Robot Programming and Control for Human Interaction

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Goal of the lecture

The lecture treats aspects of robotic manipulation and human-robot interaction starting from the theoretical basis over implementation in simulation up to hands-on validation on the KUKA-DLR light-weight robot. At the end of the lecture, the students should have gained not only theoretical knowledge but also first practical experience with compliant, torque-controlled robots and their programming. Half of the lecture will be dedicated in block units to implementations in simulation and to hands-on experiments.

Recommended lectures:

- "**Robotics**", Prof. Burschka
- "**Sensor-based Robotic Manipulation and Locomotion**", Prof. Albu-Schäffer

Contents of the lecture

- Robot modelling and parameter identification
- Position control
- Torque control
- Cartesian impedance control
- Collision detection
- Reactive path generation
- State machines for task programming

Organization

- 4 ETCS credits
- Lecture consists of:
  - Theoretical part (5 lectures)
  - Simulation part (3 sessions)
  - Practical part (5 sessions)
- Examination:
  - Simulation results
  - Experimental results
  - Oral presentation of results (20 minutes group presentation)
- Material: slides, hand-out material, Simulink models, java scripts
- Excursion to DLR (date will be announced)

Exercises

- All information available on the lecture website:
  http://www.in.tum.de/index.php?id=xxiii-teaching (just google it!)

- 4 exercise slots:
  - Tuesdays, 9-12 + 13-16 and Wednesdays 9-12 + 13-16
- Doodle poll for assigning fixed slots after next lecture
  - FCFS according to TUMonline registration

- Simulation exercises in room 03.13.008
- Robot exercises in Garching-Hochbrück, Parkring 13, lab of Prof. Burschka
- Requirements: own notebooks with Matlab Simulink (free for TUM students)

Foreknowledge you should bring along for this lecture

Basics of robotics – in a nutshell

This material should be known from „**Robotics**“ or „**Sensor-Based Robotic Manipulation and Locomotion**“

<u>Homogeneous transformations</u>

$$T = \begin{bmatrix} R & p \\ 0_{1x3} & 1 \end{bmatrix}_{4x4}$$

<u>Translation vector</u> $p \in R^3$

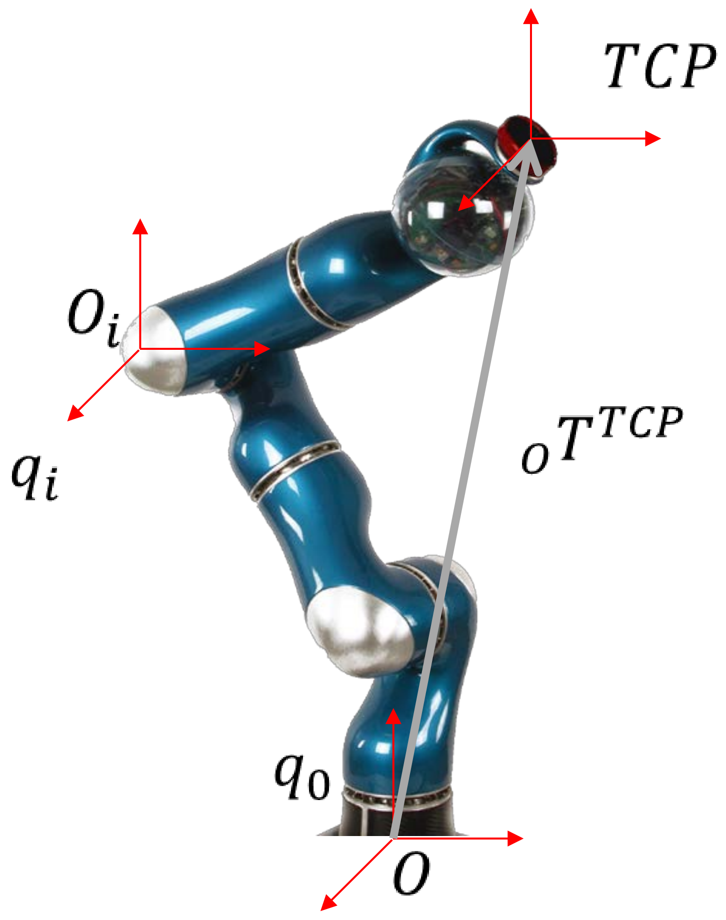
<u>Rotation matrix</u> R_{3x3}

$R^T R = I$ - orthogonal

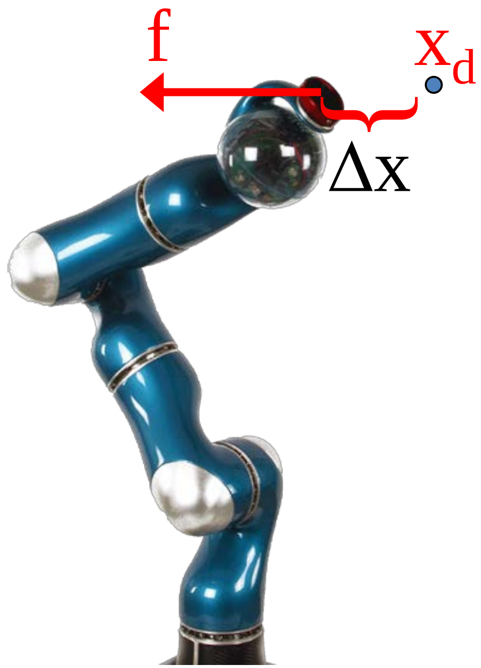
$\det(R) = 1$ - right-handed coordinate system

<u>Forward kinematics</u>

$${}_O T^{TCP}(q) = {}_O T^1(q_0)\, {}_1 T^2(q_1) \cdots {}_i T^j(q_i) \cdots {}_{n-1} T^{TCP}(q_{n-1})$$



Cartesian impedance control



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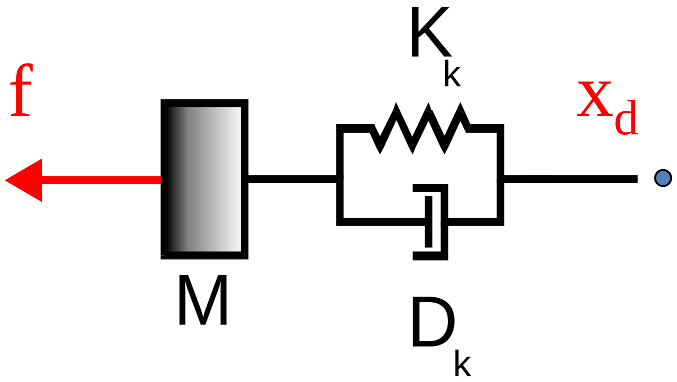


$$f = M\Delta\ddot{x} + D_k\Delta\dot{x} + K_k\Delta x$$

$$x \in R^6$$

$$\boldsymbol{x} = \begin{bmatrix} p_x \\ p_y \\ p_z \\ \alpha \\ \beta \\ \gamma \end{bmatrix}$$

Translation vector

Representation of orientation

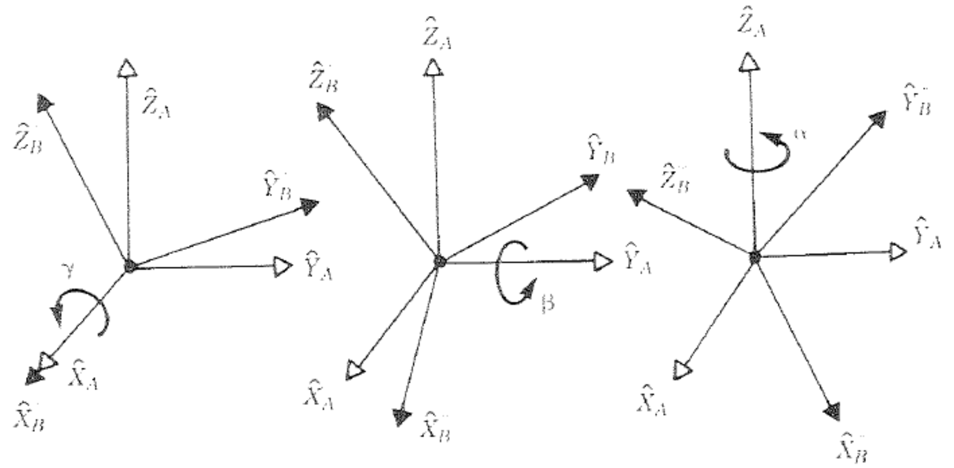
$$\dot{\boldsymbol{x}} = \begin{bmatrix} \dot{p}_x \\ \dot{p}_y \\ \dot{p}_z \\ \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{bmatrix}$$

Translational velocity

„Velocity“

Representation of orientations

Roll-Pitch-Yaw

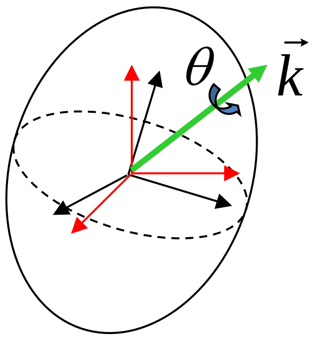


Angle-axis representation

$$\theta = \cos^{-1}\left(\frac{r_{11}+r_{22}+r_{33}-1}{2}\right)$$

$$k = \frac{1}{2\sin\theta}\begin{bmatrix} r_{32}-r_{23} \\ r_{13}-r_{31} \\ r_{21}-r_{12} \end{bmatrix}$$

Singular for
$\theta = n\pi$!



$$\left\|\vec{k}\right\| = 1$$

Quaternions (Euler parameters) not minimal, singularity-free, global

$$\lambda = [\lambda_0, \lambda_1, \lambda_2, \lambda_3] = \left[\cos\frac{\theta}{2}, \vec{k}\sin\frac{\theta}{2}\right]$$

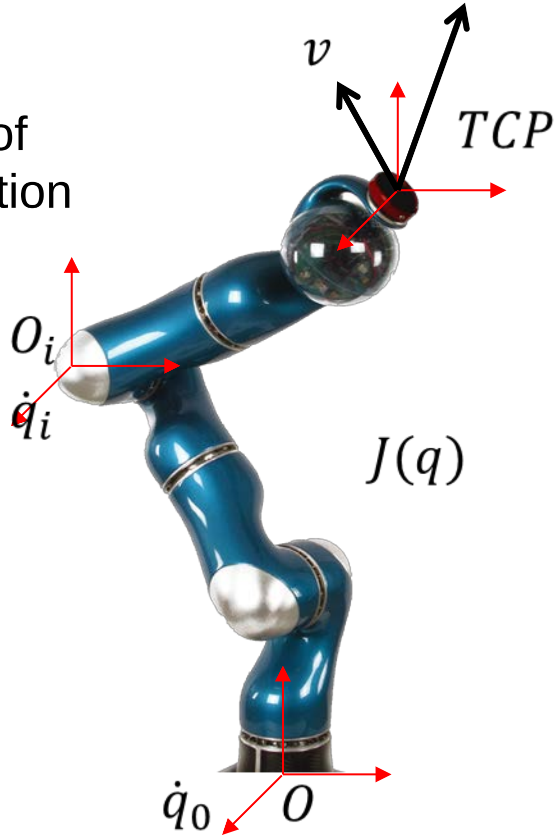
Jacobian matrices

For velocities, there is a singularity-free representation of the rotational velocity, leading to the favorite representation of the TCP velocity.

$$\dot{x}_\omega = \begin{bmatrix} \dot{p}_x \\ \dot{p}_y \\ \dot{p}_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}$$

Translation vector $p \in R^3$

Angular velocity vector $\omega \in R^3$



The Jacobian matrix defines the relation between joint velocity and Cartesian velocity

$$\dot{x} = J(q)\dot{q}$$

$$J(q) = \frac{\partial x(q)}{\partial q}$$

Depending on the representation of x and the coordinate frame in which it is represented, there exist a multitude of Jacobian matrix versions!

Basic Jacobian matrix

if $$T_{i,j} = \begin{bmatrix} R_{i,j} & p_{i,j} \\ 0 & 1 \end{bmatrix}$$

For serial manipulators with revolute joints, the basic Jacobian matrix is:

$$J_j(q) = \begin{bmatrix} R_{j,1} z_1 \times p_{1,n+1}, & \cdots & , R_{j,n} z_n \times p_{n,n+1} \\ R_{j,1} z_1, & \cdots & , R_{j,n} z_n \end{bmatrix}$$

z_i : axis of joint i

$z_i, p_{i,n+1}$

For serial manipulators with translational joints, the basic Jacobian matrix is:

$$J_j(q) = \begin{bmatrix} R_{j,1} z_1, \; \cdots, R_{j,n} z_n \\ 0, \; \cdots, 0 \end{bmatrix}$$

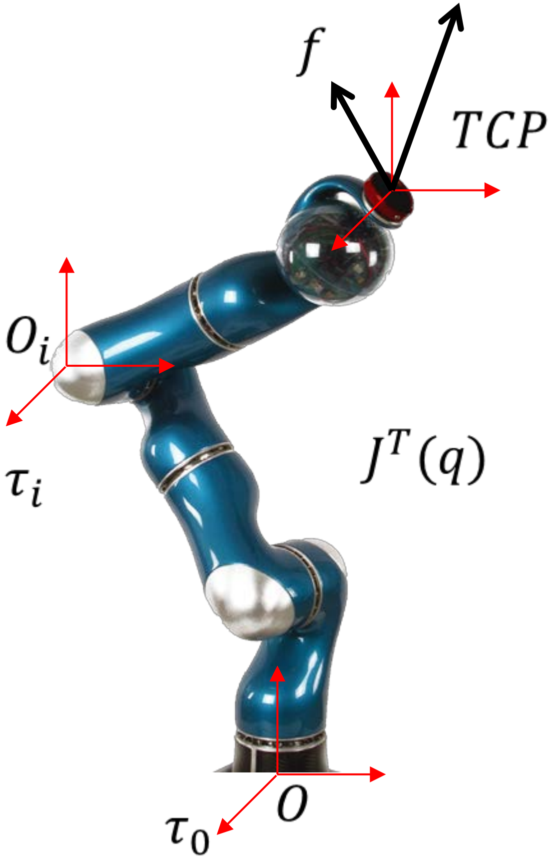
For the derivation, see [Spong, Khalil, Murray]

Joint dynamics

$$\boldsymbol{f} = \begin{bmatrix} f_x \\ f_y \\ f_z \\ m_x \\ m_y \\ m_z \end{bmatrix}$$

Force $f \in R^3$

Torque $m \in R^3$



The transposed Jacobian matrix defines the relation between Cartesian and joint torques

$$\tau = J^T(q)\, f$$

$$J(q) = \frac{\partial x(q)}{\partial q}$$

The joint-space dynamics are

$$M(q)\ddot{q} + c(q,\dot{q}) + g(q) = \tau$$

$M(q)$ - Inertia matrix

$c(q,\dot{q})$ - Vector of centripetal and Coriolis torques

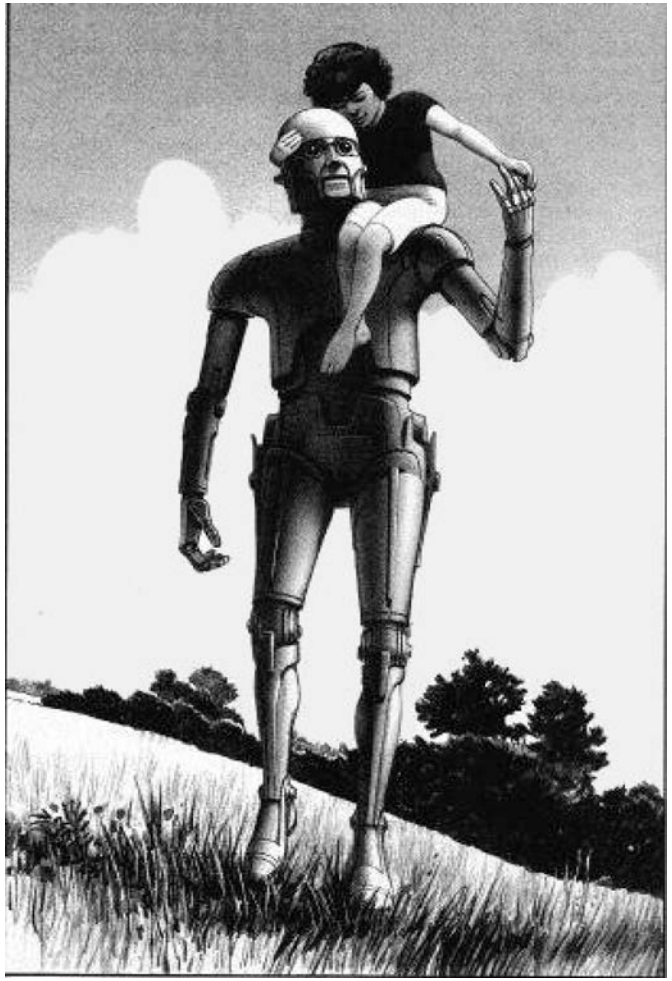
$g(q)$ - Vector of gravity torques

Today: Introduction and motivations for the lecture

What has been done with the LWR?
What is currently done with the LWR?
What is planned for the future?

Human-robot interaction

Science-fiction literature suggests coexistence of humans and robots already for a long time…

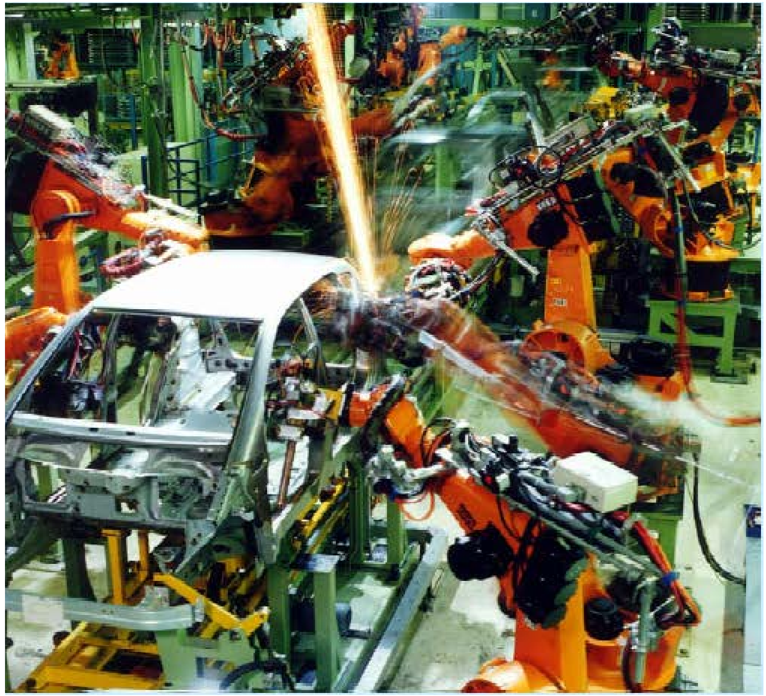


Isaac Asimov - The Caves Of Steel, pages 177-179, 1942

Until recently, robotics reality looked very differently…

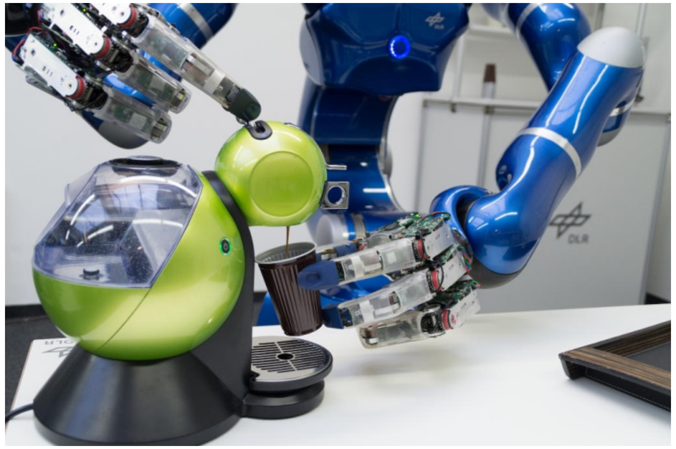
The „Lion‘s Cage“

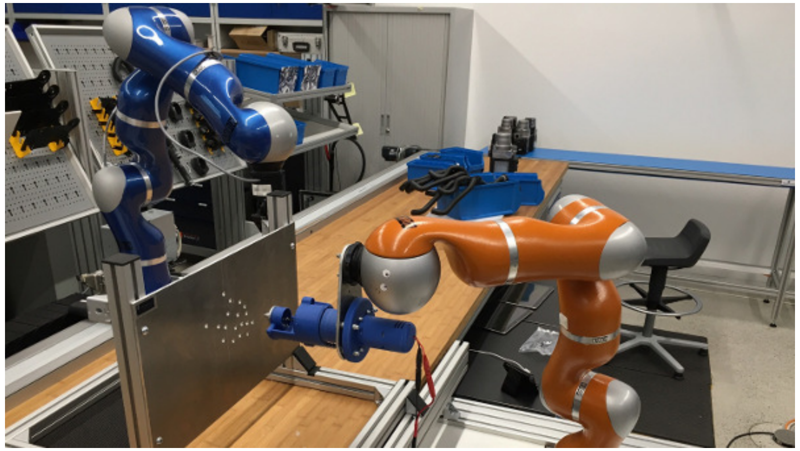
- Separation of robots from humans
- Structured environments
- Limited sensory feedback and flexibility



DLR‘s motivations: robonauts and rovonauts in earth orbit, on planets, and moons…

… but also terrestrial applications

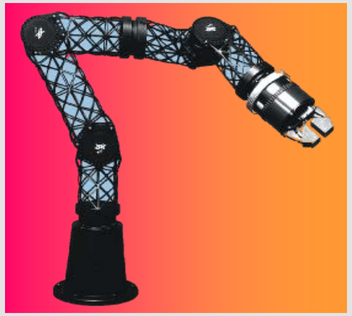


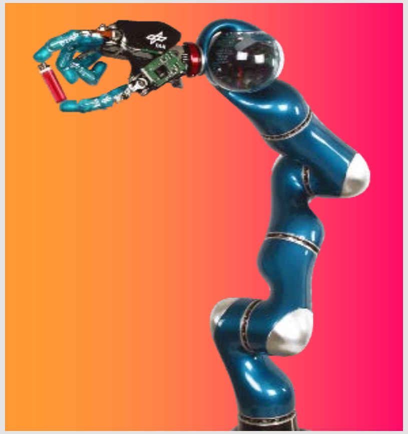


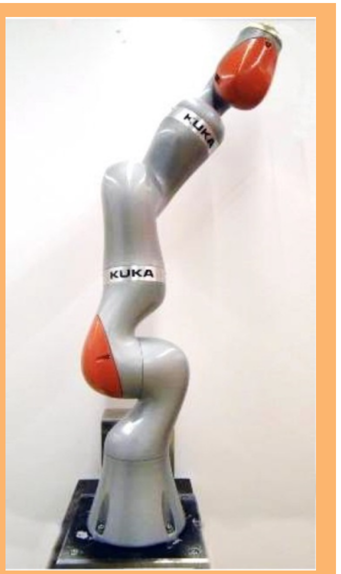
Compliant Light-Weight-Robots (LWR)

Technology transfer

Three generations of DLR LWRs







1995

1999

2003

2006-2012

2013

Basic research

Product development

„Soft Robotics“ - a paradigmatic change

from **large**, **stiff** robots with extremely **high positioning accuracy**
to **sensitive**, **compliant**, **safe** systems with **lightweight structure**.

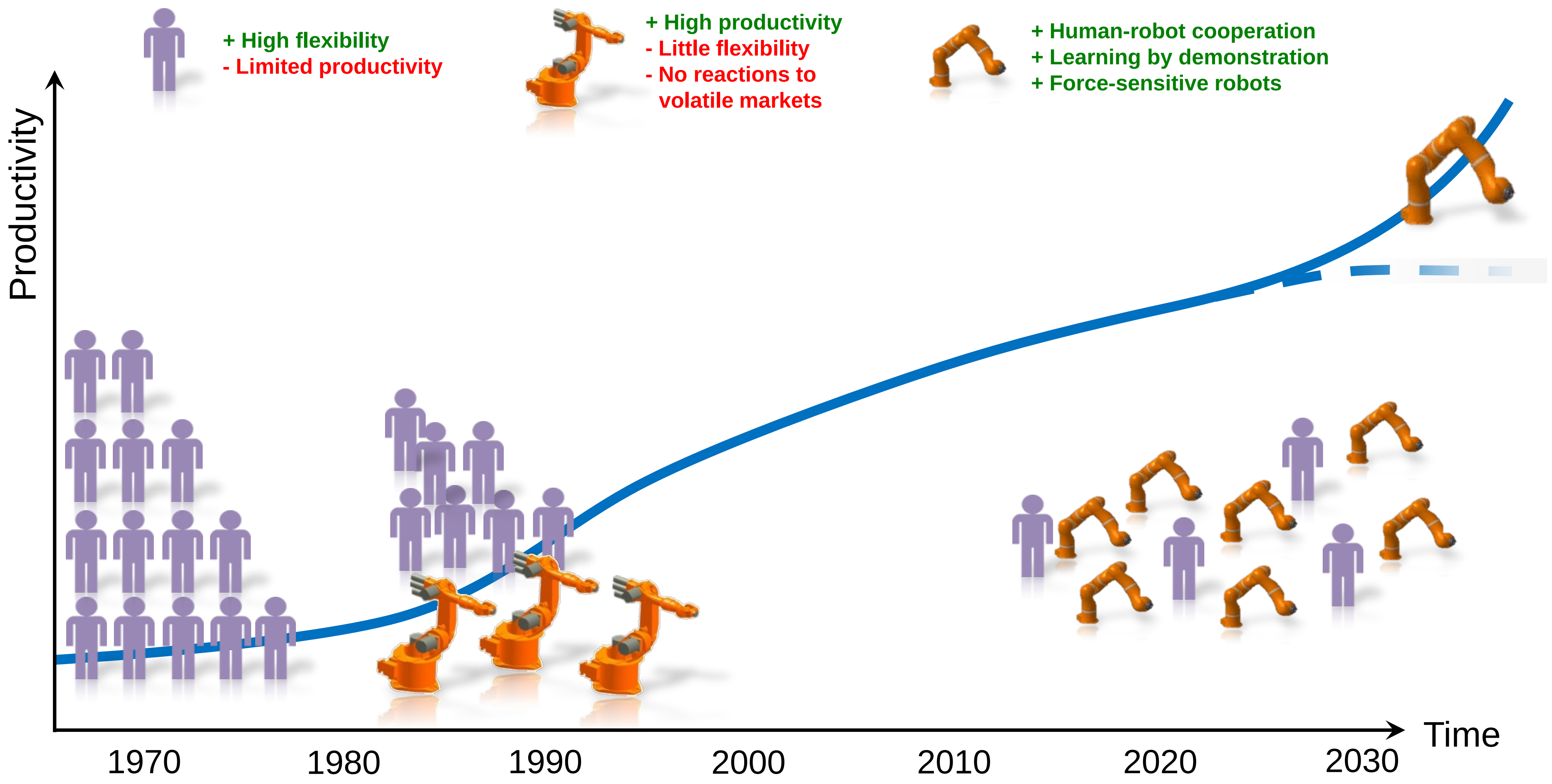
Safety

Soft Robotics

Programmable stiffness and damping

Gravity compensation

Evolution in the automotive industry: From handwork to human-robot cooperation



Human-robot cooperation is industrial reality
(most visible innovation at the Hannover Messe 2015!)

KUKA is pioneer in human-robot-cooperation
(technology transfer from DLR)

2006-2012

2013

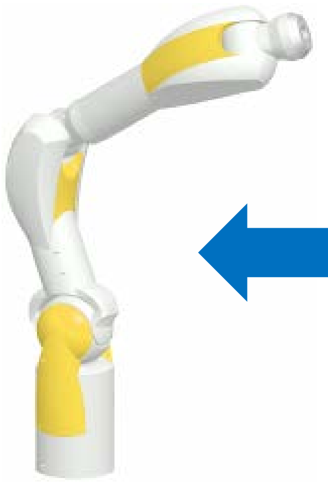
World market leader FANUC follows

Human-robot cooperation by Bosch

ABB makes Gomtec a R&D center
for human-robot cooperation
(Bernd Gombert formerly at DLR-RM)

Evolution of the arm since 2003

Technology transfer to Medtronic



DLR medical robots

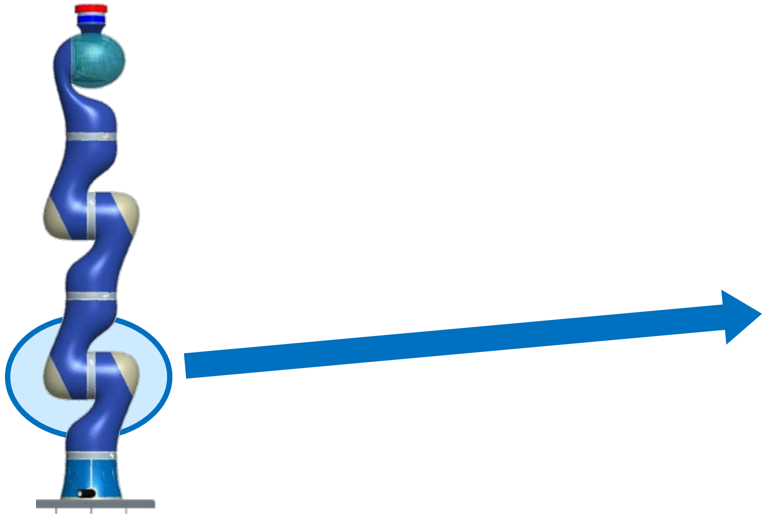
Justin

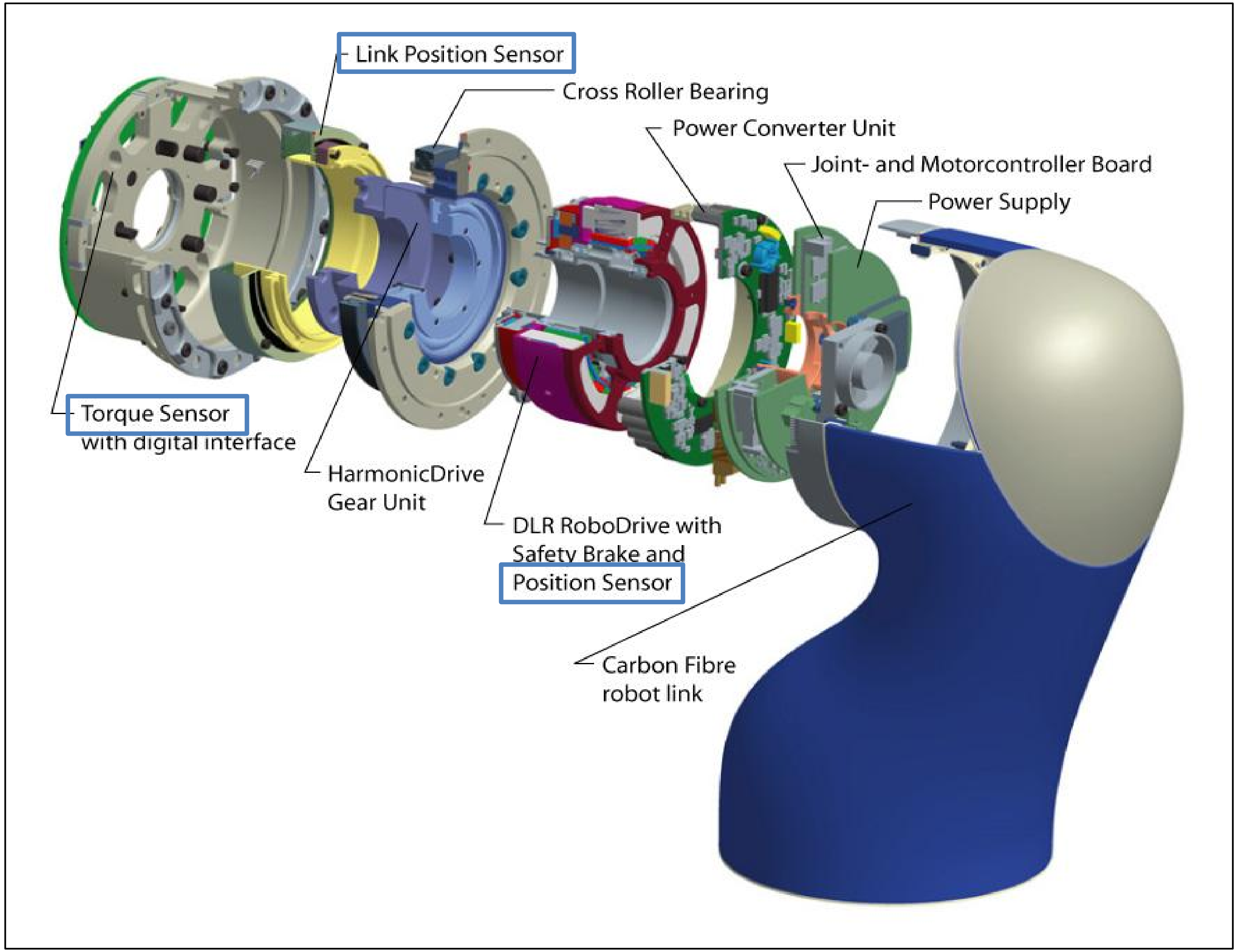
TORO

Technology transfer to KUKA

EURON Tech Transfer Award 2011

Mechatronic joint design

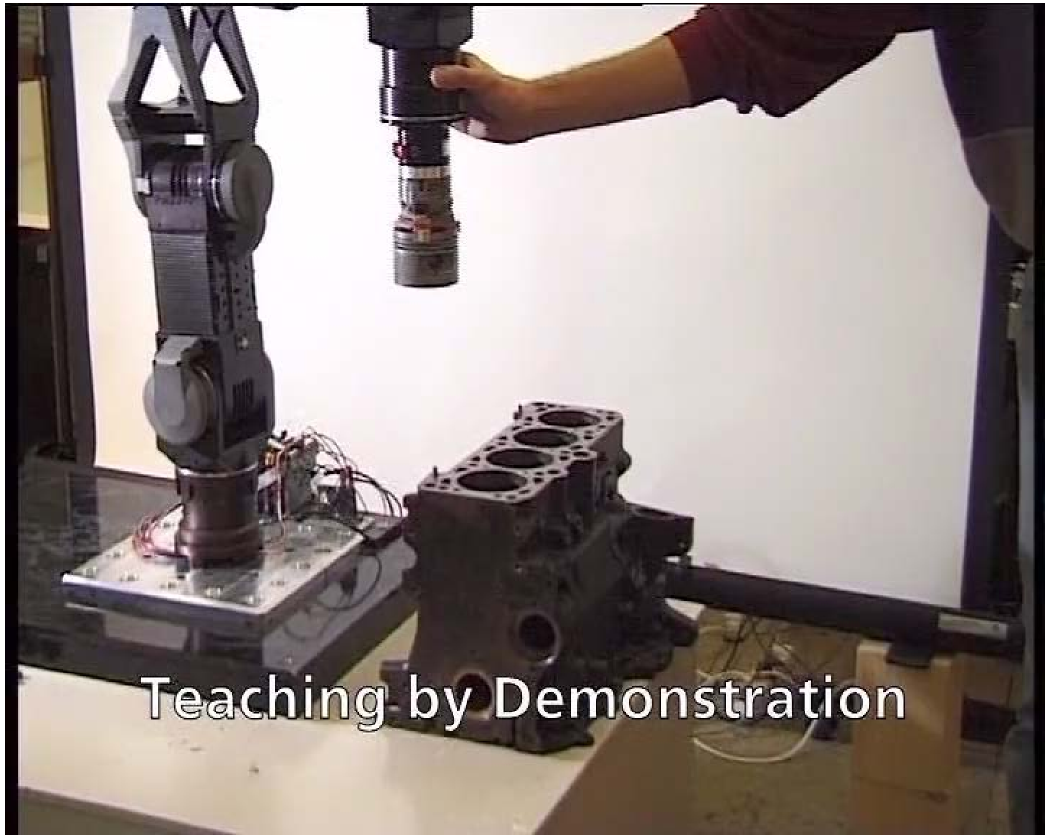




Which signals/interfaces are relevant for the controller design?

- Motor-side position sensor
- Link-side position sensor
- Joint torque sensor

Production assistance: teaching by demonstration



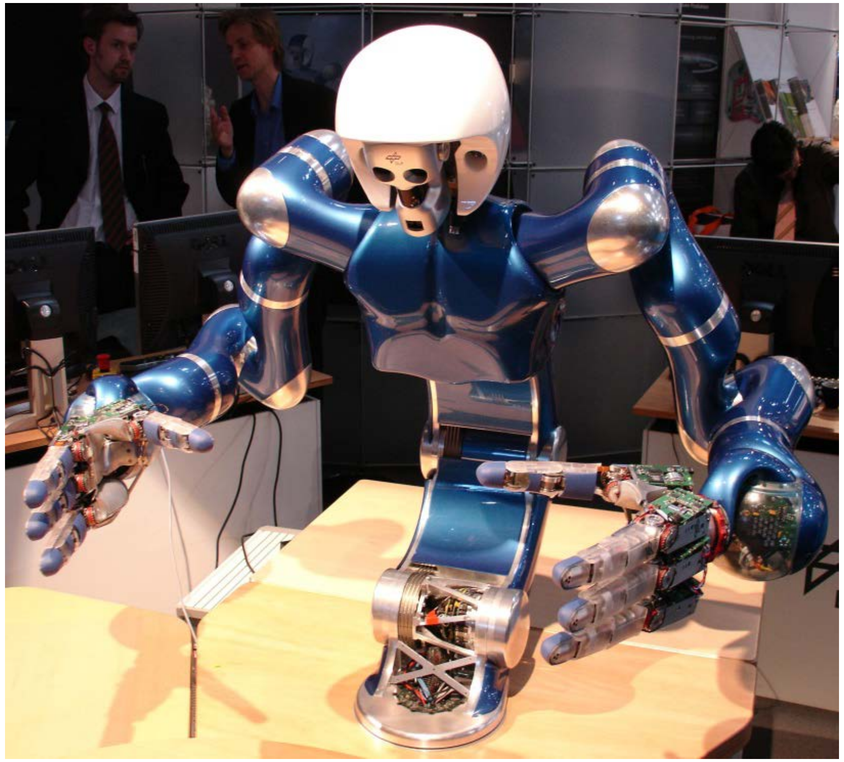
Vibration damping

Vibration damping OFF

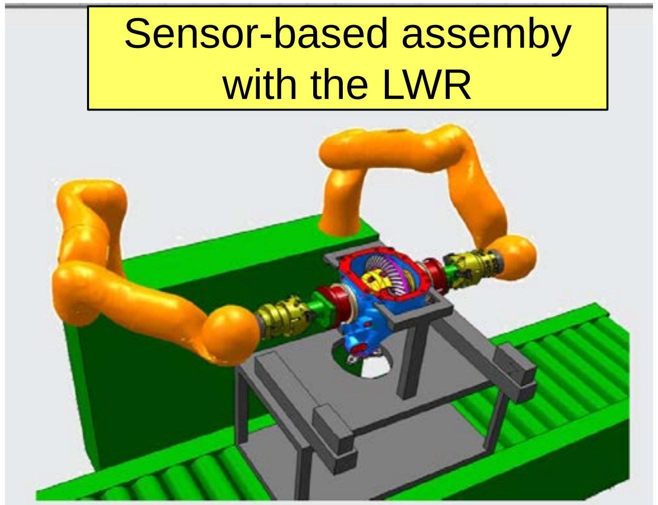
Vibration damping ON

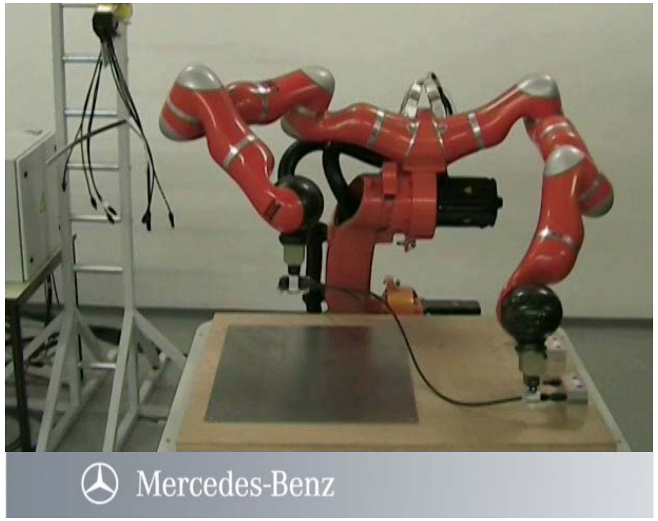
Robot reaches the dynamics and positioning accuracy of an industrial robotic arm (according to KUKA ISO tests)

First application of the technology in the automotive industry

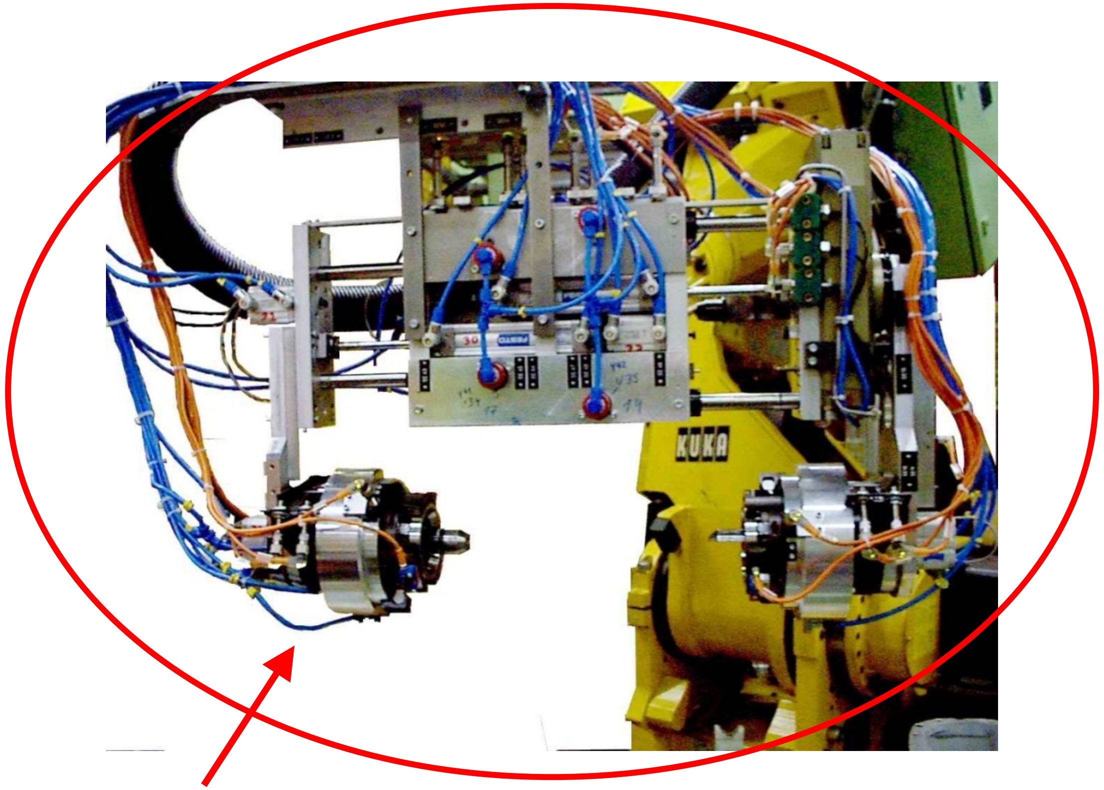


Technology transfer of bi-manual manipulation

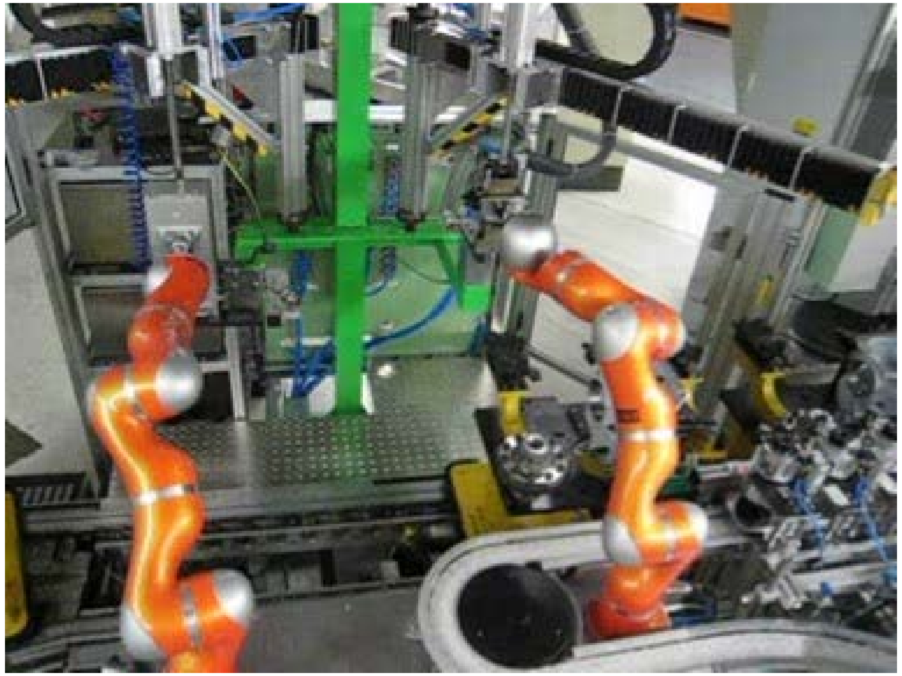




Gear box assembly at Daimler



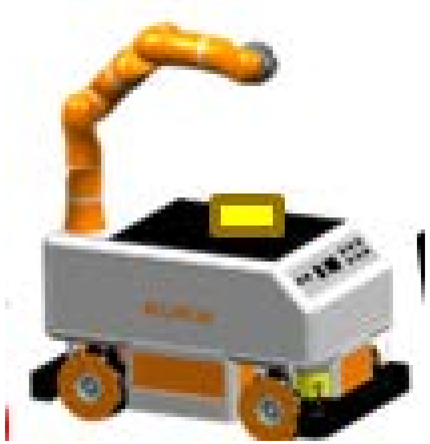
Special gripper from former solutions



- Production started in 2009: first 24/7 application with the LWR
- More than 600.000 gear boxes mounted in Mercedes cars
- Production without fences, humans can interact directly with the robots

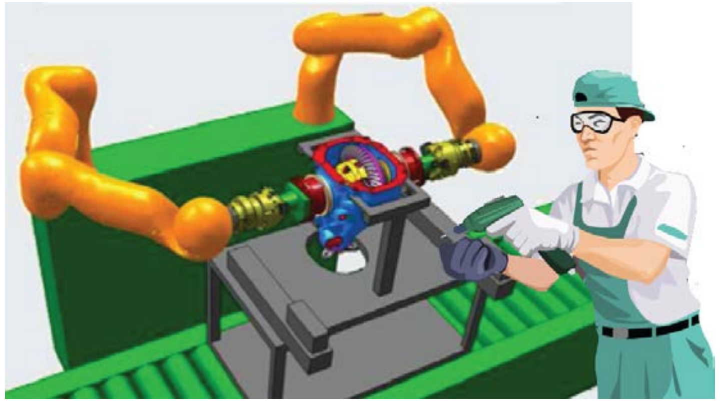
Factory automation of the future

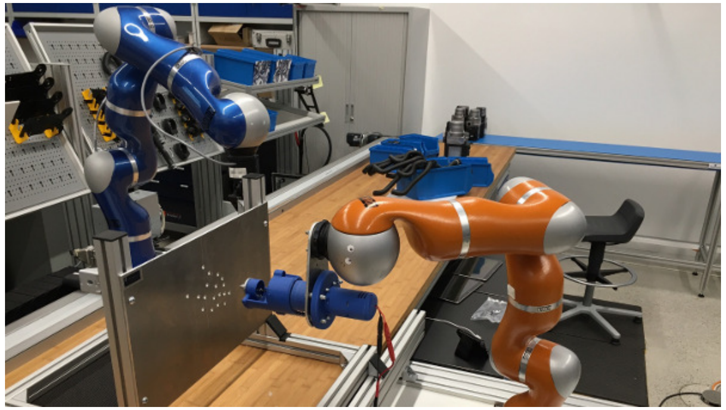
Mobile manipulators



[KIVA Systems]

Production assistant



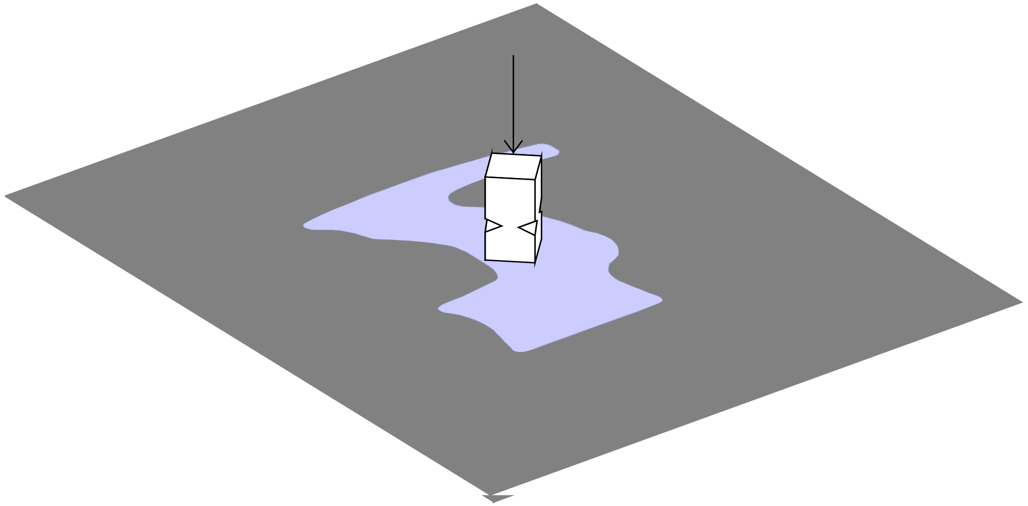


Vision- and impedance-based assembly

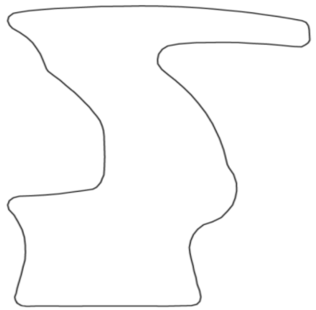
$$\boldsymbol{F} = -\boldsymbol{K}(\boldsymbol{x} - \boldsymbol{x}_d) - \boldsymbol{D}\dot{\boldsymbol{x}}$$

Problem statement:

"Automatically find and program the optimal strategy!"



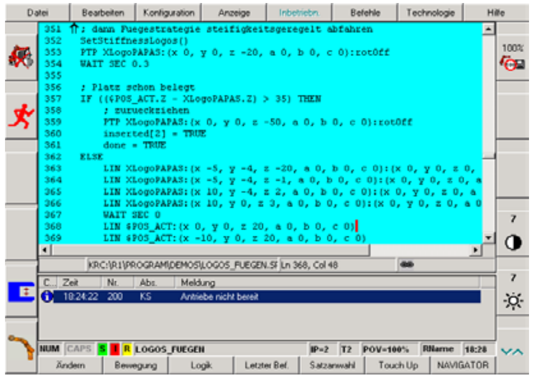
The basic idea behind it



Geometrical model
(from image processing / CAD)

Additional information:
- Tolerance
- Material properties
- Robot and camera accuracy
- Additional constraints

Assembly Planning Toolbox

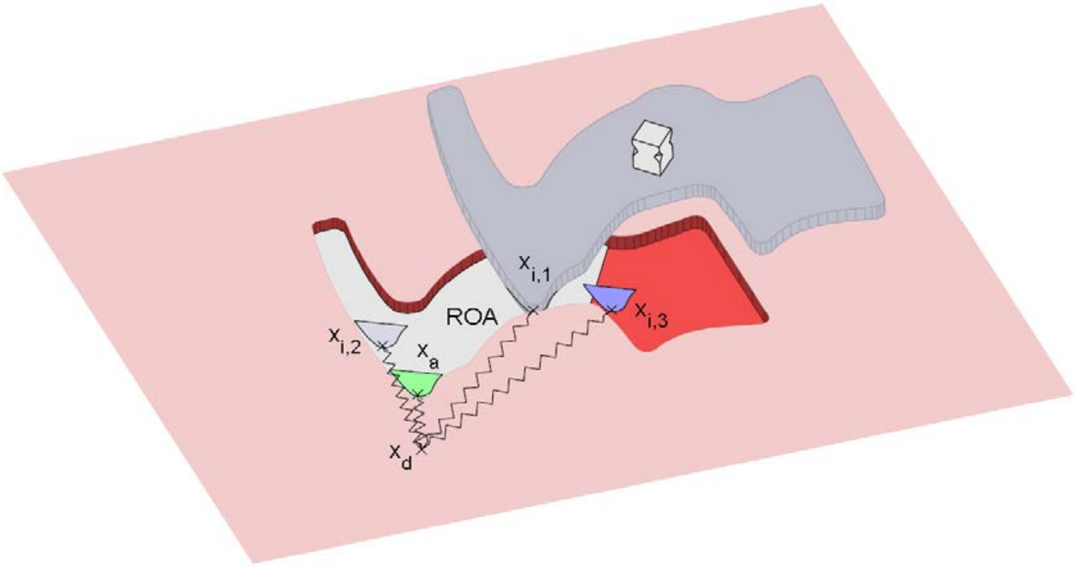


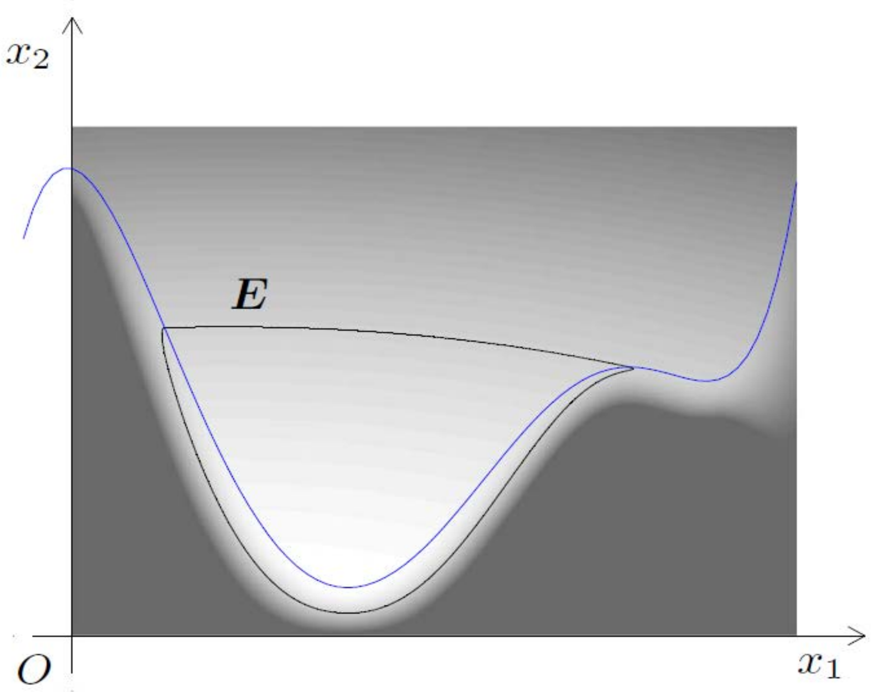
KRL code

Online-data:
- Position estimation
- Workspace limitations
- Robot configuration
- Additional sensor data

KRL: knowledge representation language

The „Region of Attraction“ (ROA)



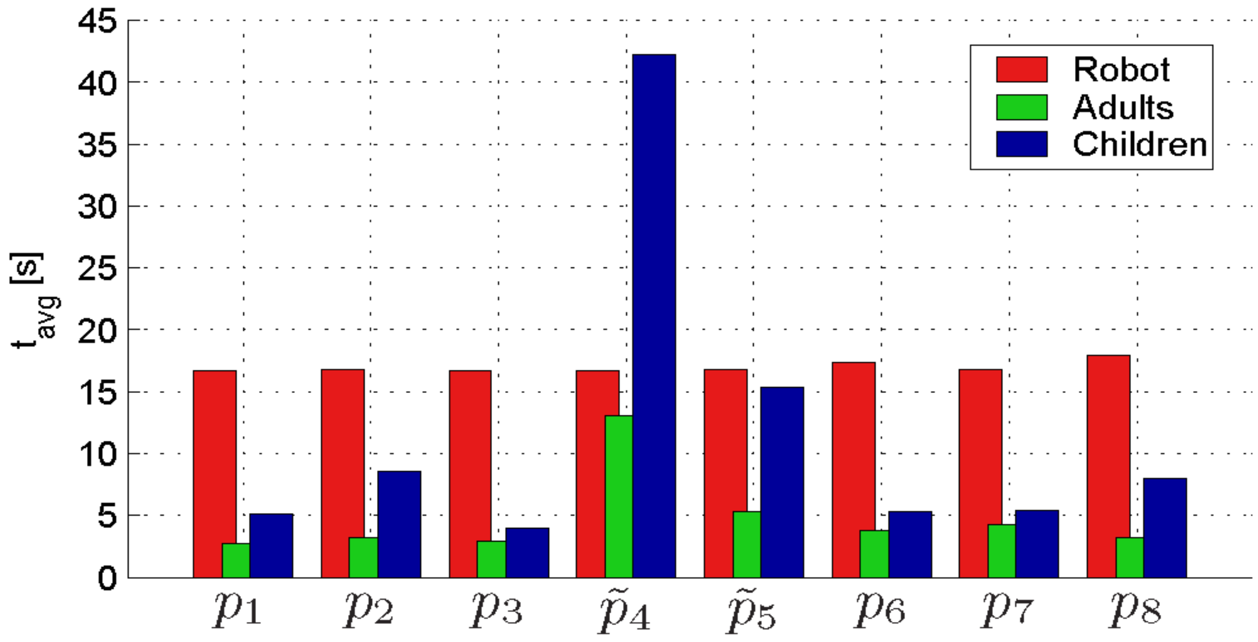


- The contact point with maximum ROA provides maximum robustness w.r.t. sensor and mode uncertainties
- A local Lyapunov-based convergence analysis is possible based on the impedance-controlled robot and the contour geometry

Experiments

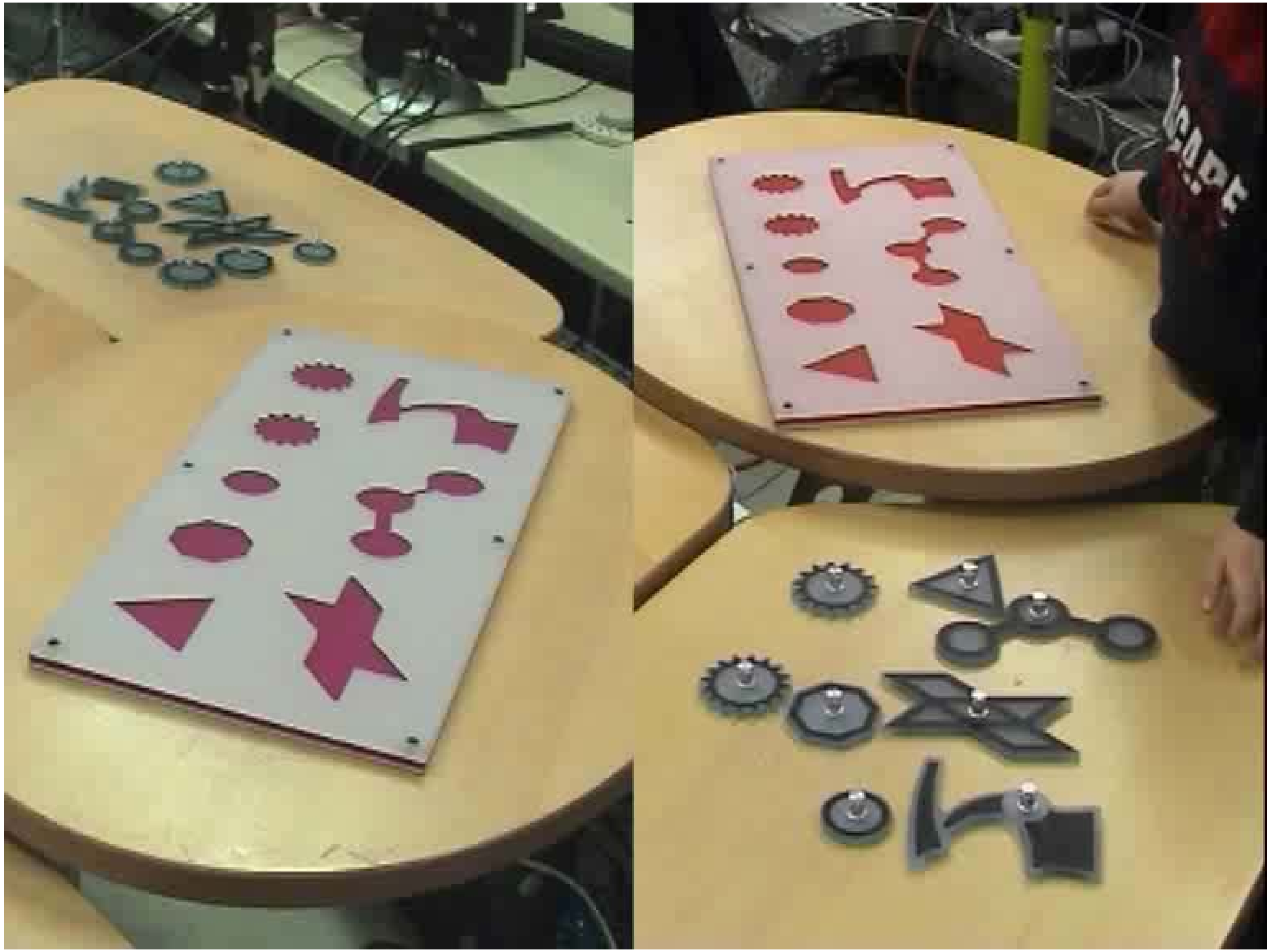
Comparison with human performance

41 test persons (35 children of 5-7 years of age, 6 adults)

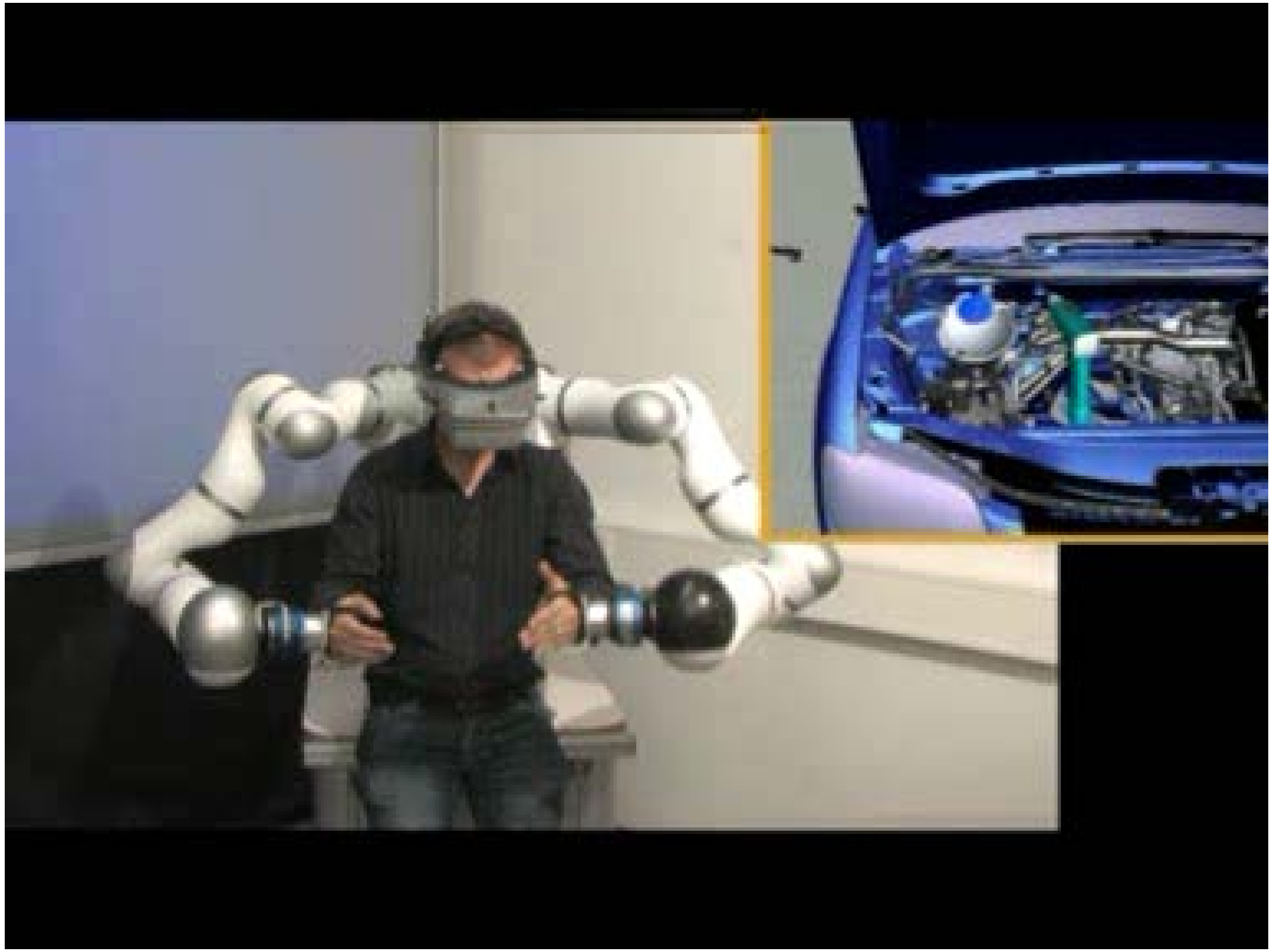


	robot	adults	children
Avg.	132s	39s	94s
Min.	130s	22s	40s
Max.	138s	53s	220s

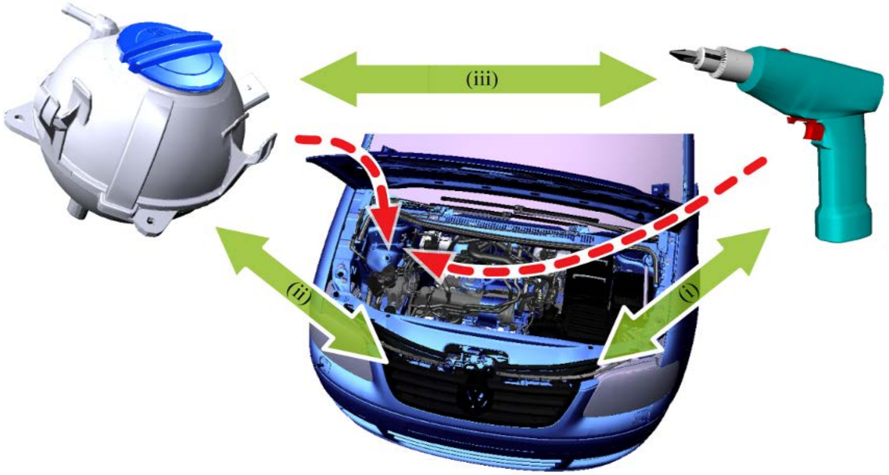
Direct comparison: human & robot



Further applications: virtual assembly verification



2 LWRs as force-reflecting devices



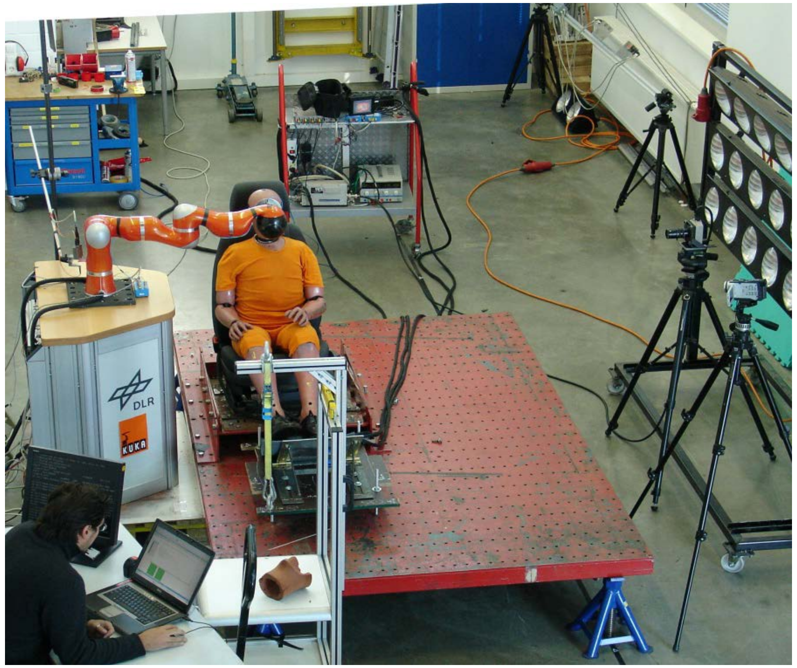
Advantages:

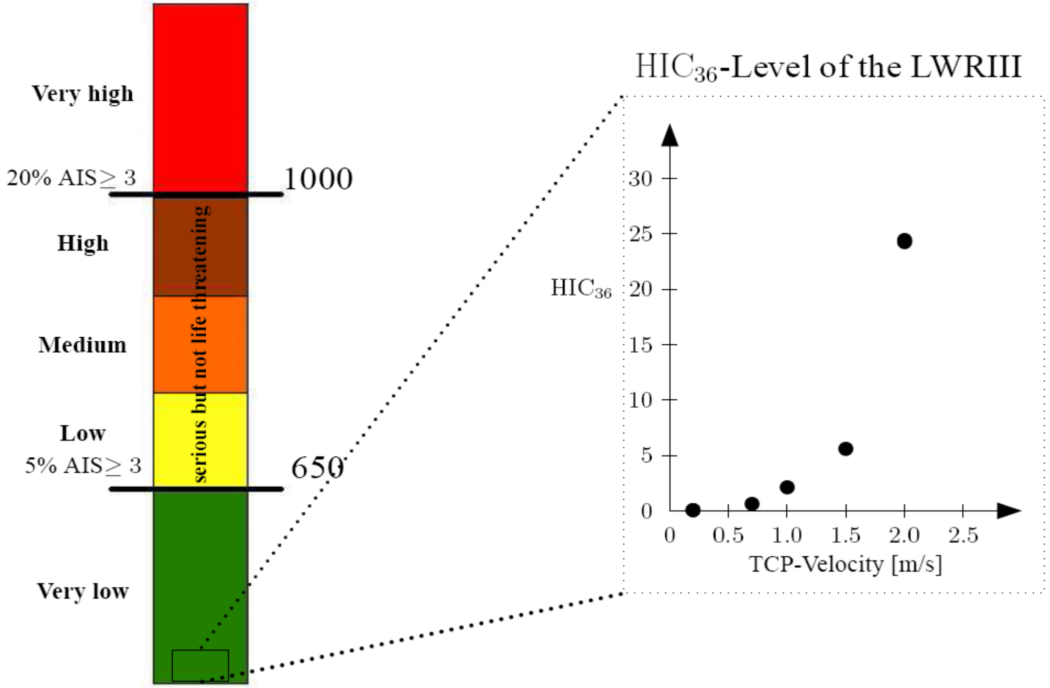
+ to train experts (e.g. technicians)

+ to check whether assembly is practical/possible or not

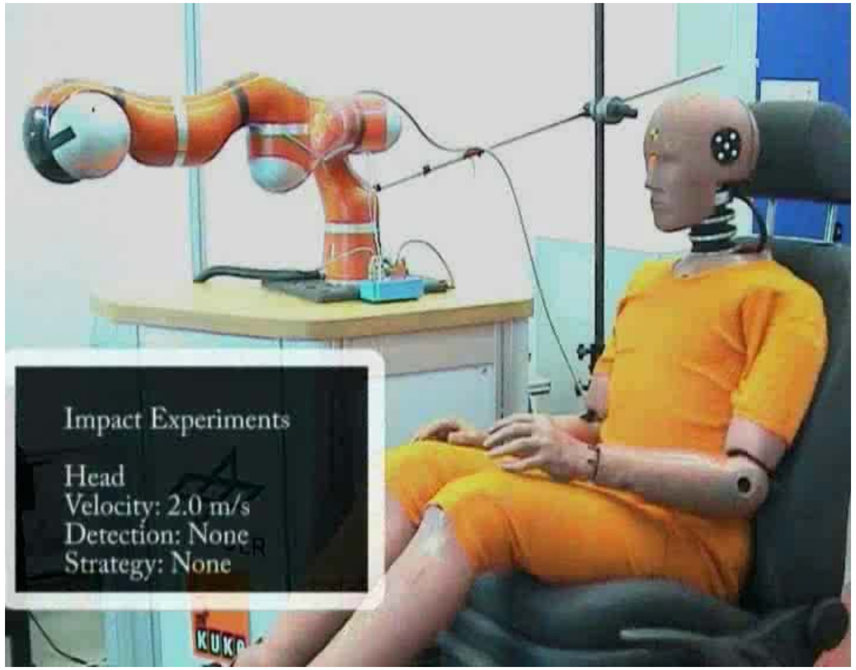
How dangerous is the robot?

First collision experiments with standardized methods to evaluate the injury potential and related safety measures.



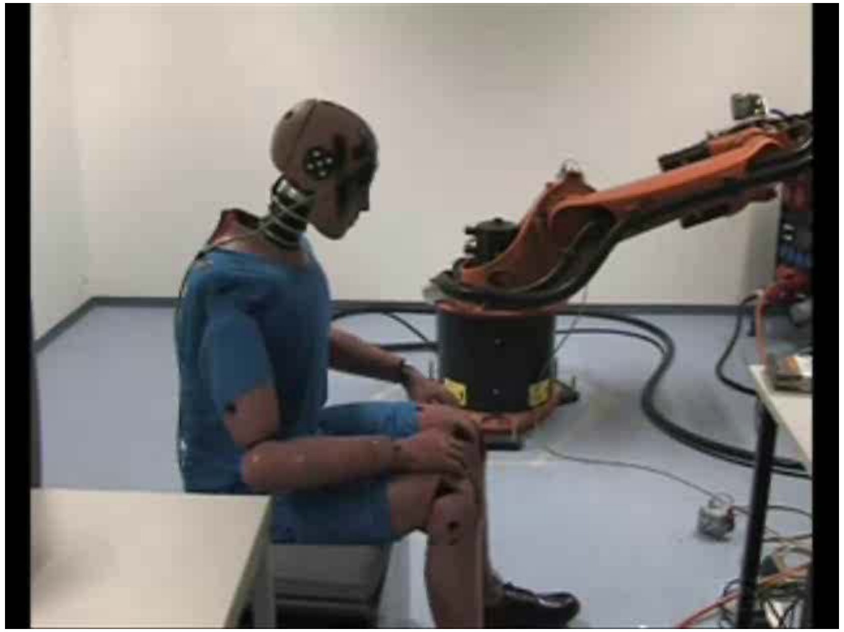


For all evaluated criteria, the LWR has proven to be in the lower quarter of the green, uncritical area.


Impact Experiments
Head
Velocity: 2.0 m/s
Detection: None
Strategy: None


DLR
No Collision Detection
DLR


DLR
III. Impact Experiments LWRIII - Human



In cooperation with the medical faculty of the TUM

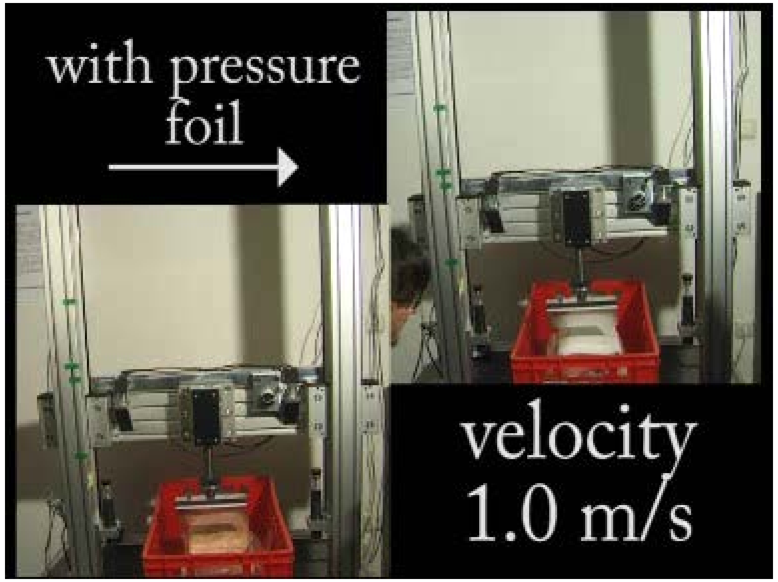
An „Injury Handbook of Robotics“

Given

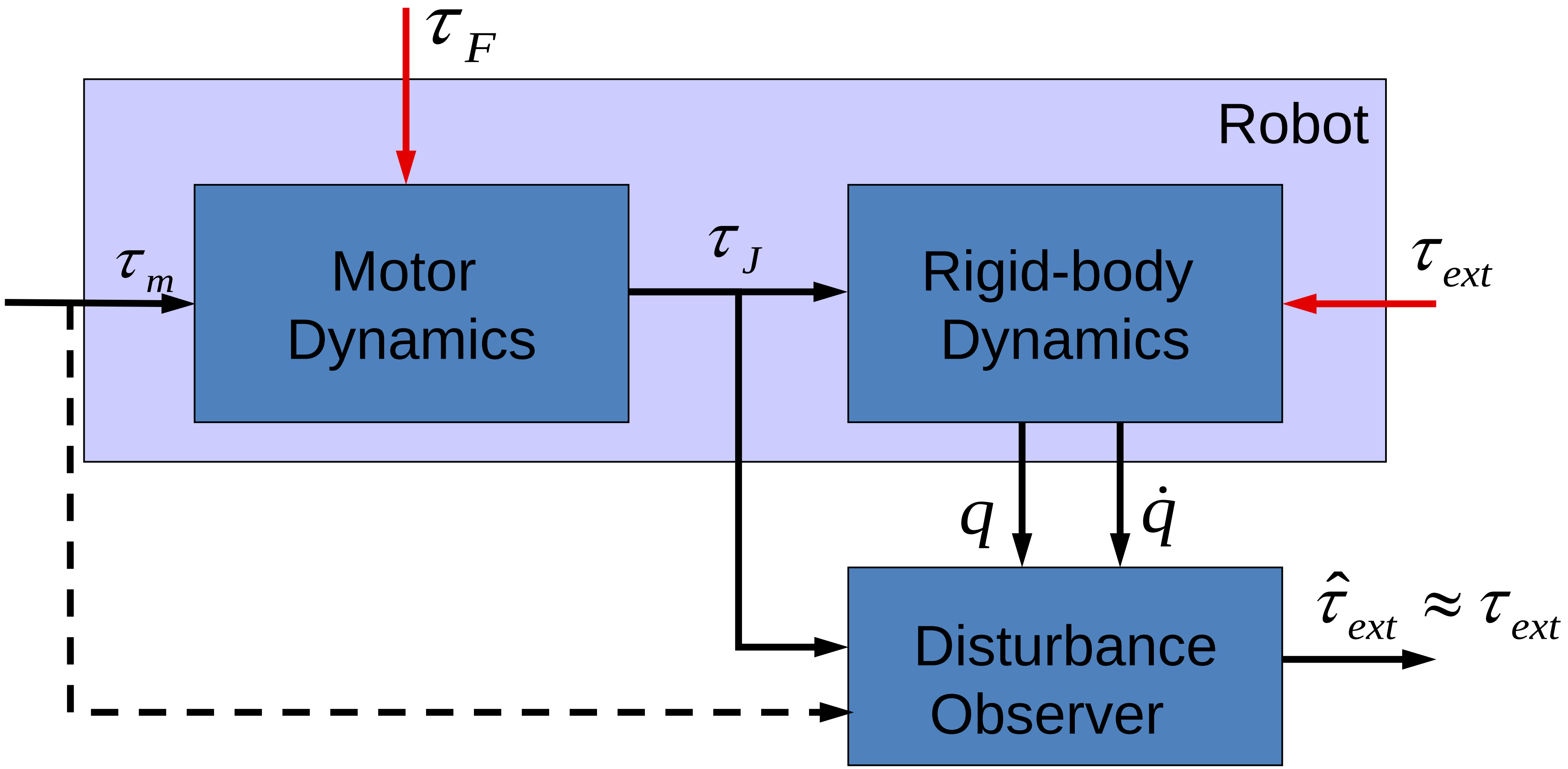
- Tool geometry
- Robot weight
- Contacted body part

• Which injury will occur at which velocity?
• How fast can the robot move to remain safe to humans?

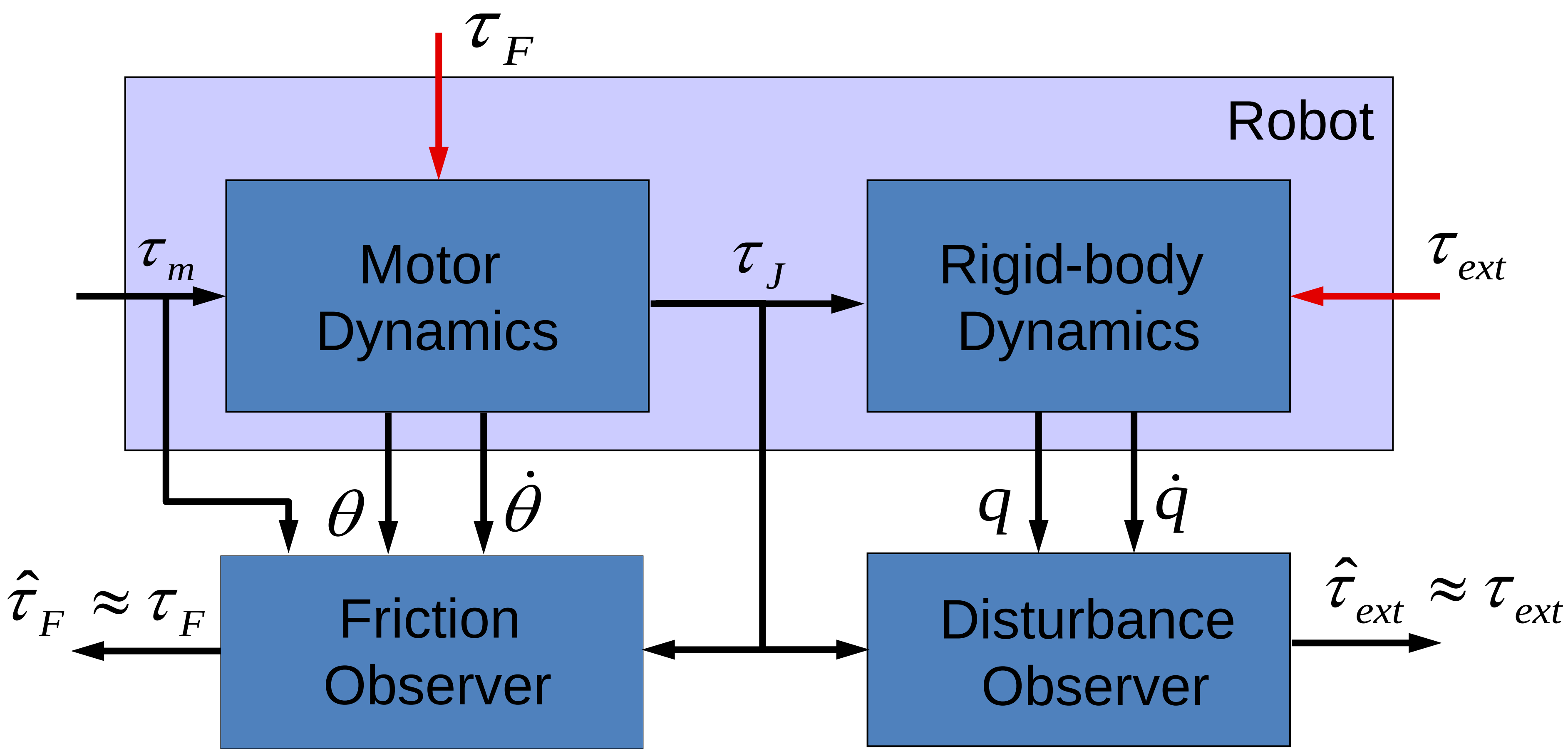
$\Rightarrow$ Safety certification of commercial robots



Disturbance observer for collision detection

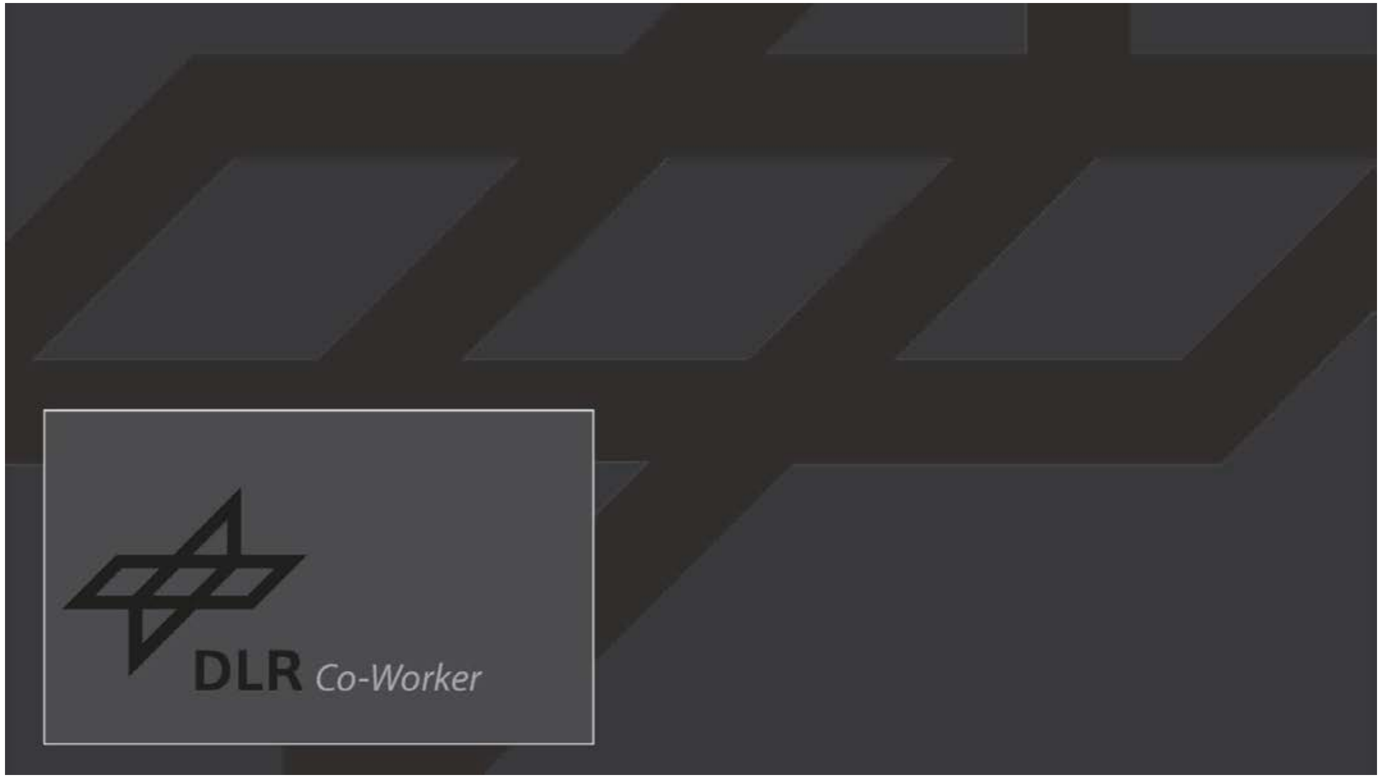


Disturbance observer for collision detection and friction compensation



Intuitive robot interfaces and hands-on programming interfaces

Integration of soft robotics features into
a consistent, unified user interface concept



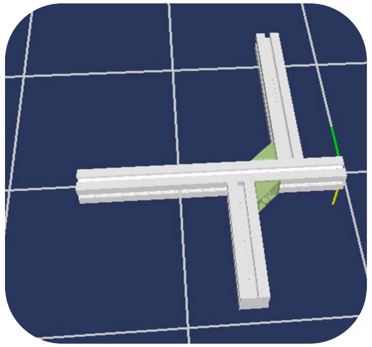
(X-Box – KINECT mainly for human detection and interaction)

How to make the large variety of control modes intuitively manageable for non-specialists?

Study on fully automated manufacturing workflow

Automatic generation of robot programs starting from CAD applications

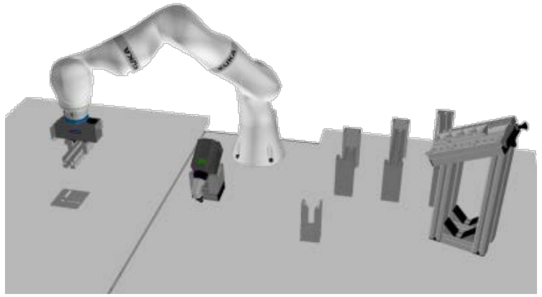
- Mass customization
- Highly variable, rapidly changing product families (towards lot size 1)



CAD
design

Automatic
assembly
planning

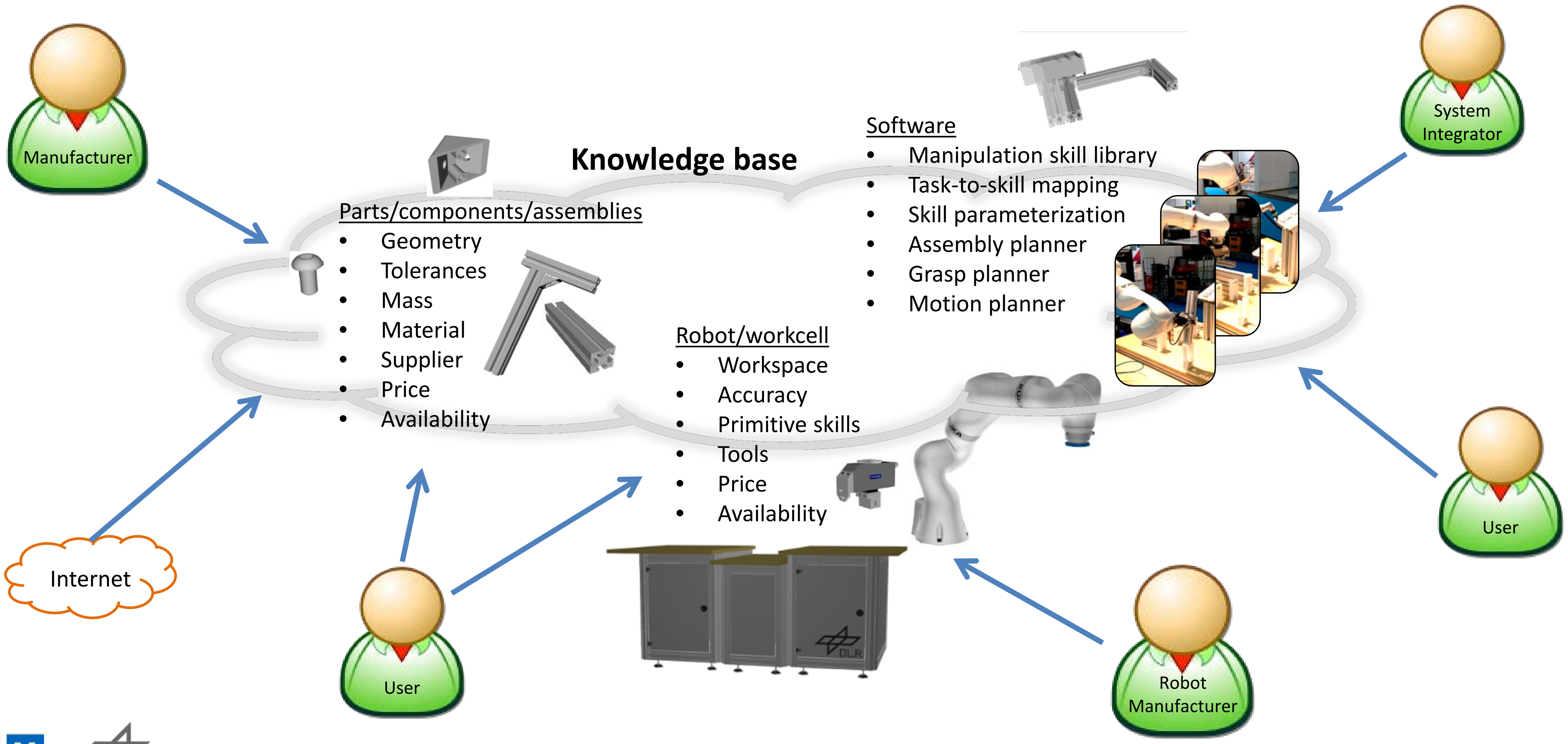
Automatic robot
program generation



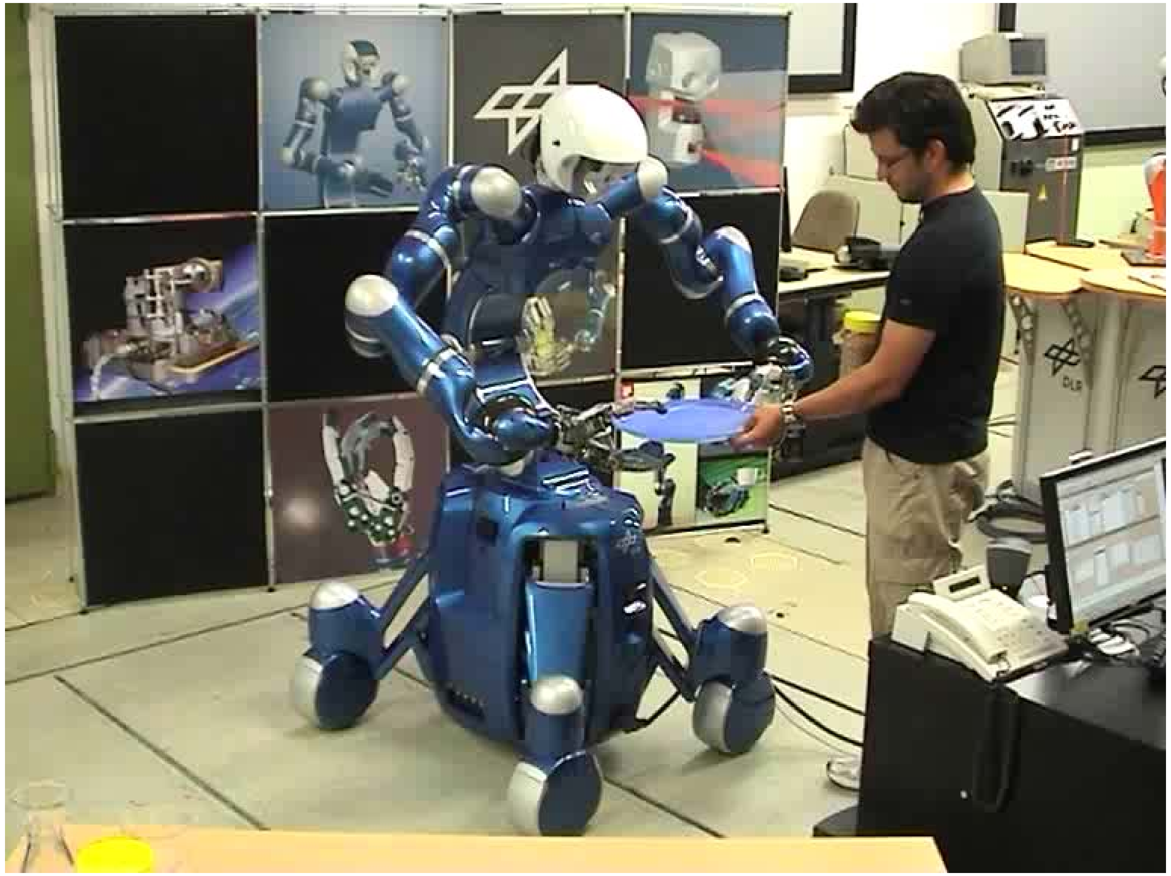
Robot
program execution

Study on fully automated manufacturing workflow

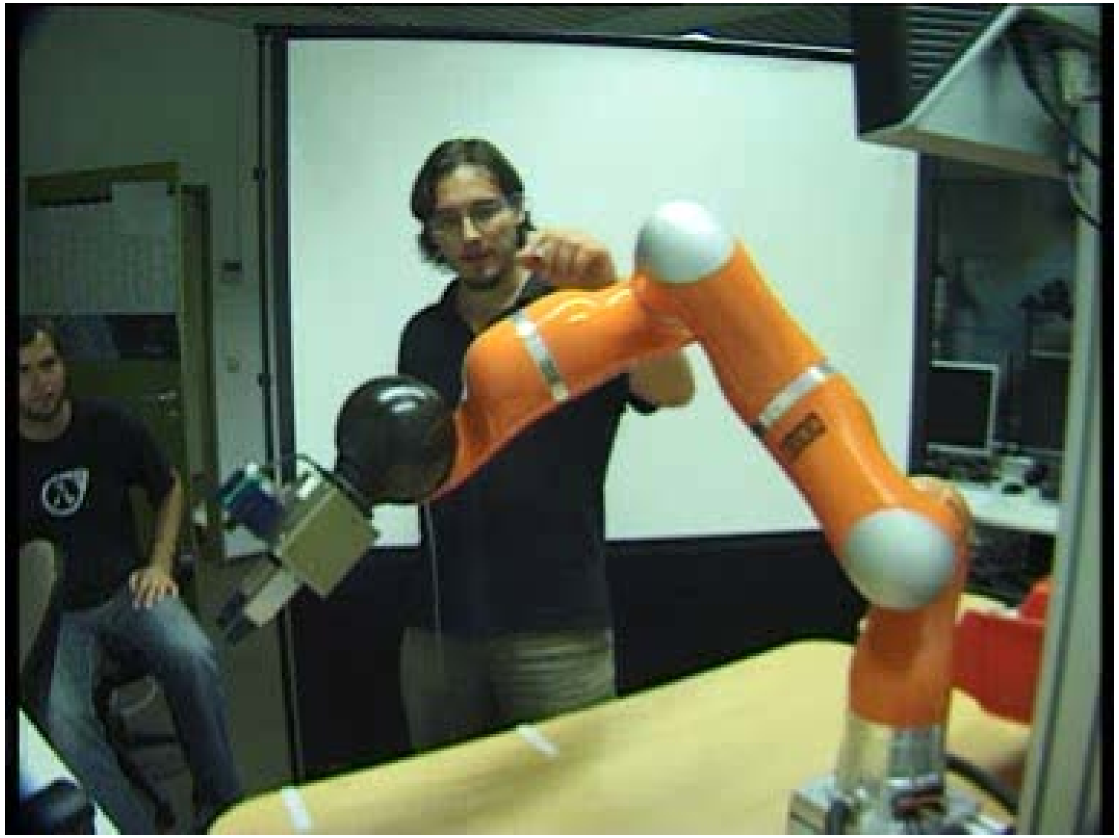
„Industry 4.0“: shared data for the automatic manufacturing workflow



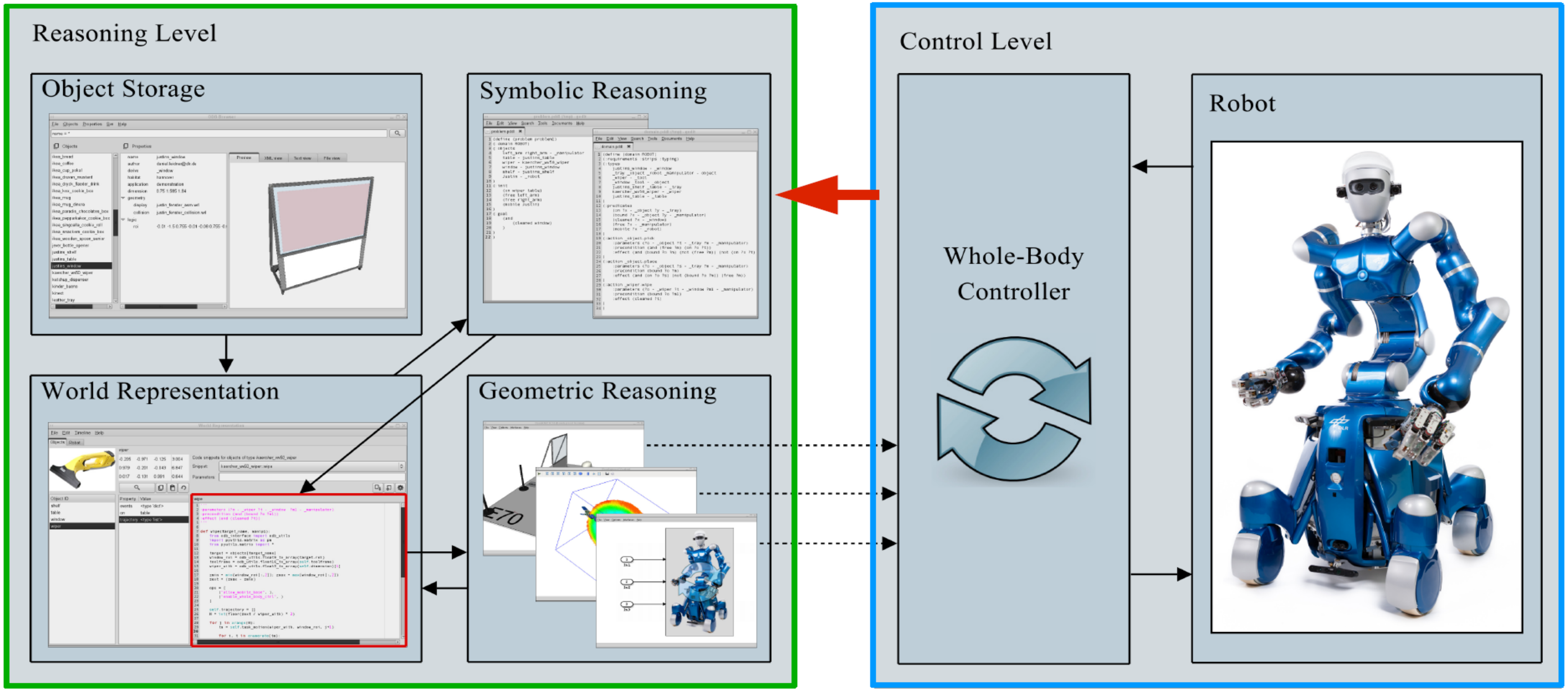
Reactive behavior and planning in low-dimensional space



Reactive behavior



Combining compliant control and AI



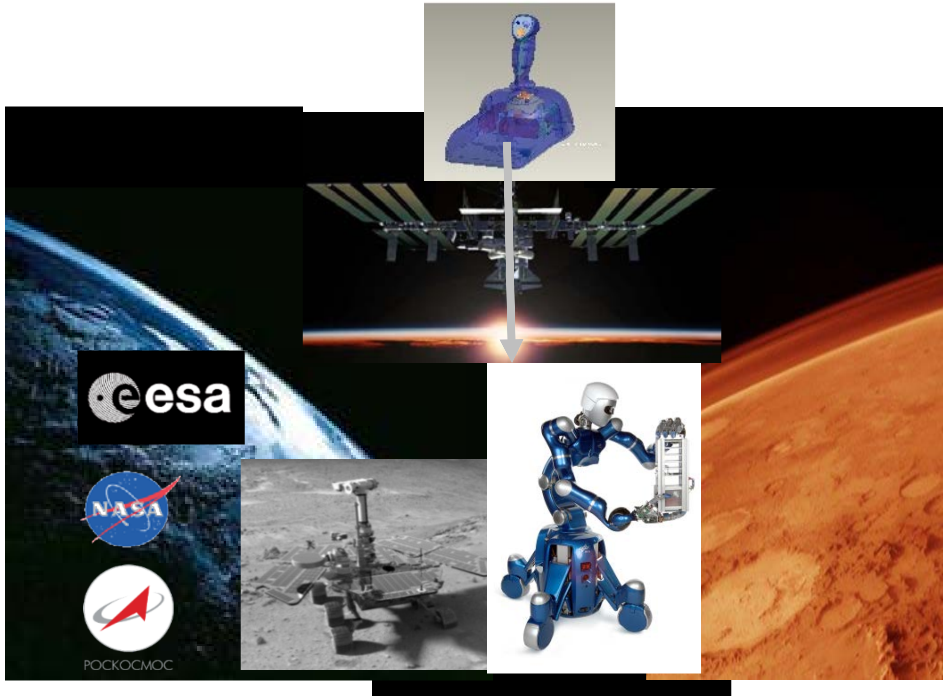
Hybrid Reasoning

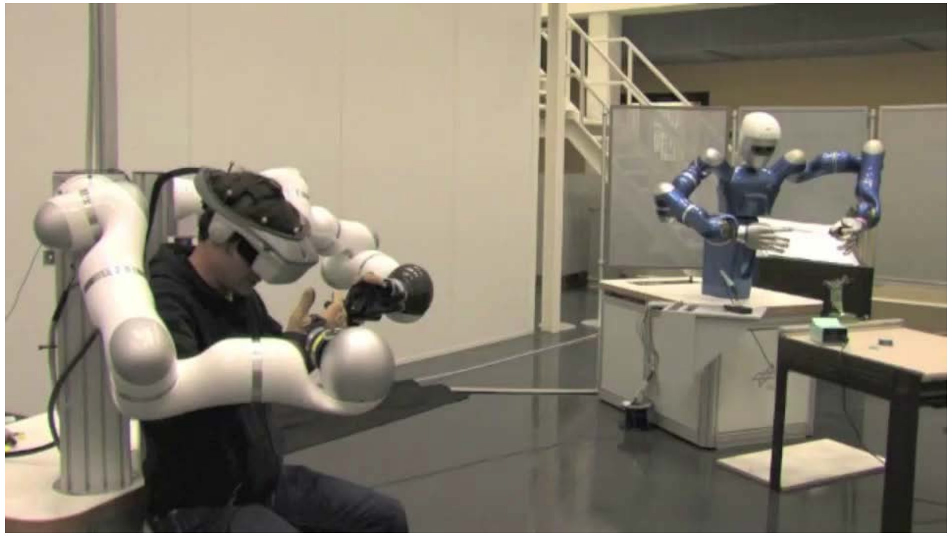
Compliant Control

Telemanipulation with time delay

- Passivity observer and passivity control concepts for handling variable time delay
- Effective operation up to 0.8s delay

Projects on the International Space Station ISS
Kontur 2 (2015)
METERON (2015-2017)





Telepresence from the ISS

- Astronauts can see, talk and interact physically with people and things on the planet surface and in orbit.
- With a good internet connection, we can operate robotic avatars on any point on earth

NTV-Report on Meteron

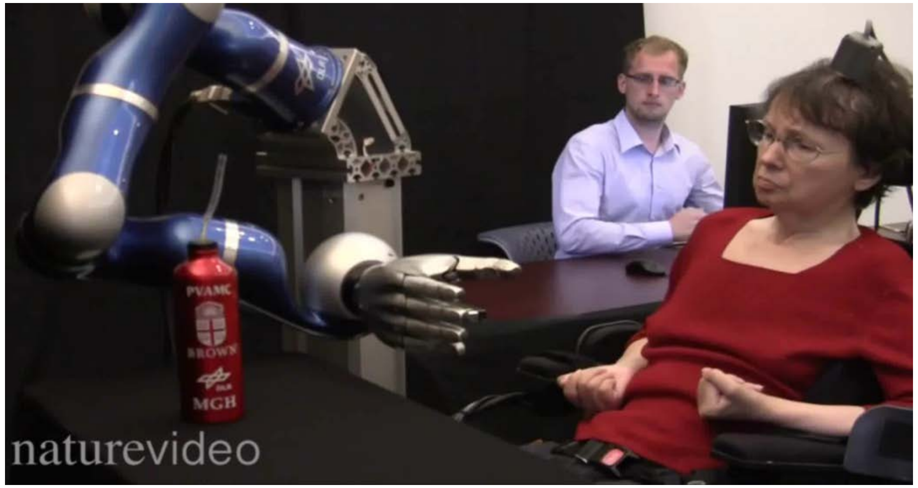
Tele-manipulation with brain interface or EMG signals

The future of teleoperation:

- Shared autonomy
- Natural interfaces (EMG, brain)

Hand pose and forces as well as arm movements can be well detected from EMG.

Calibration through incremental machine learning techniques.



Tele-manipulation with brain interface or EMG signals

Thank you for your attention!