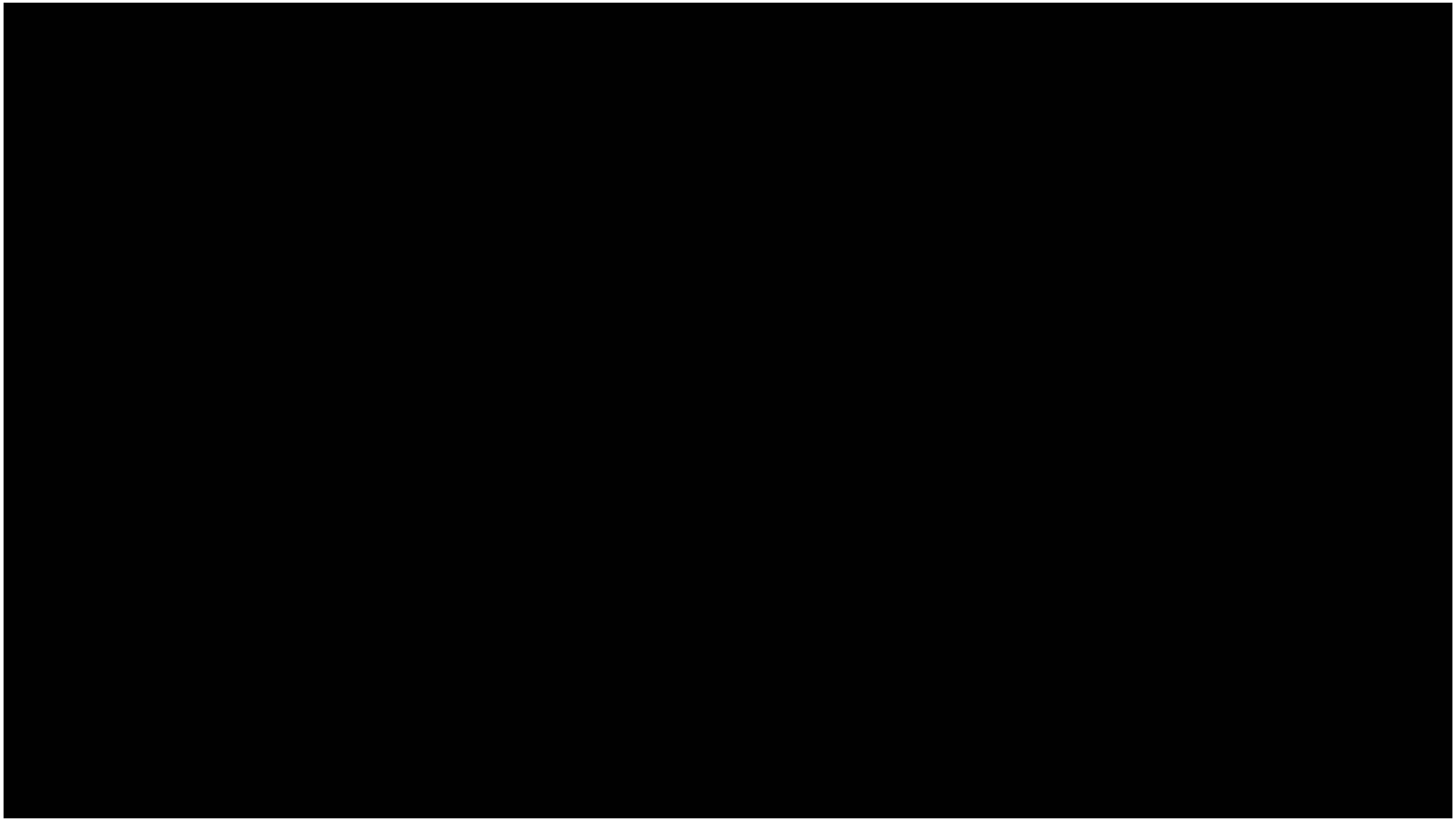
Rough guess:

- 12 M + 12*200 PM
- 10 C + 200PC
- Reflex depth: 10
- Safety set:10 different reflexes

Programming Interaction



Task and Interaction Planning: Store



together with UniBremen + TUM

Task and Interaction Planning: Retrieve

together with UniBremen + TUM

DLR

Last but not least: Intrinsically elastic robots

Newest Robot Generation

rigid and heavy

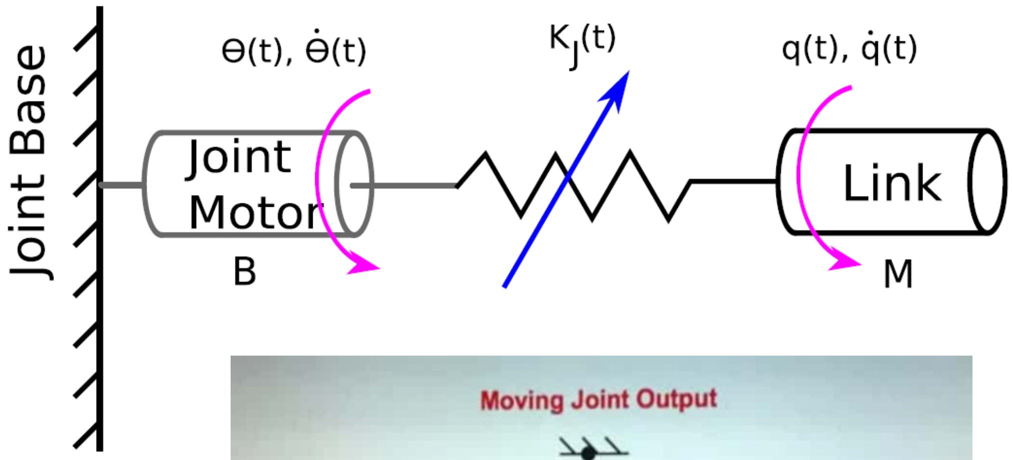
passively compliant & light

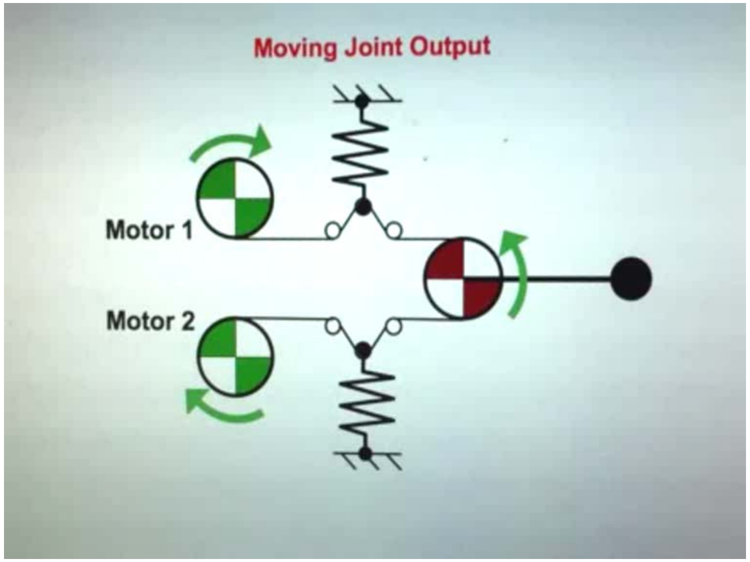
↓

→

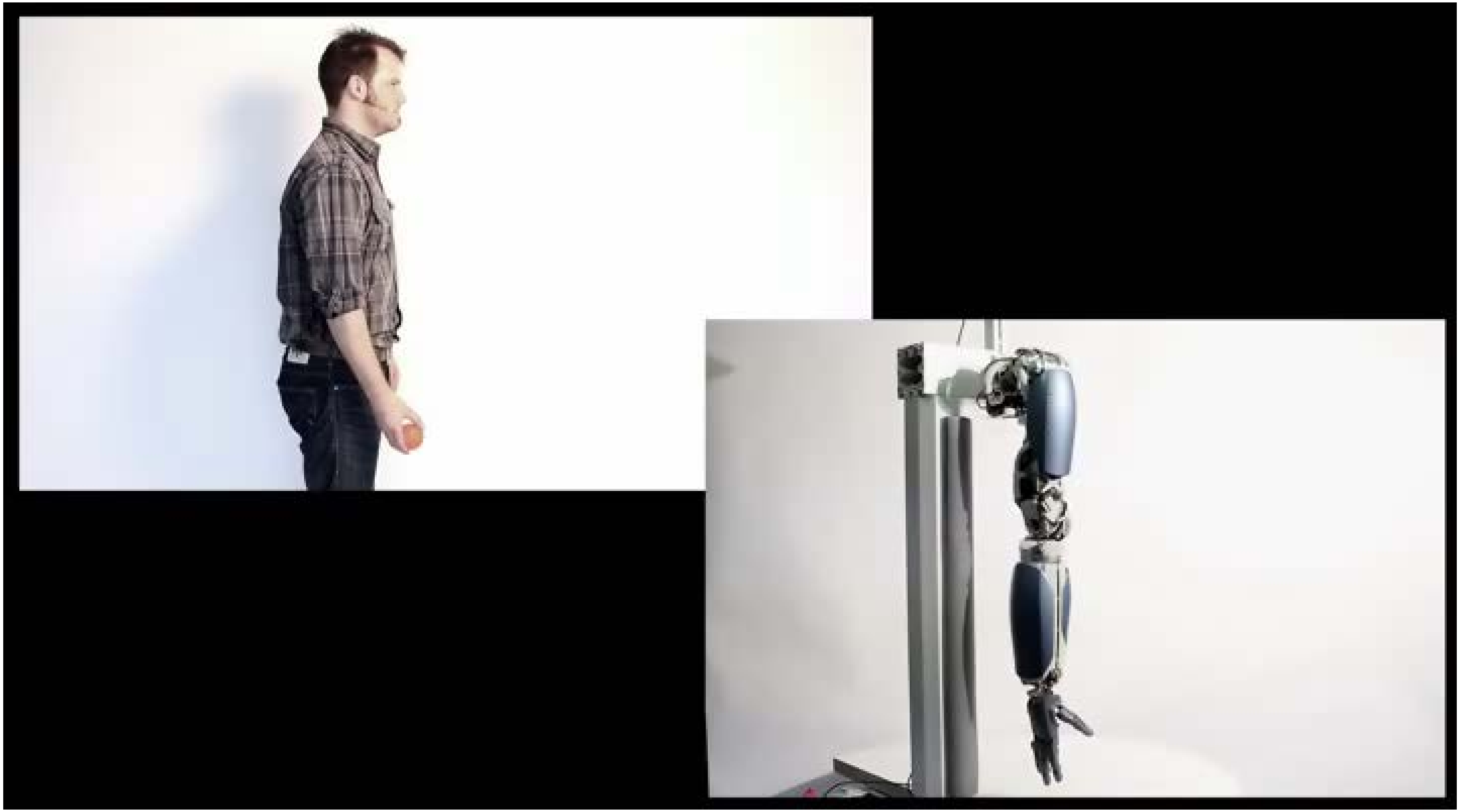
actively compliant & light

Elastic Robot Design

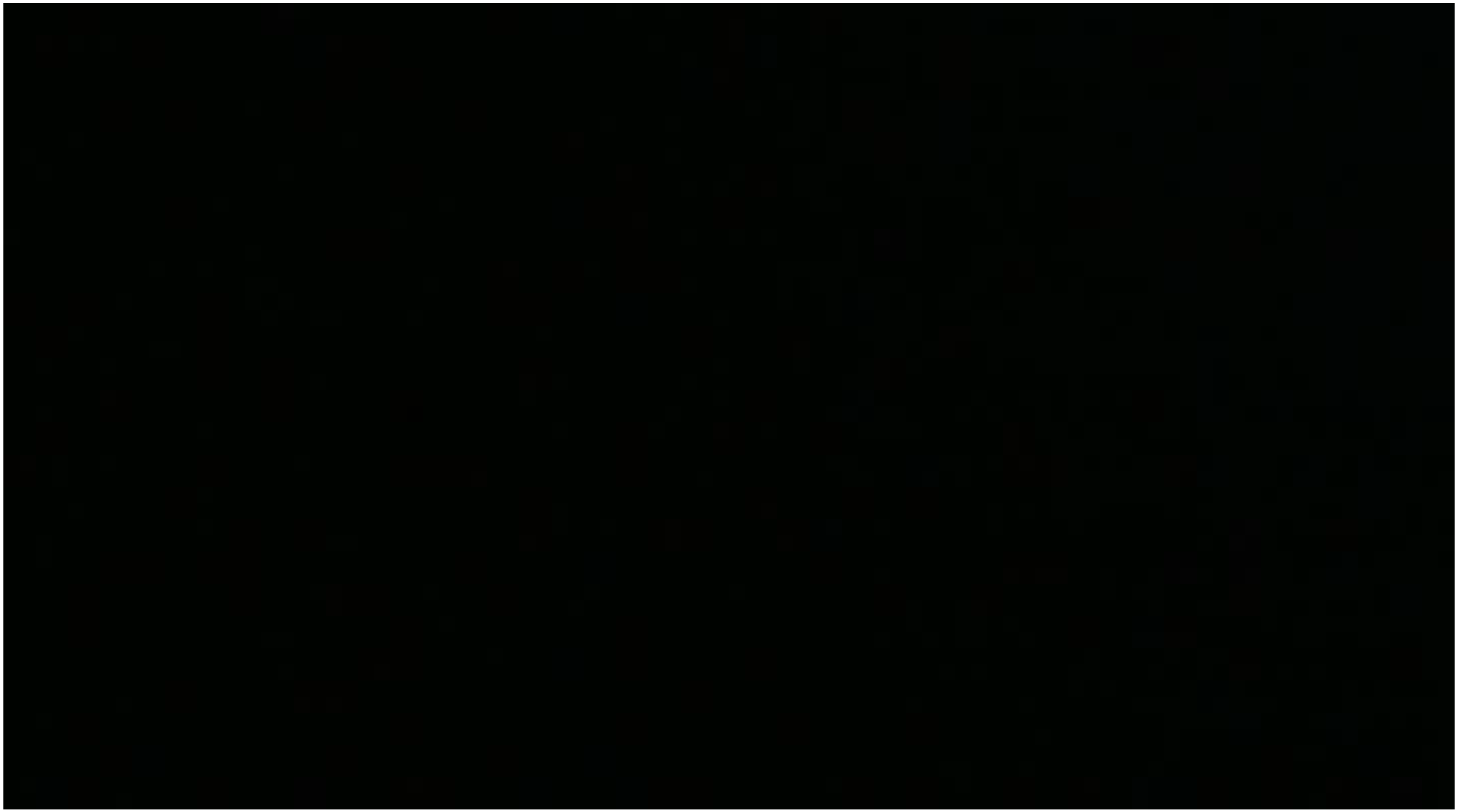




Energy storage in elastic joints



Intrinsic Elasticity: The Key to Human Like Performance



Problems

Entirely new control problems

- Tracking is only one of many motion problems
- Soft-robotics + new world of problems
- How to combine control, learning, generalization?
- This makes the aforementioned complexity even larger!

Thanks!