Safe Motion Control in physical Human-Robot Interaction

Workshop Safety for Human-Robot Interaction in Industrial Settings
2015 IEEE/RSJ International Conference on Intelligent Robots and Systems
Hamburg, Germany

Sami Haddadin

INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

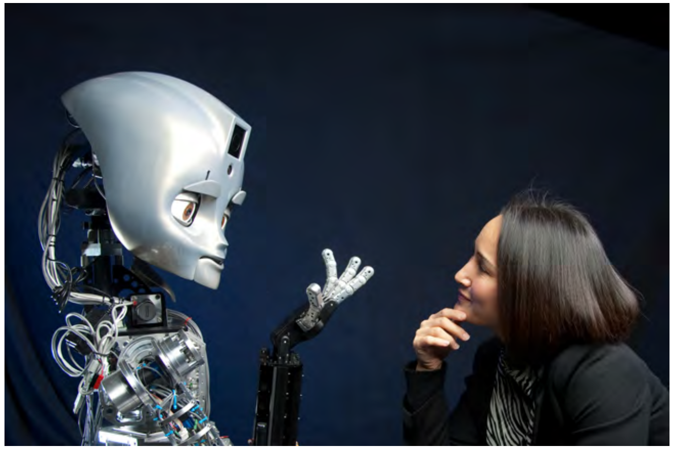
Institut für Regelungstechnik
Leibniz Universität Hannover
Appelstraße 11
30167 Hannover
www.irt.uni-hannover.de
haddadin@irt.uni-hannover.de

Source: Robot & Frank

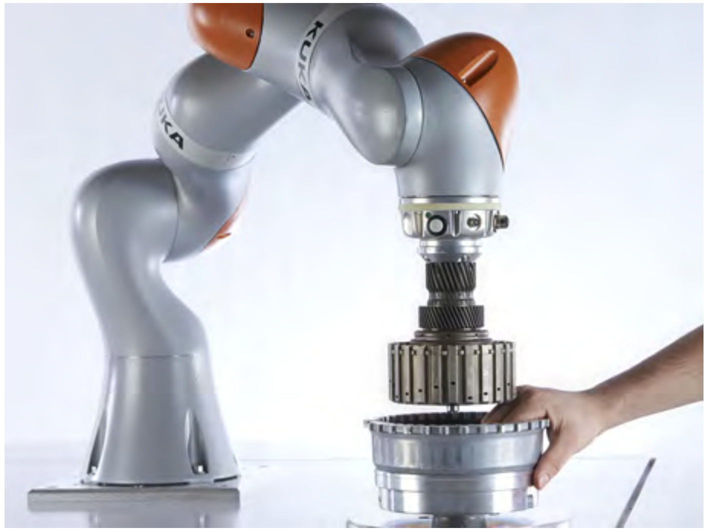
Interaction

Cognitive HRI

Physical HRI

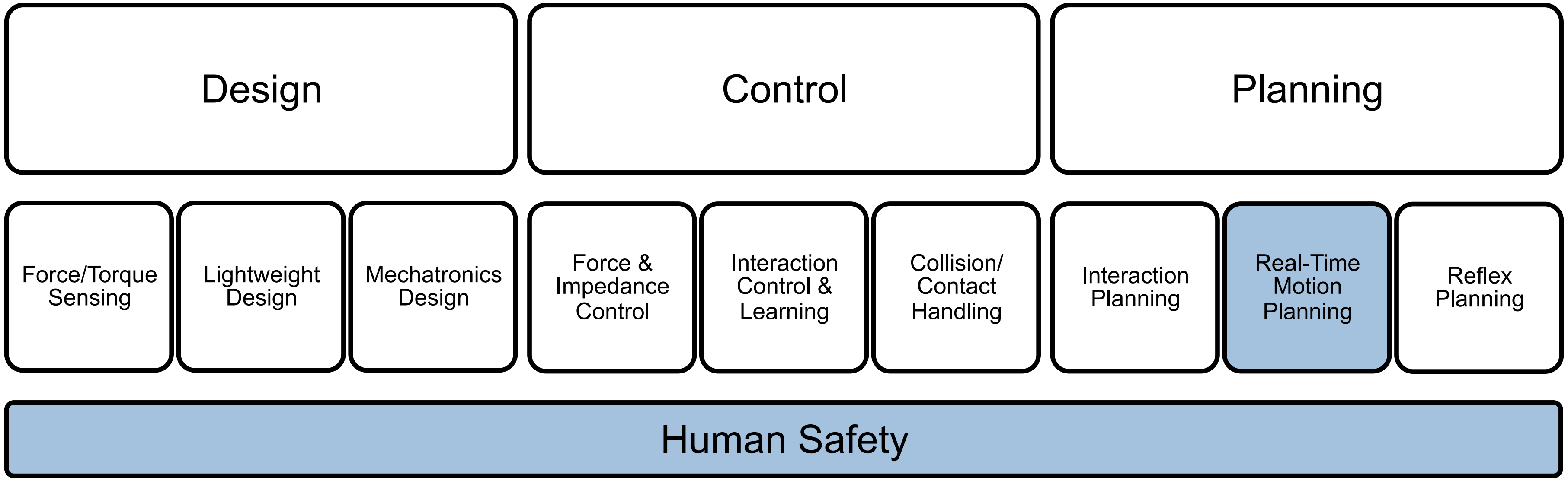


Source: MIT Media Lab



Source: KUKA

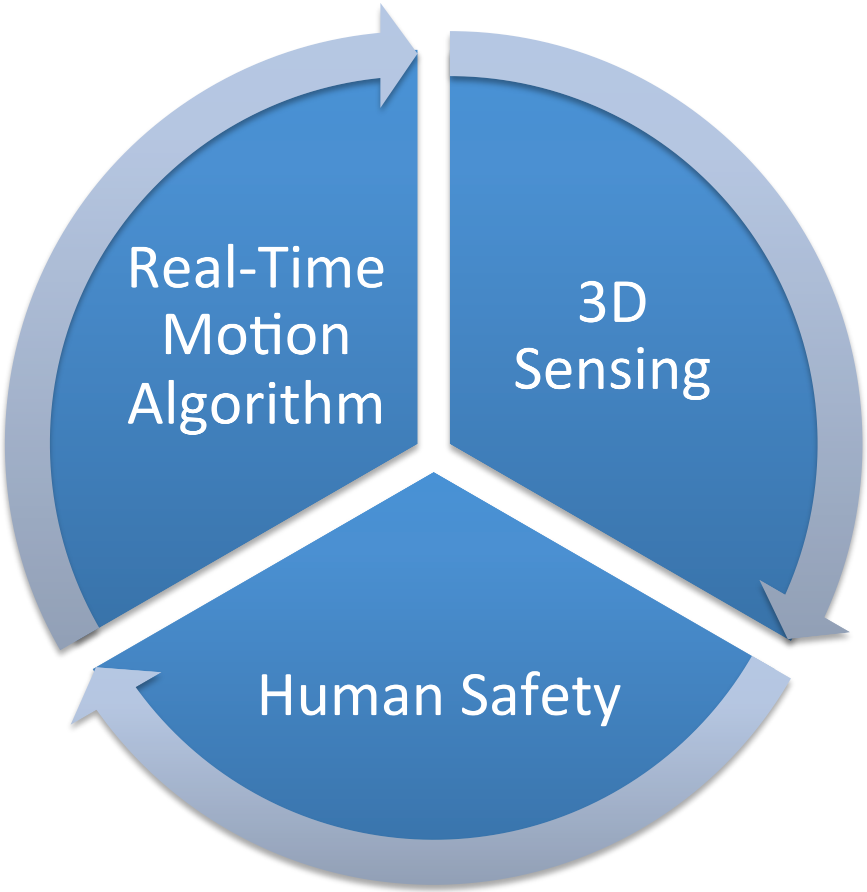
Physical Interaction



1. **Act compliant**
2. **Feel and understand contacts**
3. **Move safely**

Leibniz Universität Hannover

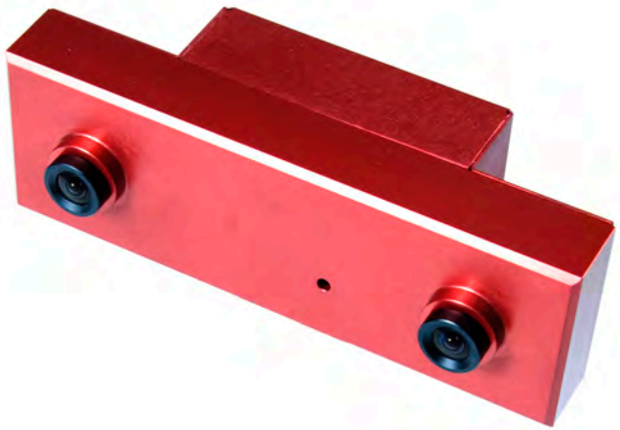
Safe Real-Time Motion Planning



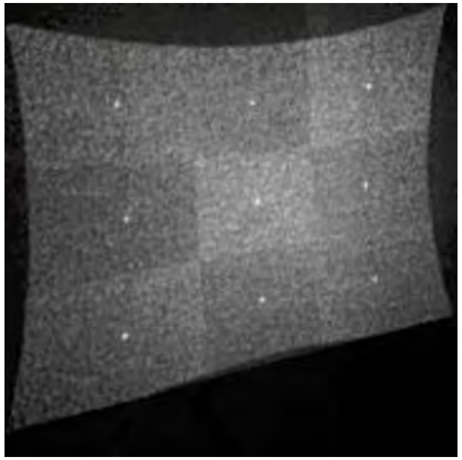
INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

Depth Sensors: From Stereo Vision to Kinect

Stereo Vision



Time of Flight



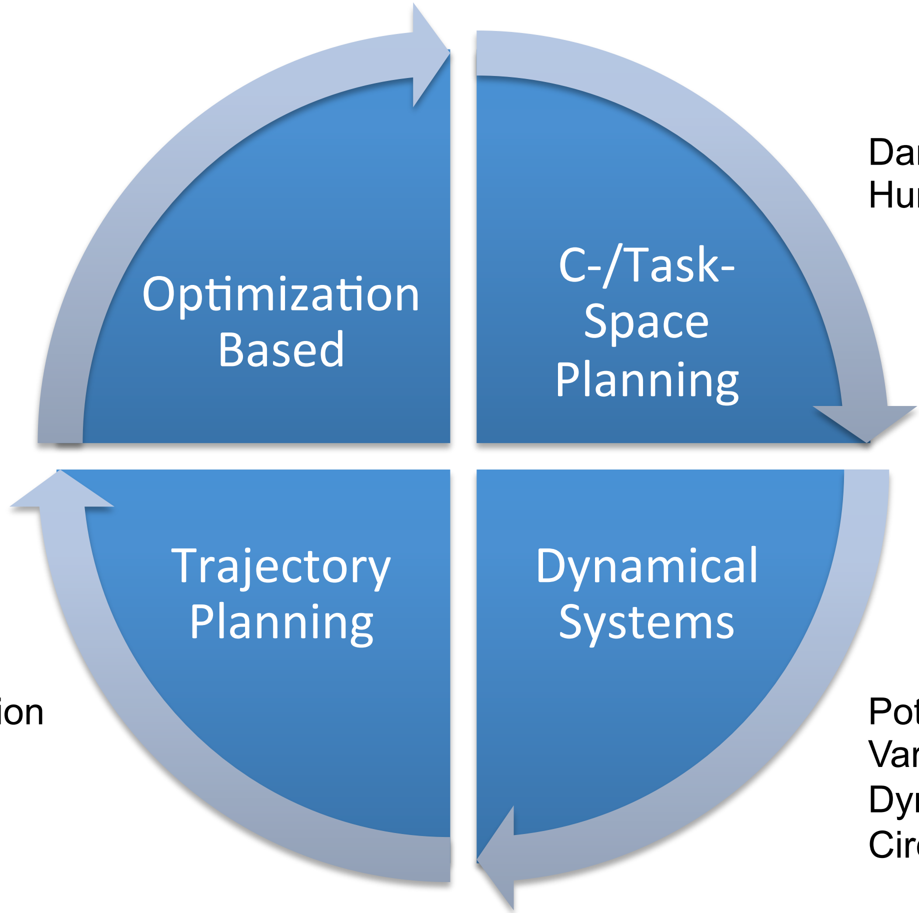
Structured Light

→More later on…

Algorithm Classes

Safe Brachistochrone
Learning safet behaviors

Danger Index Based Planning
Human Aware Motion Planning



Online Trajectory Generation

Potential Fields
Variable Attractor Dynamics
Dynamic Movement Primitives
Circular Fields

Work of Andrea Maria Zanchettin and Paolo Rocco in Safe Motion Planning!

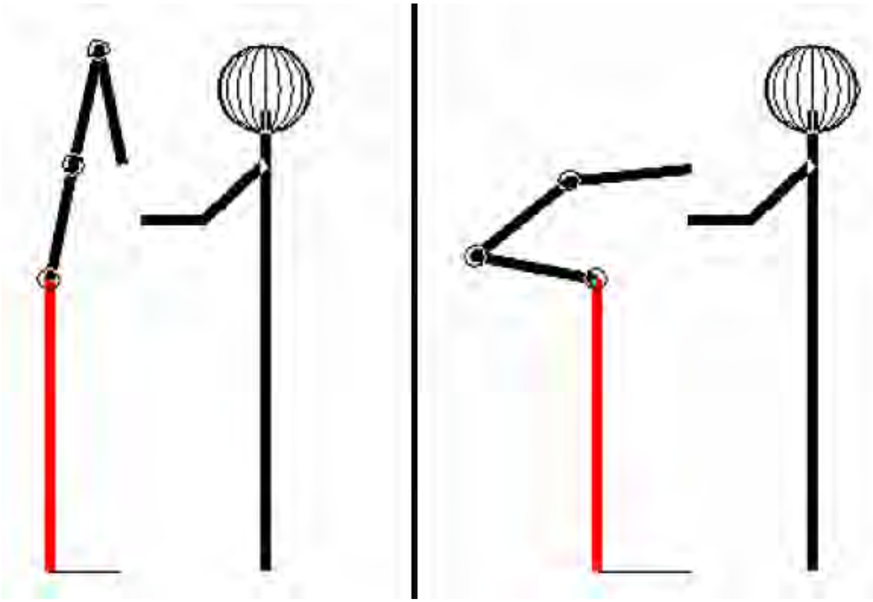
C-Space Planning: Kulić & Croft 2006-2006

$$J = w_G f_G(d_G) + w_0 f_0(d_0) + w_D K \cdot DC$$

- „Extension“ of (Nokata, Ikuta et al., 2002)
- C-space planner based on *best-first planning approach* , meaning following steepest decent of cost function (Latombe, 1991)

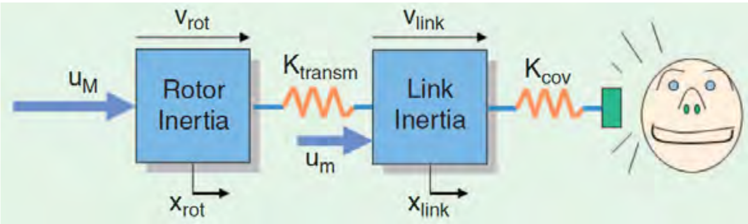
- Danger Criterion:

$$DC = \frac{I_S}{I_{\max}} f_{CoM}(D_{CoM})$$



- *Reflected inertia* based safety coefficient
- *Distance based* safety coefficient

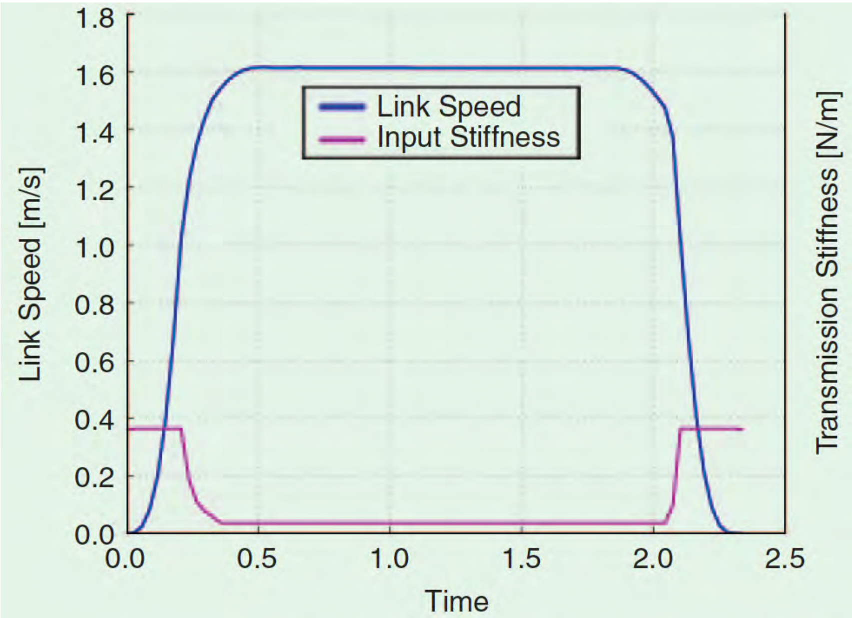
Optimization: Bicchi et. al. 2003-2005



$$
\begin{cases}
\min_T \int_0^T 1 \; dt \\
M_{rot}\ddot{x}_{rot} + K_{transm}(x_{rot} - x_{link}) = u \\
M_{link}\ddot{x}_{link} + K_{transm}(x_{link} - x_{rot}) = 0 \\
|\dot{x}_{link}| \leq v_{safe}(K_{transm}) \\
|u| \leq U_{max},
\end{cases}
$$

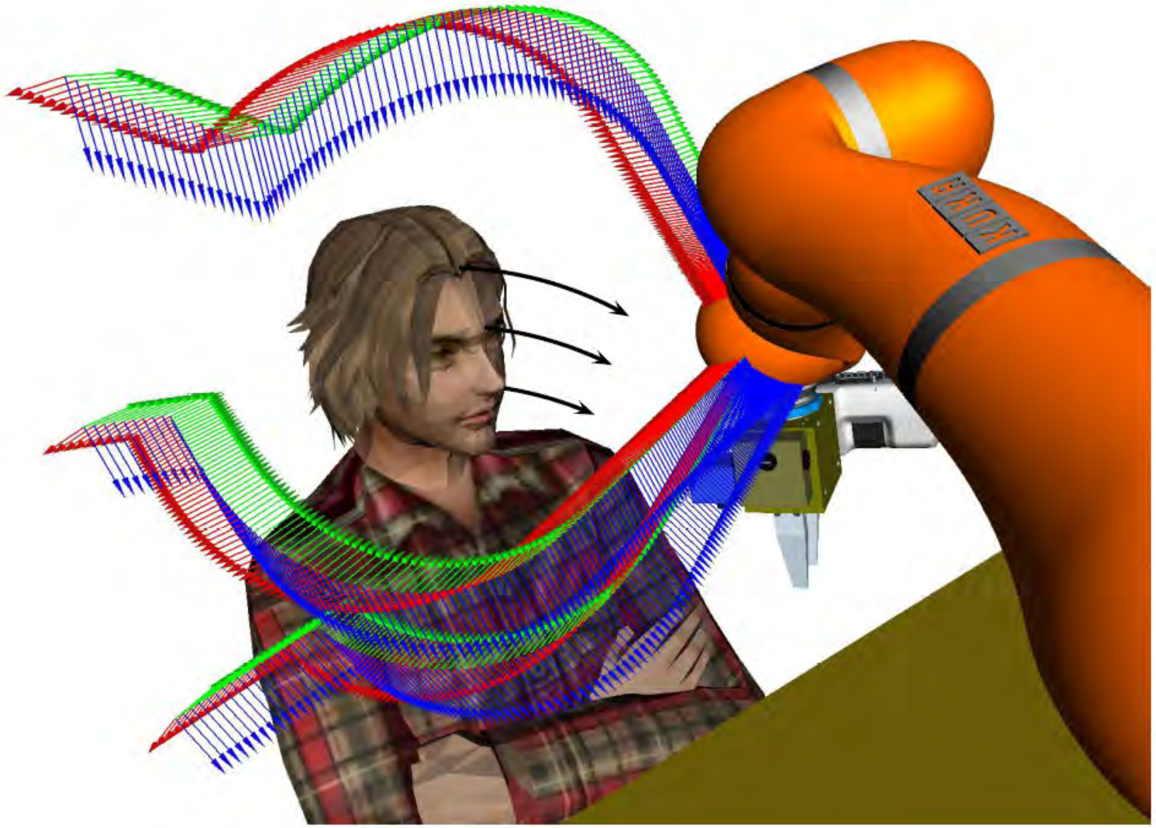
with initial and terminal conditions:

$$
\begin{cases}
x_{rot}(0) = 1, \dot{x}_{rot}(0) = 0 \\
x_{link}(0) = 1, \dot{x}_{link}(0) = 0 \\
x_{rot}(T) = 0, \dot{x}_{rot}(T) = 0 \\
x_{link}(T) = 0, \dot{x}_{link}(T) = 0,
\end{cases}
$$



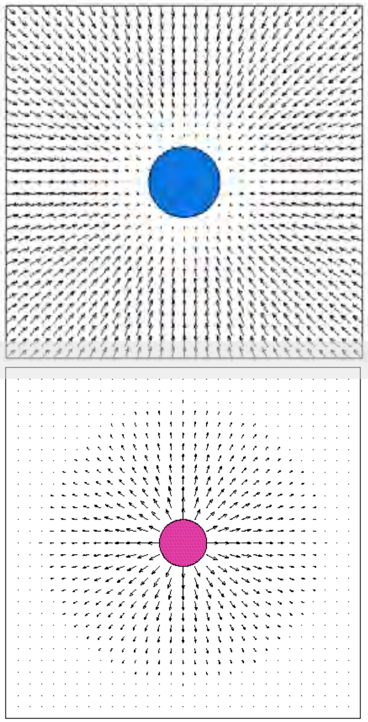
Leibniz Universität Hannover

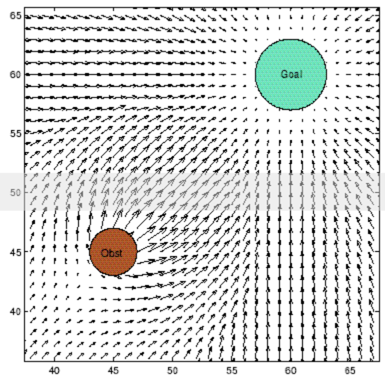
Real-Time Motion Planning

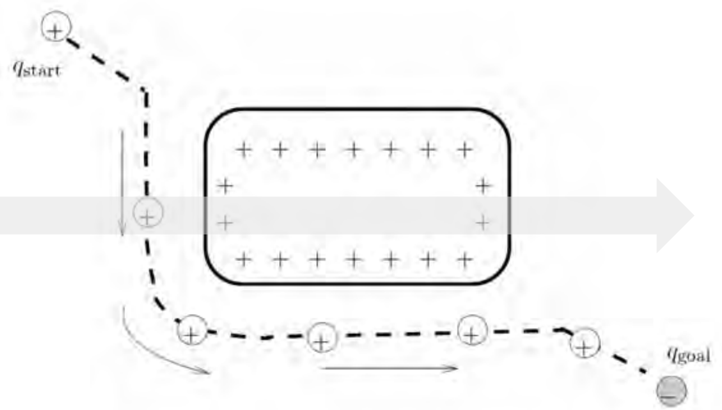


Potential Fields: Khatib 1986

The manipulator moves in a field of forces.
The position to be reached is an attractive pole for the end effector and obstacles are repulsive surfaces for the manipulator parts.







„Borrowed slide“ from Howie Choset

Potential Fields: Khatib 1986

Dynamical Systems for Collision Avoidance

2nd order dynamical system: $M\ddot{x}_d + K(x_d - x_g) + D\dot{x}_d = 0$

Potential Fields $M\ddot{x}_d + K(x_d - x_g) + D\dot{x}_d = \sum F_i(x_{o,i}, x_d, \ldots)$

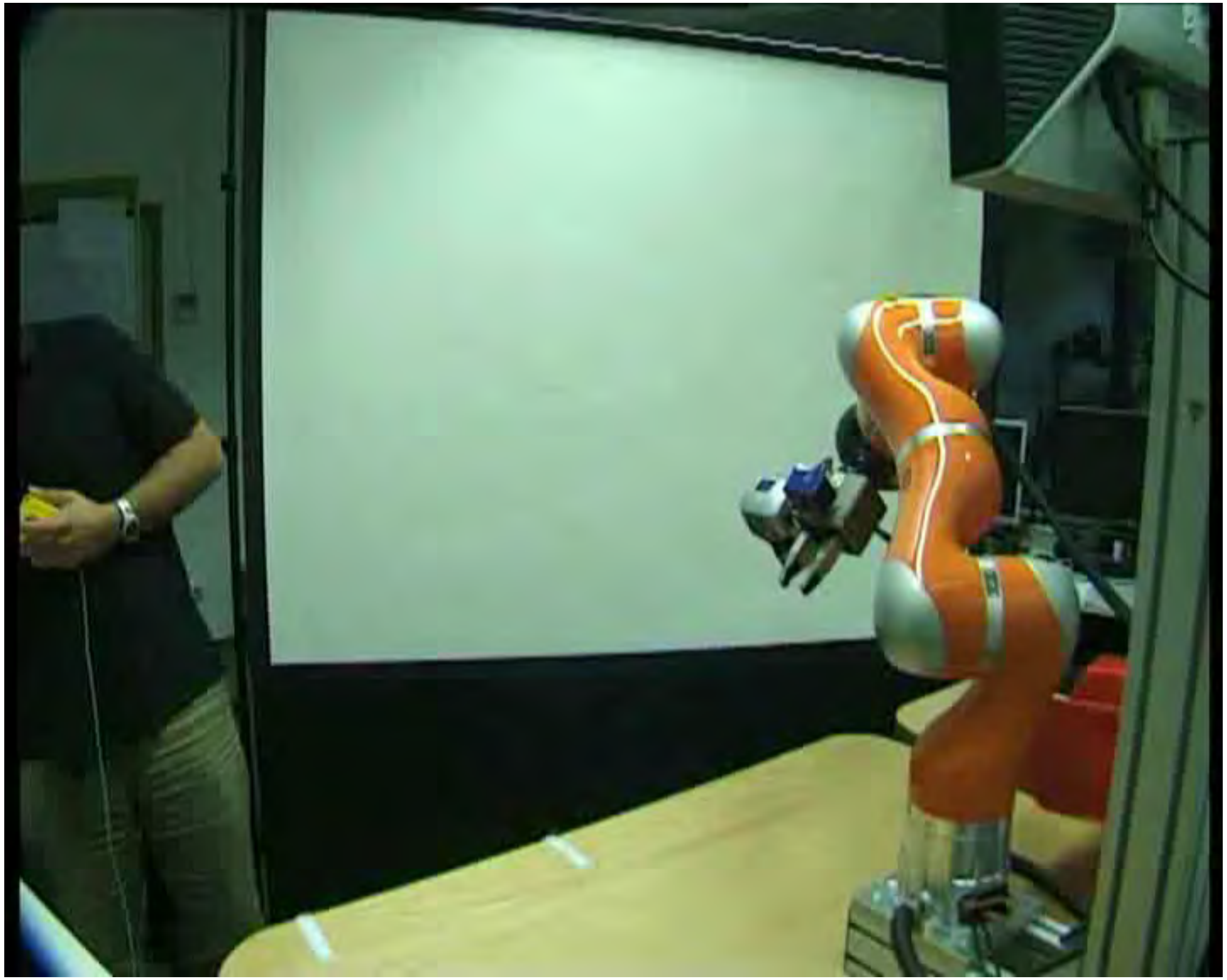
Task knowledge

Potential Fields+Task feed-forward, like DMP $M\ddot{x}_d + K(x_d - x_g) + D\dot{x}_d = \sum F_i(x_{o,i}, x_d, \ldots) + F_{task}$

Variable Attractor Dynamics $M\ddot{x}_d + K(x_d - x_g) + D\dot{x}_d = \sum F_i(x_{o,i}, x_d, \ldots)$

Variable Attractor Dynamics + Velocity scaling $M\ddot{x}_d + K(x_d - x_g) + D\dot{x}_d = \sum F_i(x_{o,i}, x_d, \ldots)$

Variable Attractor Dynamics: Haddadin et al. 2009



Variable Attractor Dynamics: Haddadin et al. 2009

INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

Dynamic Movement Primitives: Park et al. 2008

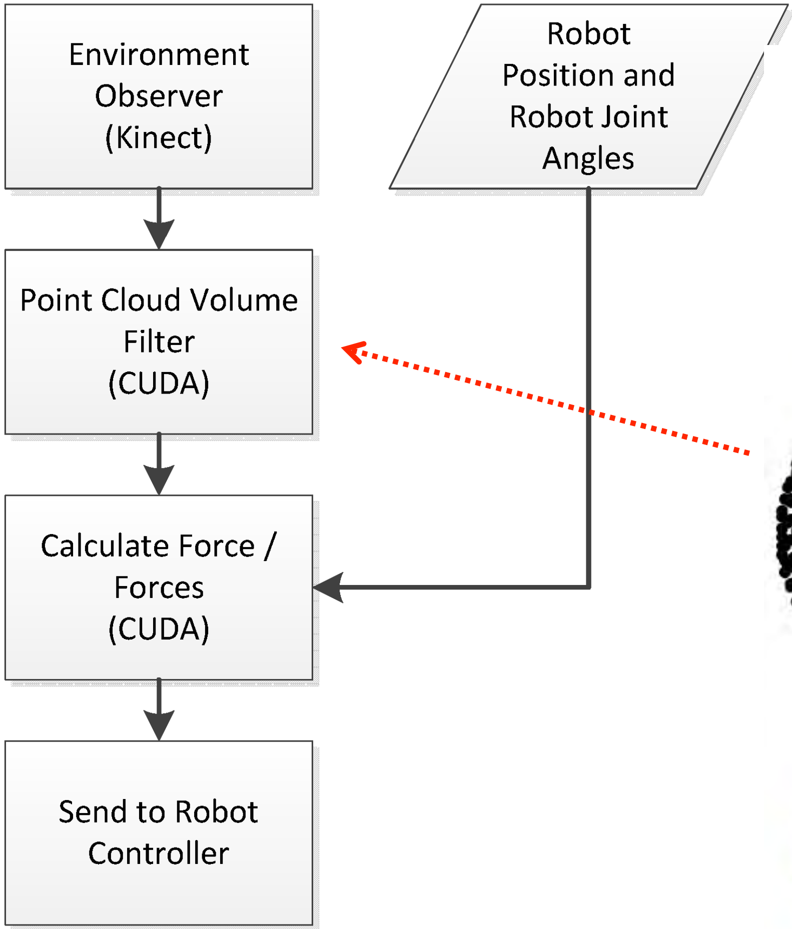
$$\begin{aligned}\tau\dot{\mathbf{v}} &= \mathbf{K}(\mathbf{g}-\mathbf{x}) - \mathbf{D}\mathbf{v} - \mathbf{K}(\mathbf{g}-\mathbf{x}_0)\theta + \mathbf{K}\mathbf{f}(\theta) \\ &\quad + \varphi(\mathbf{x},\mathbf{v}) \\ \tau\dot{\mathbf{x}} &= \mathbf{v}\ .\end{aligned}$$

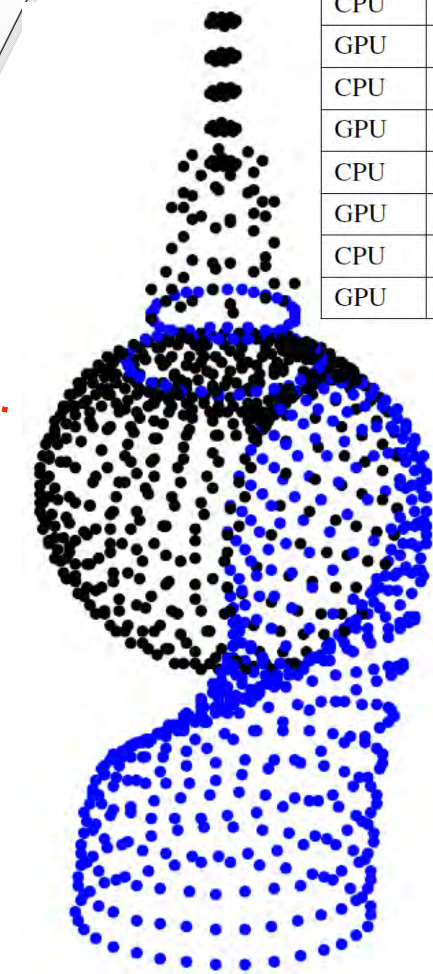
$$\begin{aligned}\varphi(\mathbf{x},\mathbf{v}) &= -\nabla_x U_{\text{dyn}}(\mathbf{x},\mathbf{v}) \\ &= \lambda(-\cos\theta)^{\beta-1}\frac{||\mathbf{v}||}{p}\left(\beta\,\nabla_x\cos\theta - \frac{\cos\theta}{p}\nabla_x p\right)\end{aligned}$$

$$U_{\text{static}}(\mathbf{x}) = \left\{\begin{array}{ll}\frac{\eta}{2}\left(\frac{1}{p(\mathbf{x})}-\frac{1}{p_0}\right)^2 & : \quad p(\mathbf{x}) \le p_0 \\ 0 & : \quad p(\mathbf{x}) > p_0\end{array}\right\} \quad U_{\text{dyn}}(\mathbf{x},\mathbf{v}) = \left\{\begin{array}{ll}\lambda(-cos\theta)^\beta\frac{||\mathbf{v}||}{p(\mathbf{x})} & : \quad \frac{\pi}{2} < \theta \le \pi \\ 0 & : \quad 0 \le \theta \le \frac{\pi}{2}\end{array}\right\}$$

Dynamic Movement Primitives: Park et al. 2008

GPU-Enhanced Variable Attractor Dynamics: Kaldestadt et al. 2014





Archi-tecture	Voxel map resolution	Robot vertices	Algorithm calculation time	Performance factor
CPU	10 mm	4701	1.426 s	129.63x
GPU	10 mm	4701	0.011 s	
CPU	5 mm	4701	5.692 s	402.07x
GPU	5 mm	4701	0.014 s	
CPU	10 mm	2468	0.755 s	68.63x
GPU	10 mm	2468	0.011 s	
CPU	5 mm	2468	3.009 s	273.54x
GPU	5 mm	2468	0.011 s	

Leibniz Universität Hannover

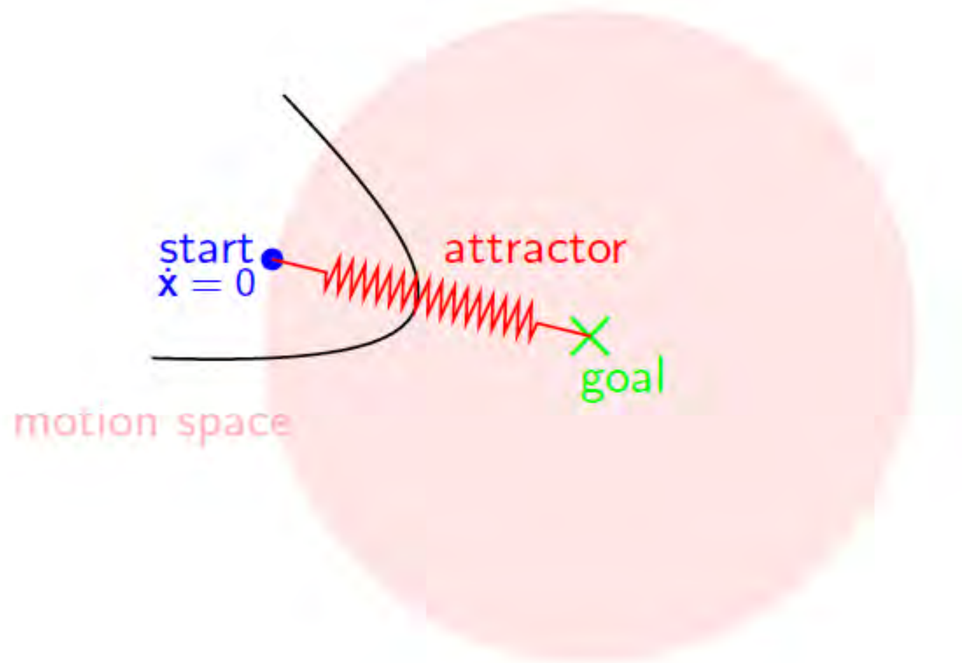
GPU-Enhanced Variable Attractor Dynamics: Kaldestadt et al. 2014

INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

Leibniz Universität Hannover

Circular Fields: Haddadin et. al. 2011

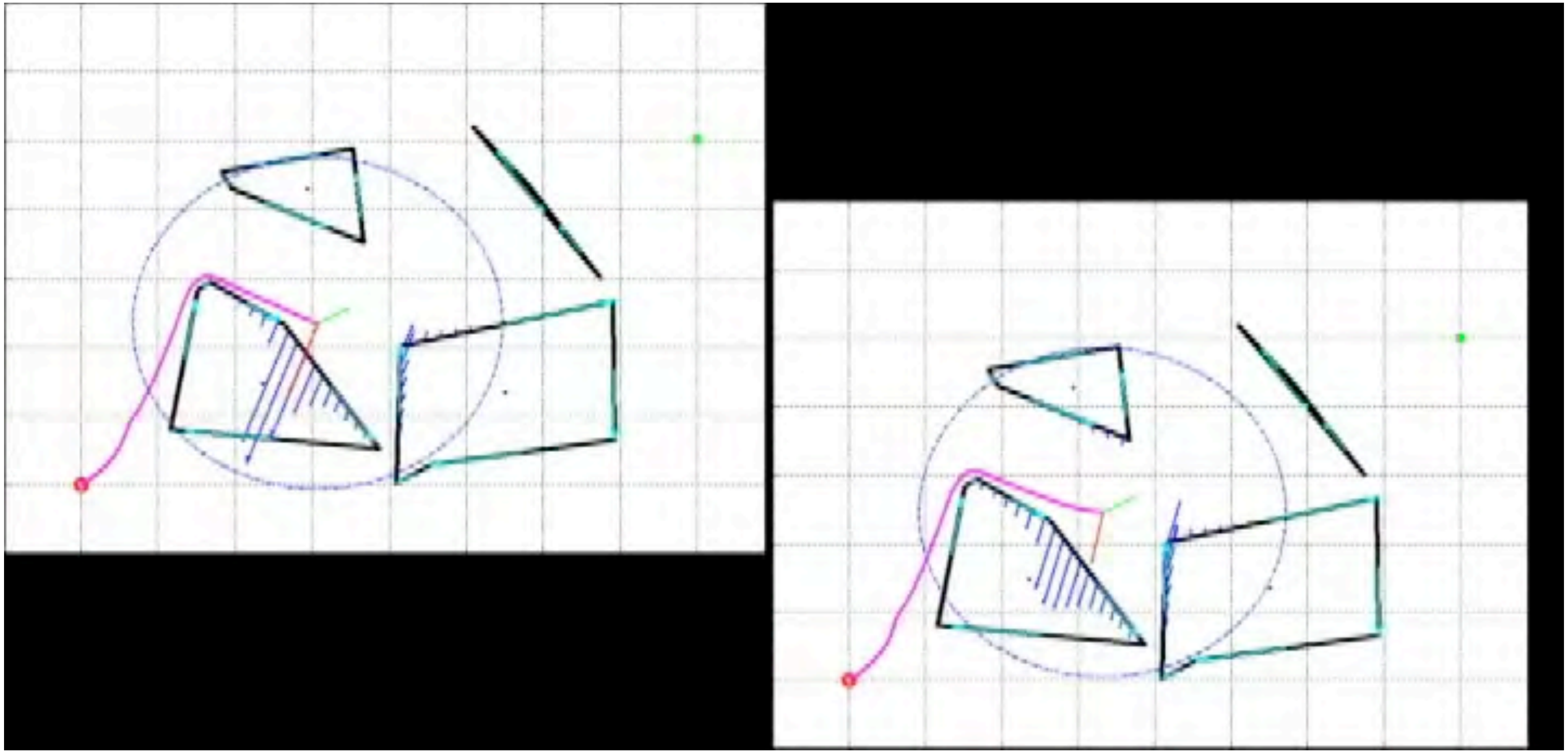
$$F = \dot{x}_r \times B = \dot{x}_r \times \sum_i I \frac{c_i \times \frac{\dot{x}_r}{\|\dot{x}_r\|}}{l_i^2} da_i$$



INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

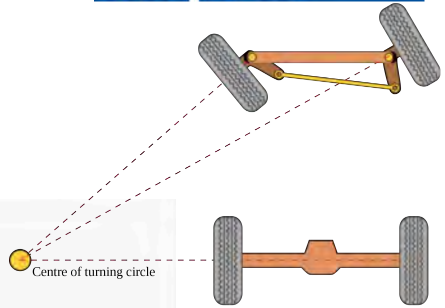
Haddadin & al., IFAC2011

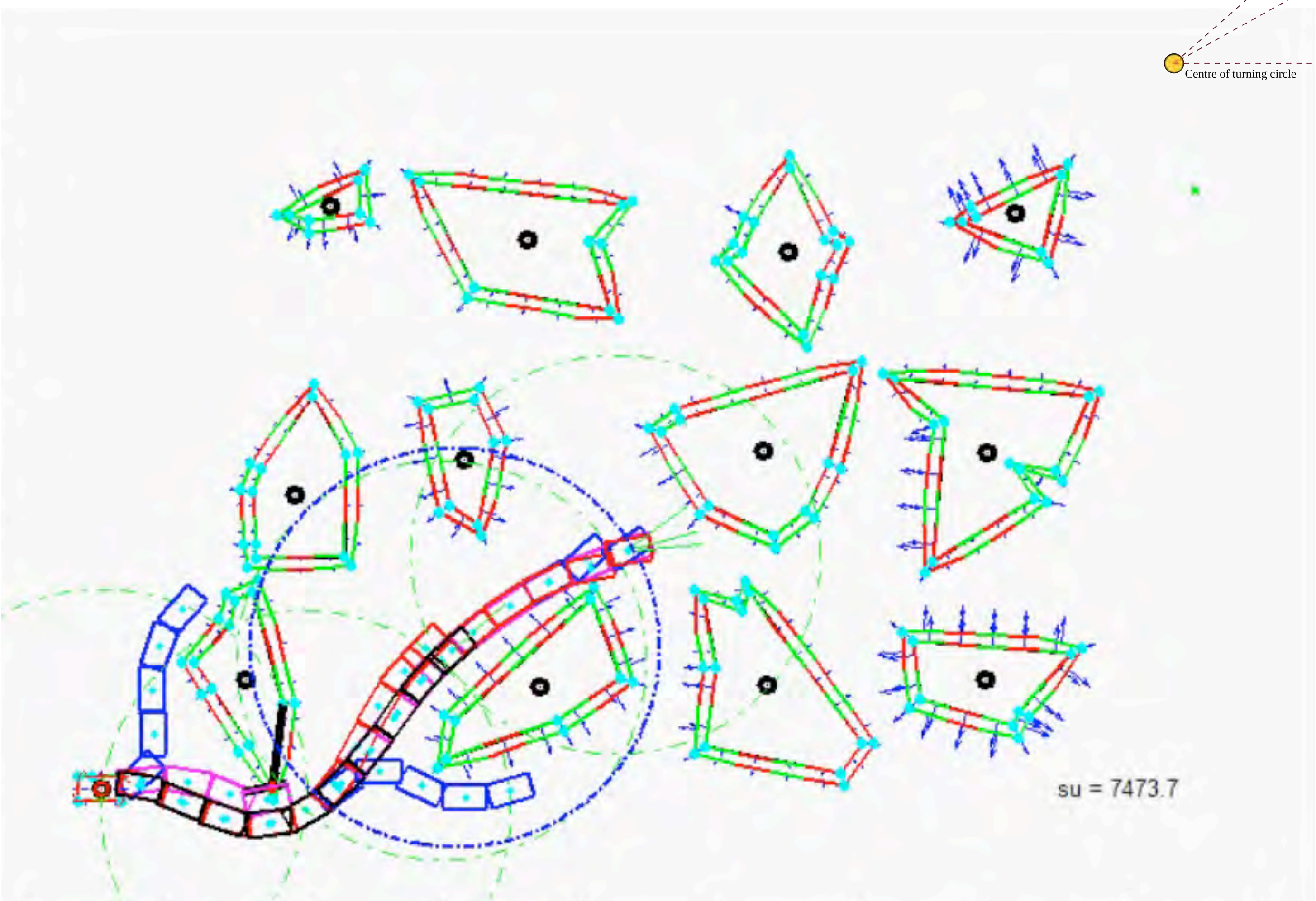
Circular Fields: Haddadin et. al. 2011



Haddadin & al., IFAC2011

Multi-Agent Based Prediction: Haddadin et al. 2013

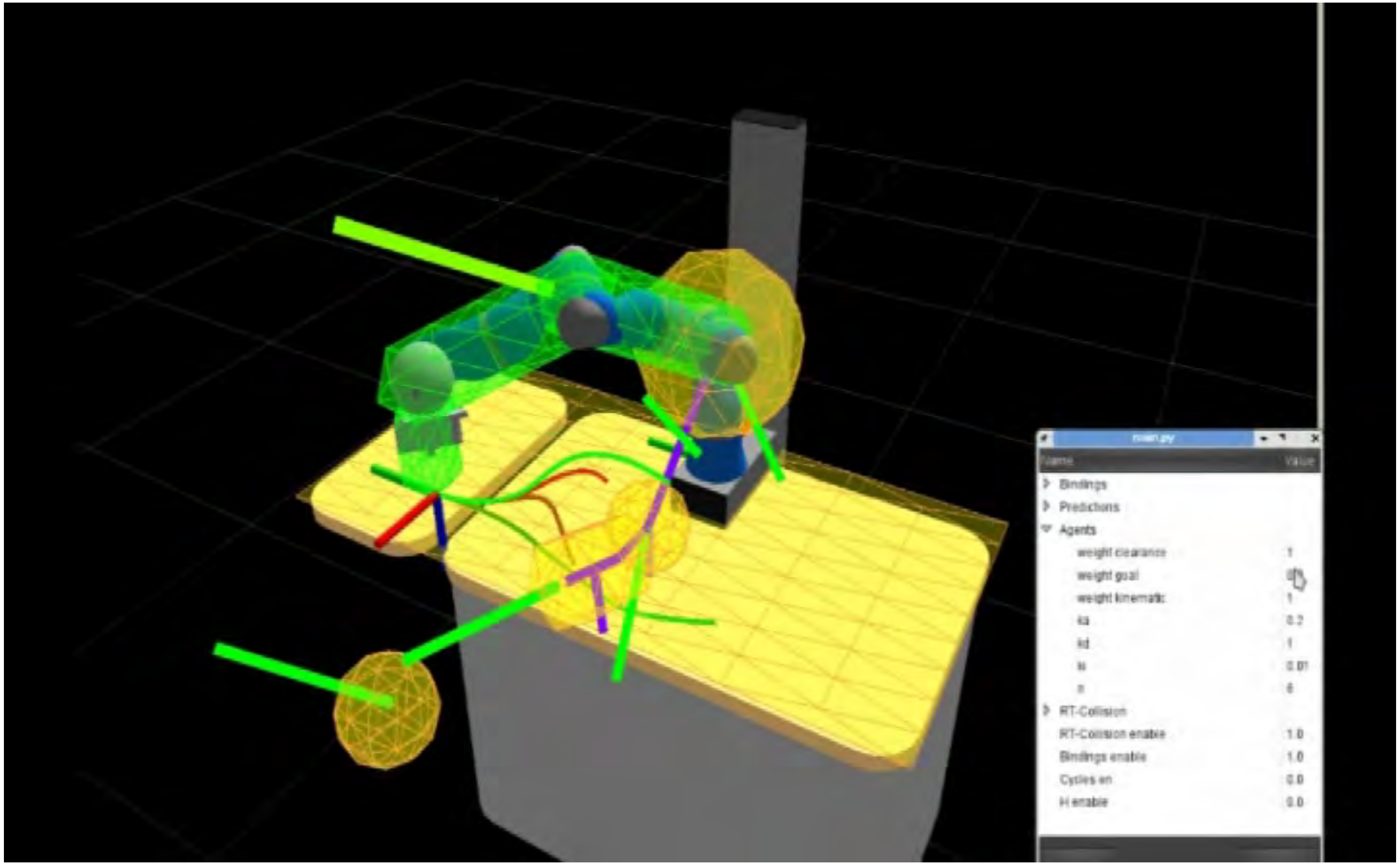




INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

Haddadin & al., Safecomp2013

Cost Based Multi-Agents + Dynamical Systems

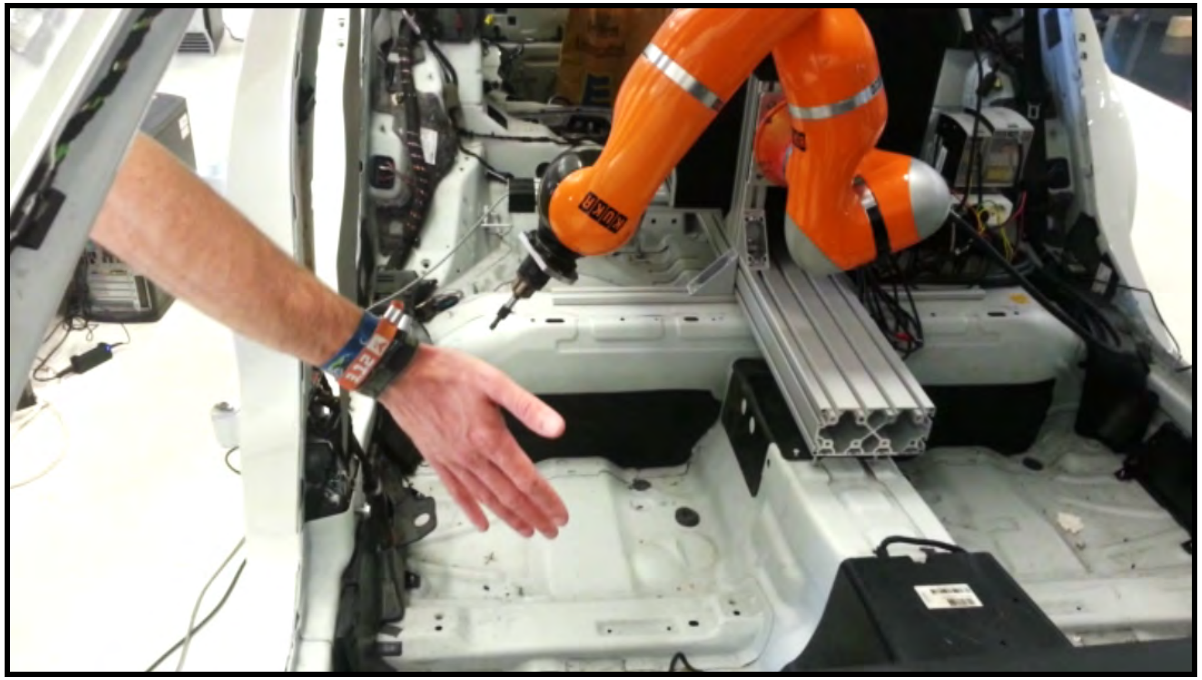


Haddadin & al., Safecomp2013

How can we ensure that a motion is **safe for a human**?

Leibniz Universität Hannover

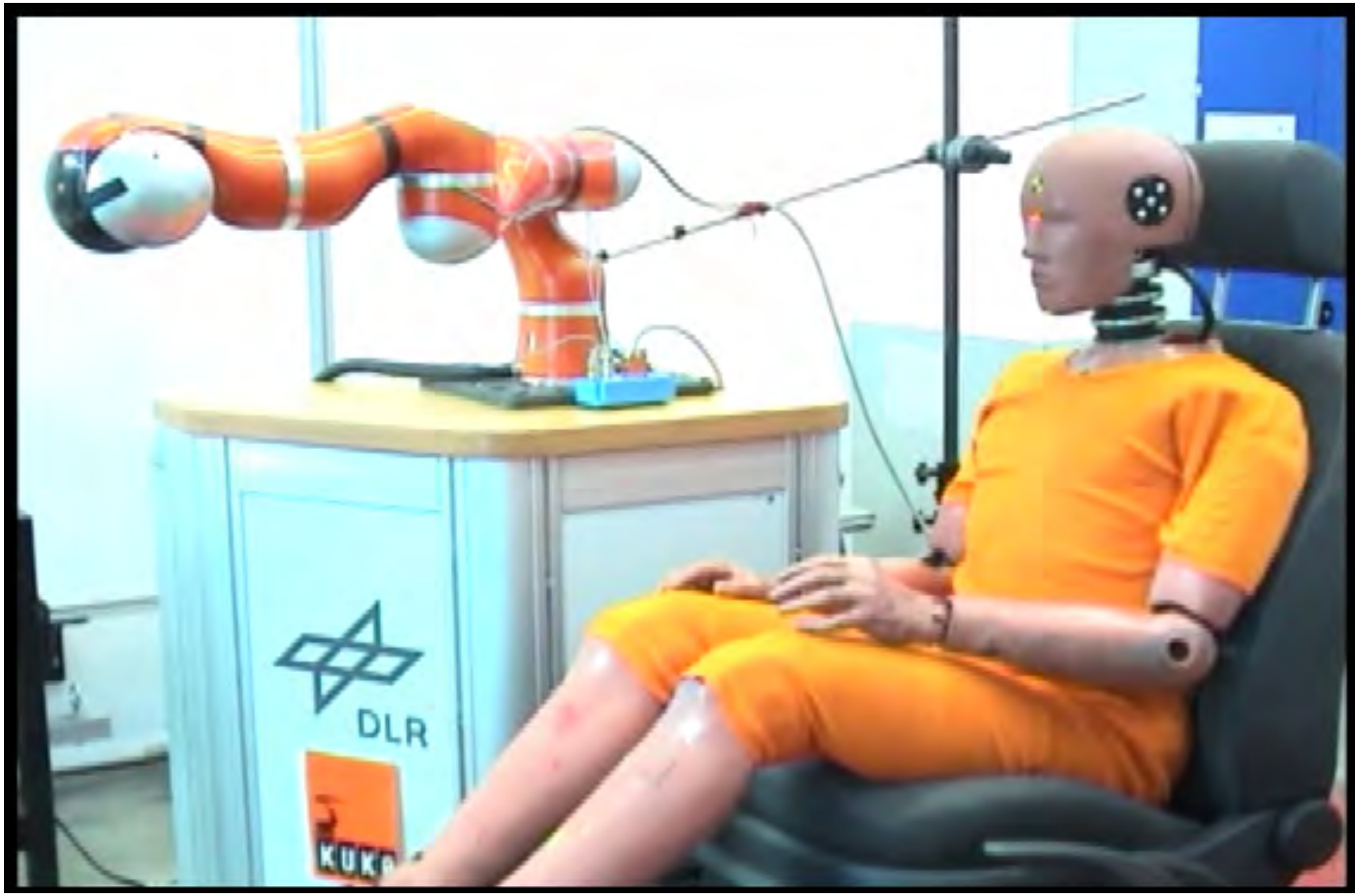
Concretely: Safety Analysis of Human Injury & Pain



Is this safe?

INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

Crash-Testing in Robotics

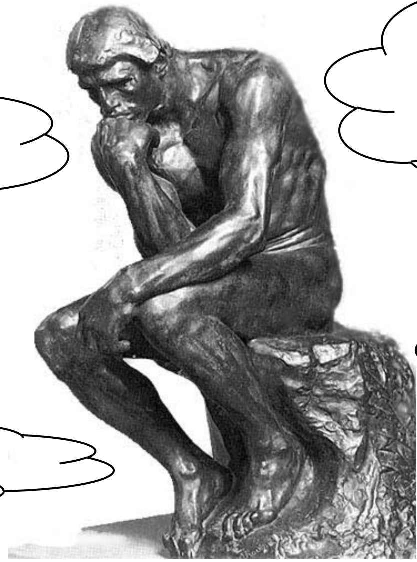


Haddadin et. al. RSS 2007

Haddadin et. al. RSS 2007

How to Connect Injury Data with Robot Motion?

But the robot **configuration changes**...

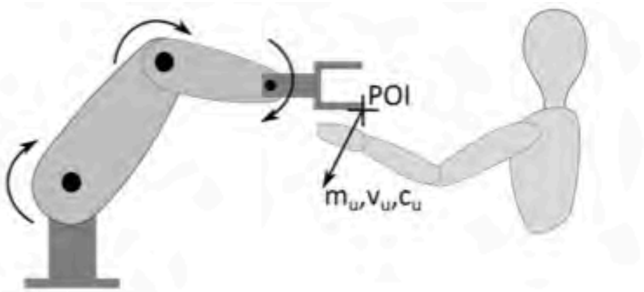


Is it **maximum forces, velocities, energies, stress**,...?

And there are so **many contact situations**...

It may carry a **tool**...

Embedding Injury Knowledge into Control: Haddadin et al. 2010-2012



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

$$\Rightarrow \quad m_u = [\boldsymbol{u}^T \Lambda_v(\boldsymbol{q})^{-1}\boldsymbol{u}]^{-1}$$

with $\Lambda(\boldsymbol{q}) = (J(\boldsymbol{q})M(\boldsymbol{q})^{-1}J(\boldsymbol{q})^T)^{-1}$

Cannot change m_u anyways.

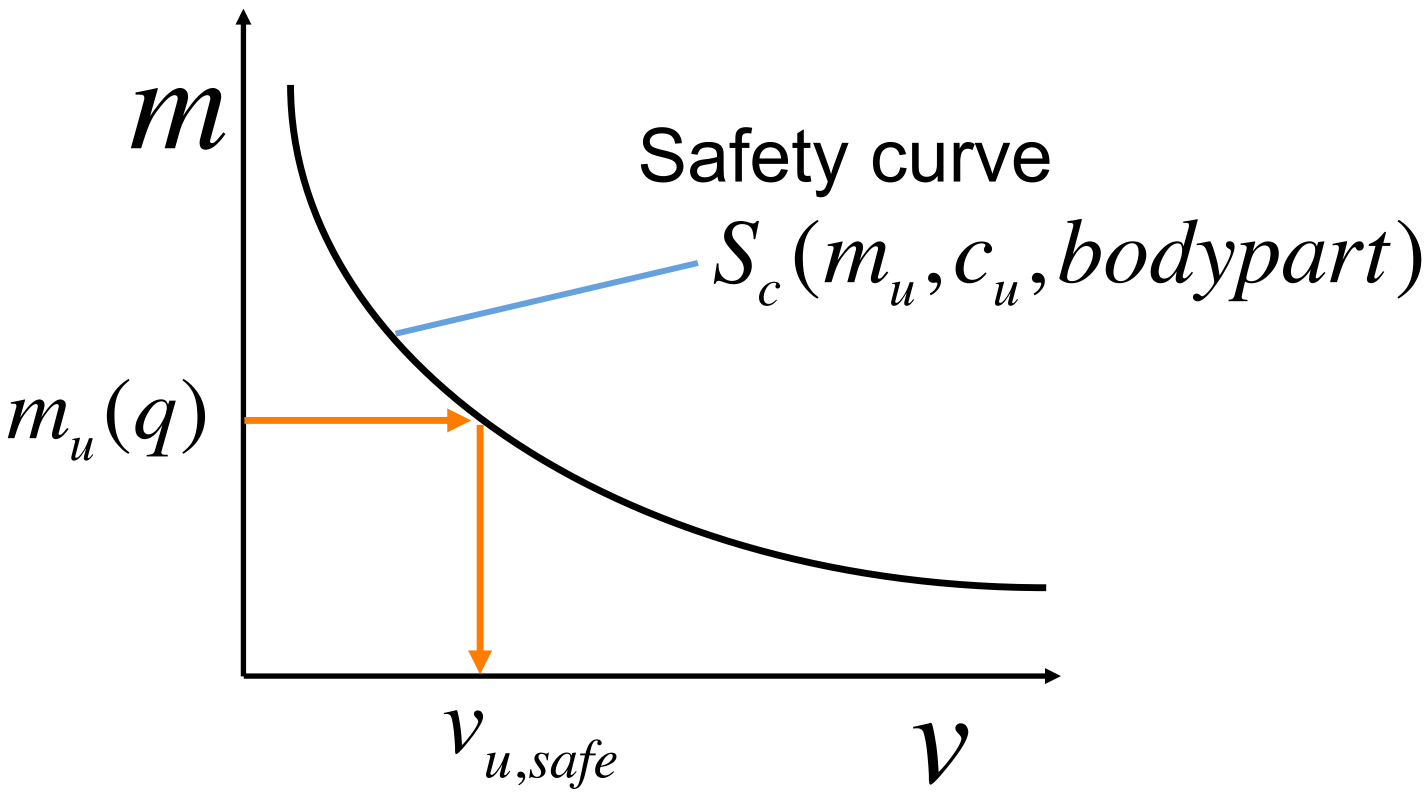
↓

v_u in impact direction u governs the impact.

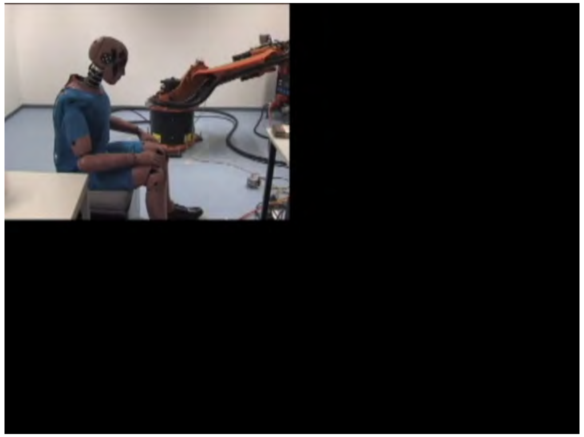
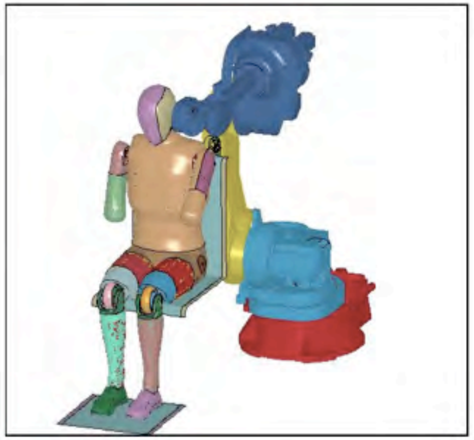
↓

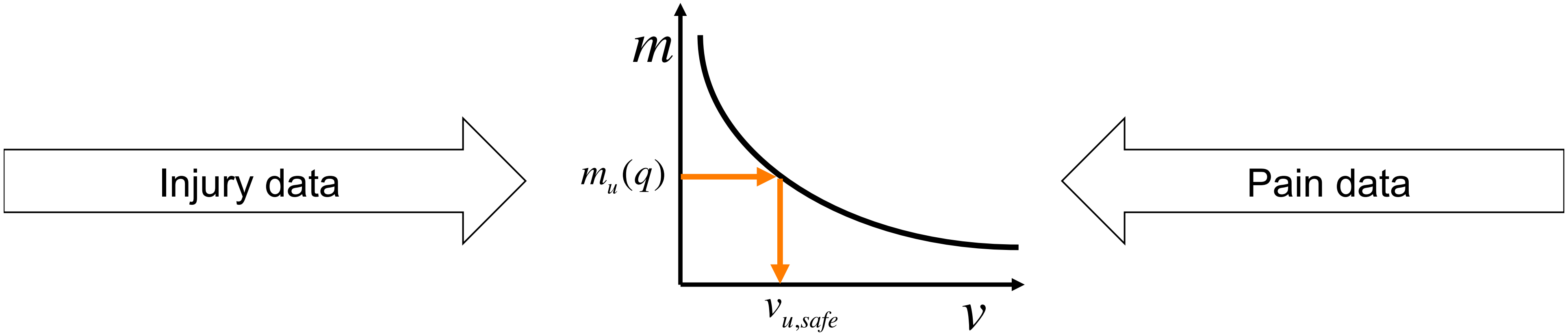
Determine $v_{u,safe}$ of point of interest given m_u and c_u.

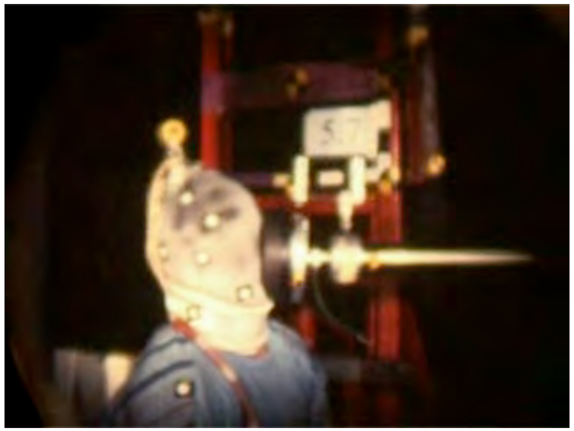
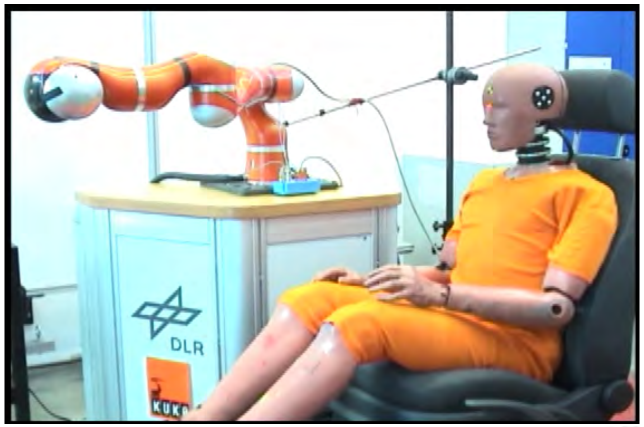
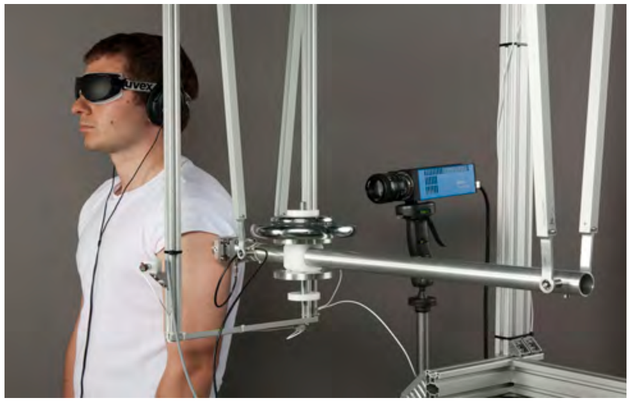
Embedding Injury Knowledge into Control: Haddadin et al. 2010-2012



INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

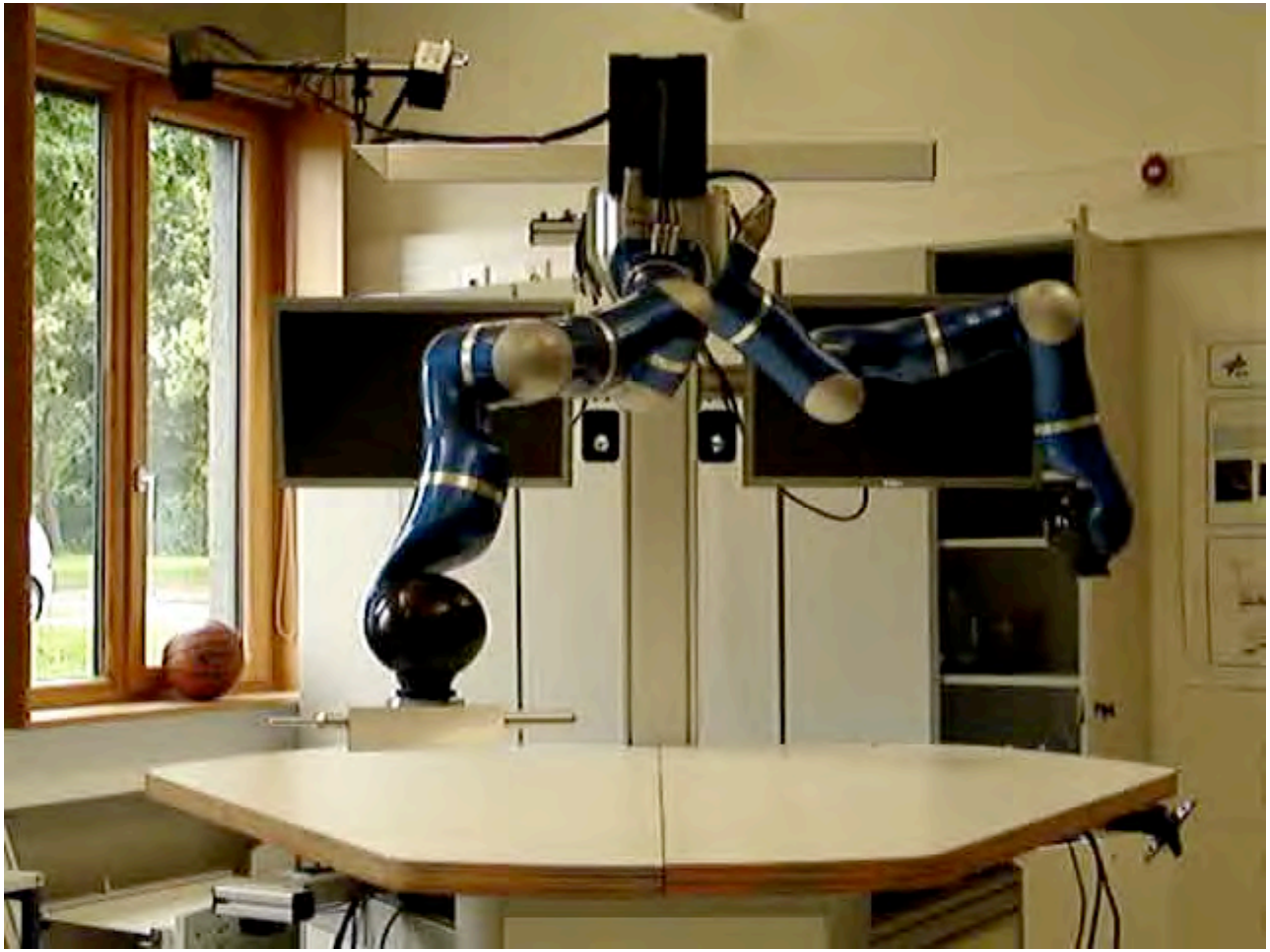


$$(mass, velocity, geometry, bodypart) \rightarrow observed\ injury / pain$$

Embedding Injury Knowledge into Control: Haddadin et al. 2010-2012

with



INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

together with Antonio Bicchi, University of Pisa

with

Example Usecase: Safe Motion Unit

Haddadin et. al. IJRR2012, Haddadin et. al. at 2014,
Haddadin et. al. IROS2012, Haddadin & Haddadin Biomecanica Hungaria 2012

INSTITUT FÜR REGELUNGSTECHNIK
Leibniz Universität Hannover

Embedding Injury Knowledge into Control: Haddadin et al. 2010-2012

with

1. Assume biomechanical injury/pain data required your application
2. Need to know your robot dynamics.
   - Solutions:
     1. Ask your robot manufacturer for the data.
     2. Do it yourself (e.g. Oussama's PUMA paper, Alessandro's LWR paper).
     3. Build your own robot.
3. Attach to the safety relevant surface locations of your robot (Points of Interest, POIs) surface primitives that can be associated to your basic injury/pain data
4. Run through the set of POIs and calculate their respectively safe velocity.
5. Scale the commanded velocity to the most conservative POI.

Result:

$$v_{max} \text{ s.t. safety!!}$$

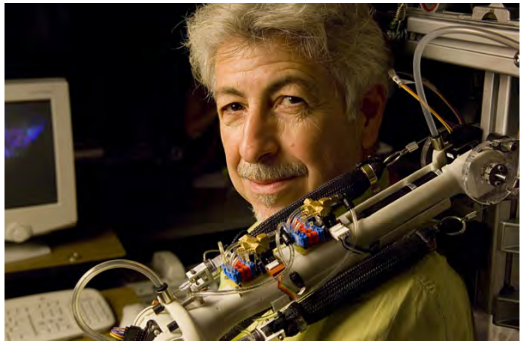
Leibniz Universität Hannover

Thanks to ...
and many others!

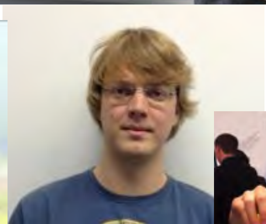
KUKA

HELMHOLTZ ASSOCIATION

TEAM ViGIR



SAPHARI
Safe and Autonomous Physical Human-Aware Robot Interaction



PHRIENDS

Leibniz Universität Hannover

Thanks!