Elective in Robotics/Control Problems in Robotics

Physical Human-Robot Interaction

Introduction

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DIPARTIMENTO DI INGEGNERIA INFORMATICA
AUTOMATICA E GESTIONALE ANTONIO RUBERTI

SAPIENZA
UNIVERSITÀ DI ROMA

pHRI module – 2022-23

- first half of II semester Tuesday, February 21 – Tuesday, April 4, 2023
- masters Artificial Intelligence and Robotics & Control Engineering
- credits 3 = 75h (1 ECTS = 25h of student work)
  - lectures (~30h), individual study (~45h)
- lecture schedule
  - Tuesday (14:00-16:00) in room A7, Thursday (8:00-11:00) in room A4
- G-group https://groups.google.com/a/diag.uniroma1.it/g/phri_module_2022-23
- prerequisites Robotics 1 (passed!) and Robotics 2 (studied!!)
  - redundancy; dynamics; admittance/impedance/hybrid force-motion control
- exam with an attendance of **at least 2/3** of the lectures

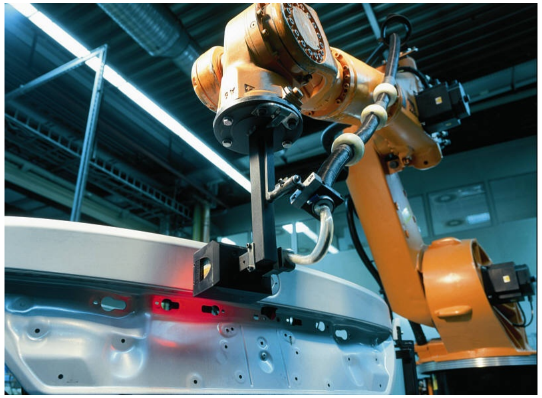
  ⇒ presentation with slides on a topic (with technical papers) or short project

  else an oral exam
- web page http://www.diag.uniroma1.it/deluca/pHRI.php

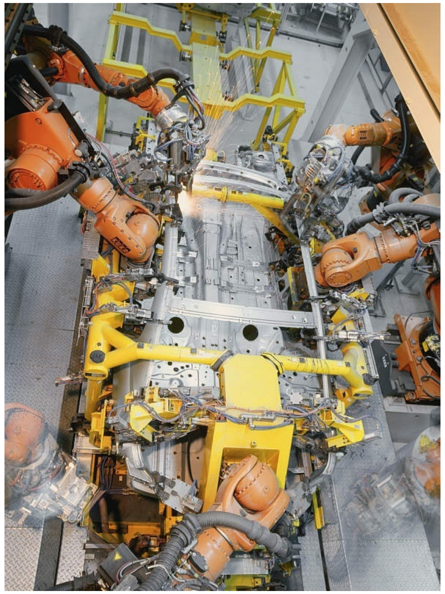
Robots and humans

science fiction and popular notions of robotics have long foreseen humans and robots **existing side-by-side** and **collaborating to do work** together

until very recently, the reality has been quite different in the factories: heavy industrial robots were far **too dangerous** to share their workspace with humans



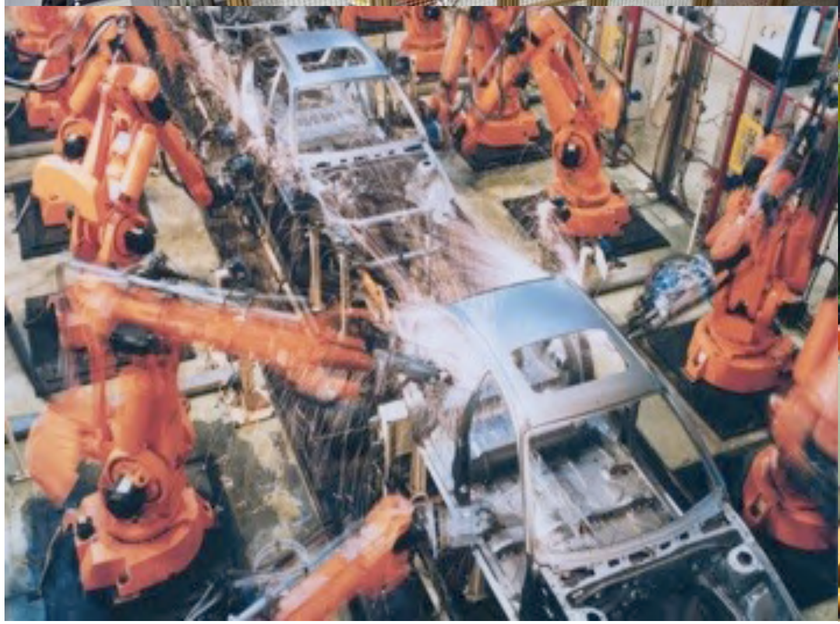
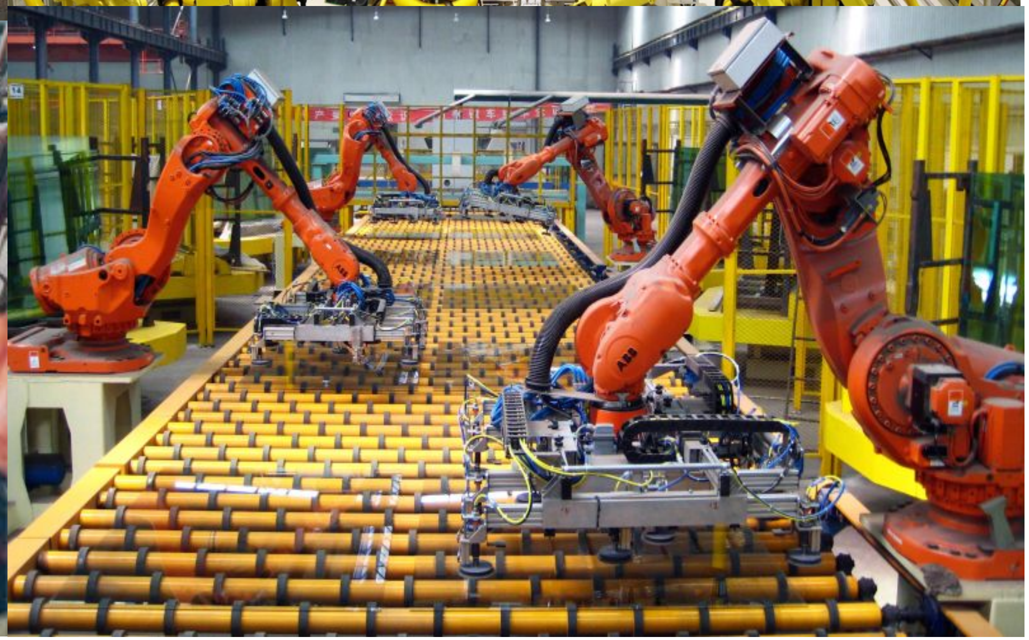
no humans here!



no humans?!

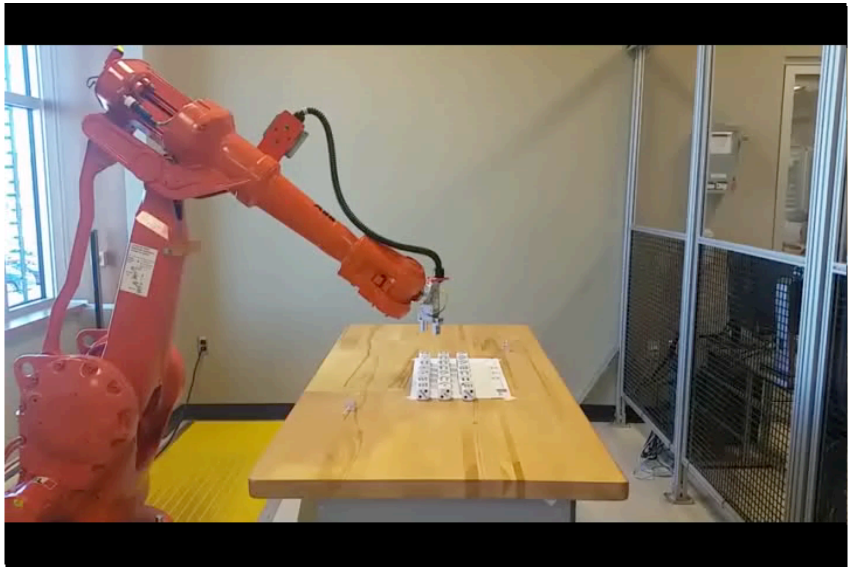
Industrial factory floor



Crashes, collisions …

3 videos
from the web



https://youtu.be/7FwdMjYUyKM

https://youtu.be/Cpg_3syMT_U

https://youtu.be/npItpe4U8KY

… and related tragic news

Berliner Zeitung

Panorama - 01.07.2015

TRAGISCHER ARBEITSUNFALL IN BAUNATAL

Roboter tötet Arbeiter in VW-Werk

Tragischer Arbeitsunfall im VW-Werk in Baunatal: Beim Aufbau einer neuen Anlage wurde ein 22-jähriger Arbeiter von einem Roboter erfasst und getötet.

R.it | Esteri

July 1, 2015

Robot uccide operaio in fabbrica Volkswagen

E' successo a Baunatal a circa 100 km da Francoforte. La procura ha aperto inchiesta per stabilire se si sia trattato di errore umano o se l'automa sia stato programmato male

theguardian

Winner of the Pulitzer prize 2014

Robot kills worker at Volkswagen plant in Germany

Contractor was setting up the stationary robot when it grabbed and crushed him against a metal plate at the plant in Baunatal

Associated Press in Berlin

Thursday 2 July 2015 02.48 BST

A robot has killed a contractor at one of Volkswagen's production plants in Germany, the automaker has said.

The man died on Monday at the plant in Baunatal, about 100km (62 miles) north of Frankfurt, VW spokesman Heiko Hillwig said.

The 22-year-old was part of a team that was setting up the stationary robot when it grabbed and crushed him against a metal plate, Hillwig said.

He said initial conclusions indicate that human error was to blame, rather than a problem with the robot, which can be programmed to perform various tasks in the assembly process. He said it normally operates within a confined area at the plant, grabbing auto parts and manipulating them.

Another contractor was present when the incident occurred, but was not harmed, Hillwig said. He declined to give any more details about the case, citing an ongoing investigation.

German news agency DPA reported that prosecutors were considering whether to bring charges, and if so, against whom.

Ansa
Mondo

Dipendente Volkswagen ucciso da robot

Afferrato e schiacciato contro pannello di metallo

- **Redazione ANSA**
- BERLINO
02 luglio 2015 - 19:19
- NEWS

Suggerisci
Facebook
Twitter
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Altri

Robot 'uccide' operaio in Germania © ANSA/Ansa

CLICCA PER INGRANDIRE +

Stampa
Scrivi alla redazione

Un giovane dipendente della tedesca Volkswagen è stato ucciso da un robot della fabbrica. È accaduto a Baunatal, a

Traditional industrial perspective

- slow down/stop the robot when workspace is accessed by humans

commercial video by ABB

https://youtu.be/Fo_RvSmqZF8

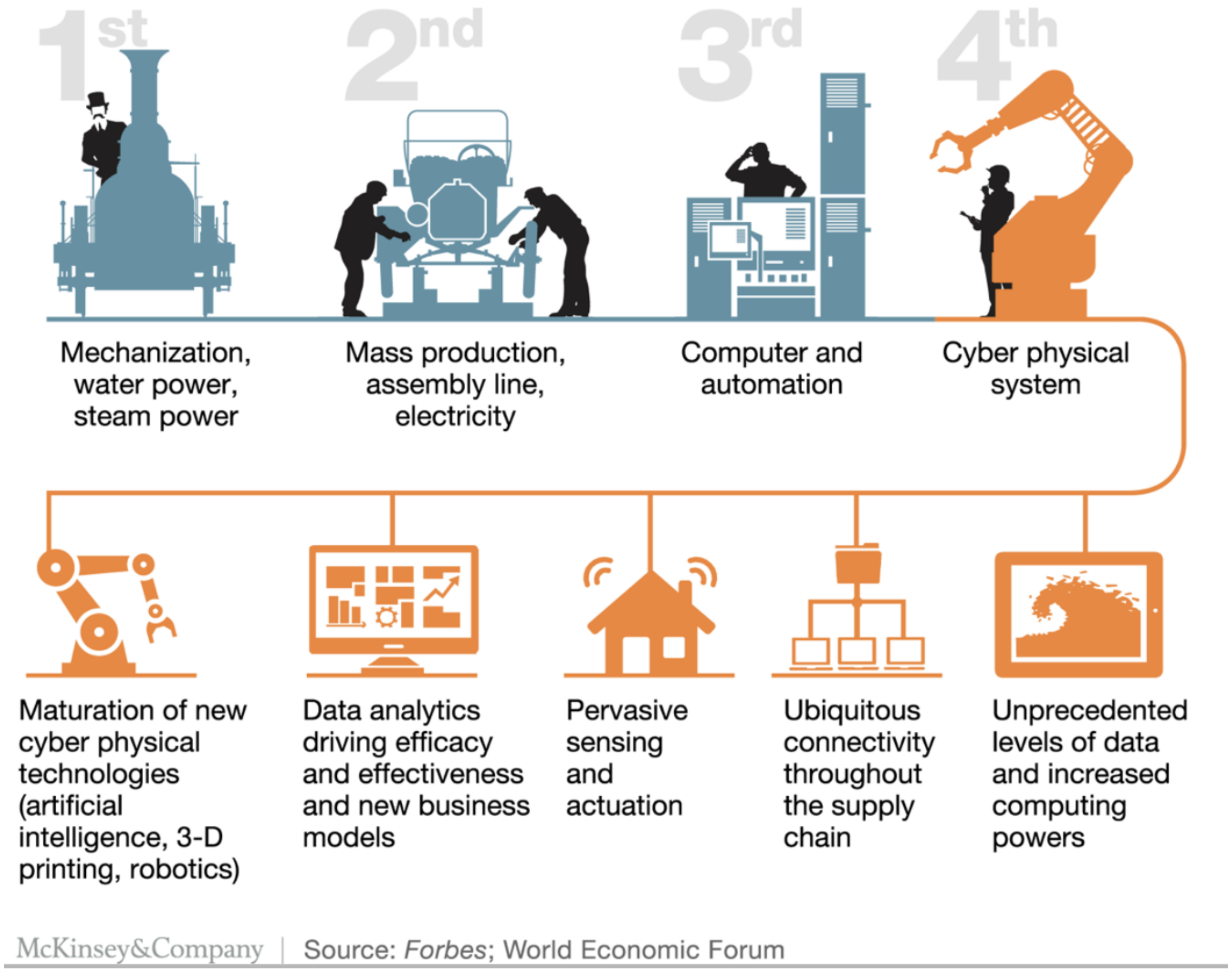
Innovative industrial perspective

- robot co-workers …

video by SMERobot (EU project)

https://youtu.be/tTxdYViHnmI

Industrial revolutions



Industry 4.0

a list of key enabling technologies for the 4th industrial revolution

- Collaborative robots, networked and easily programmable
- 3D additive printers with software for digital design
- Augmented reality to support production processes
- Simulation tools of interconnected machines/cells for process optimization
- Integration of information along the value chain from suppliers to customers
- Bidirectional communication between production processes and products
- Big data storage and exchange in open network systems
- Security in operation of networks and open systems
- Big data analysis to optimize products and production processes

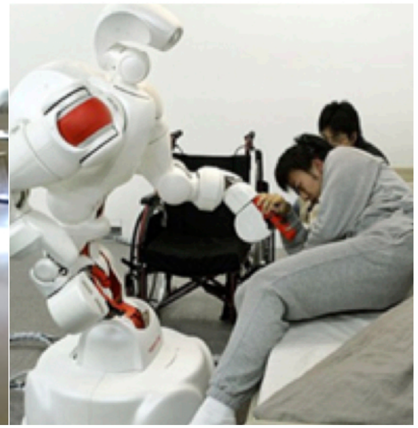
Human-robot collaboration

traditional robotics

replacing humans

human-friendly robotics

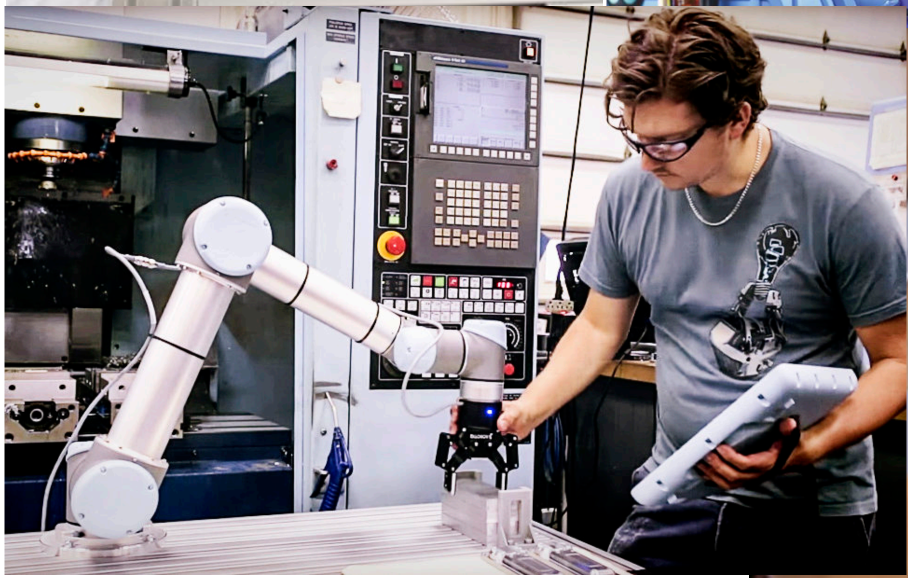
collaborating with humans



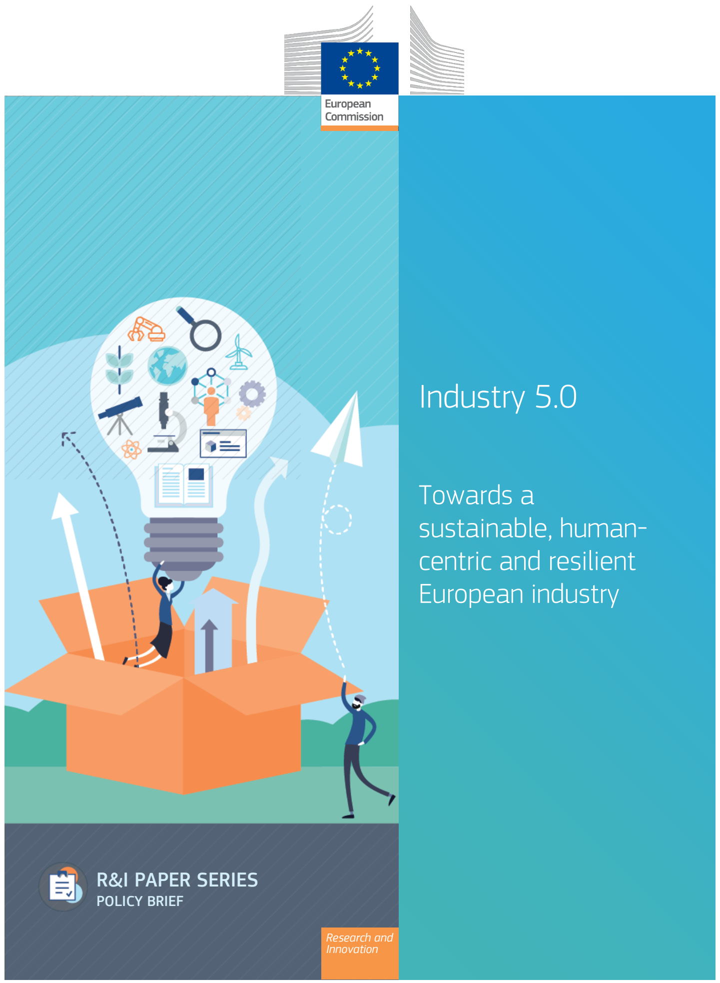
co-workers on factory floor

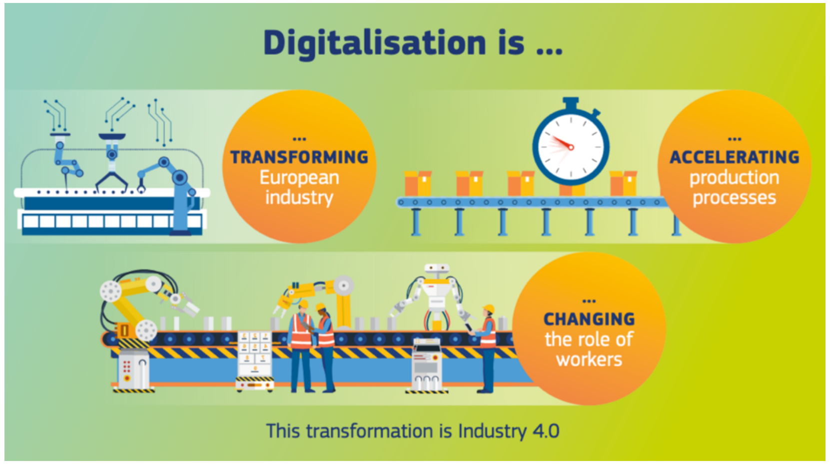
personal robots in service

Human-friendly factory floor



Industry 5.0 !!


European Commission
Industry 5.0
Towards a sustainable, human-centric and resilient European industry
R&I PAPER SERIES
POLICY BRIEF
Research and Innovation


Digitalisation is ...
... TRANSFORMING European industry
... ACCELERATING production processes
... CHANGING the role of workers
This transformation is Industry 4.0


Industry 5.0 ...
HUMAN-CENTRIC
... promotes talents, diversity and empowerment
RESILIENT
... is agile and resilient with flexible and adaptable technologies
SUSTAINABLE
... leads action on sustainability and respects planetary boundaries

Human-Robot Interaction (HRI)

physical and cognitive interaction between a Sarcos robot and a human

intrinsic compliance and natural dynamic behavior of the robot
are here more important than fast and accurate motion execution

physical vs cognitive HRI

video

cognitive interaction (cHRI)
– Robot@CWE EU Project

video

physical interaction (pHRI)
– handshaking at @PAL Robotics

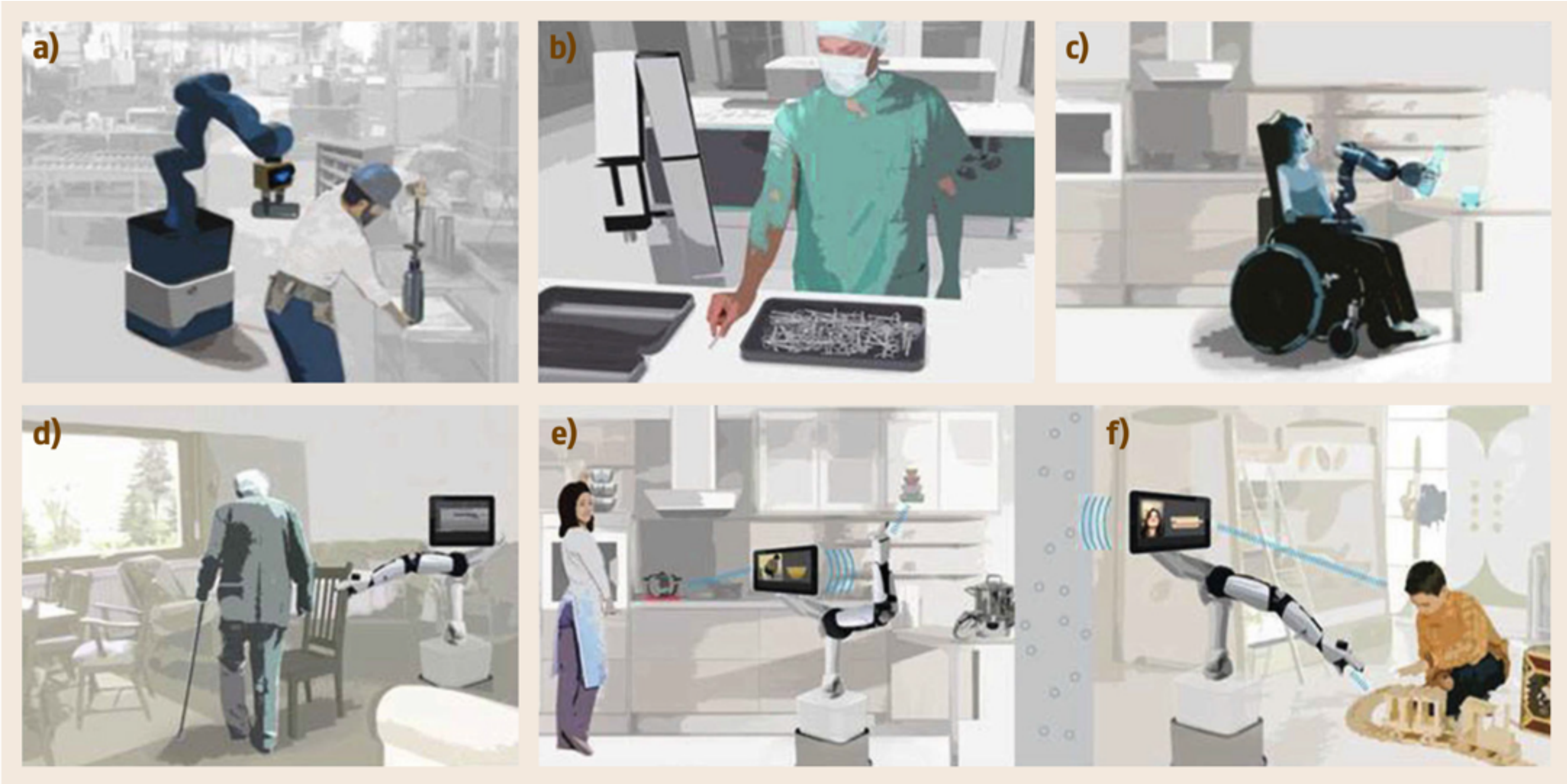
more videos on cHRI at http://handbookofrobotics.org/view-chapter/videodetails/71

State of the art

- foundational components of physical human–robot interaction have grown over the last two decades, with successful developments in
  - mechatronics (actuation/sensing), planning, and control
  - design of lightweight and compliant robots
  - safe interaction control schemes

  ⇒ beyond high-payload/high-precision position-controlled industrial robots
- rise of a new generation of robots capable of
  - sensing or estimating physical contacts
  - rendering compliant behavior along the robot structure
  - planning legible motions that respect human preferences
  - generating interaction plans for collaboration and coaction with humans
- advances in the field of human safety in industrial robotics
- novel and unforeseen application domains are now open

Some application domains

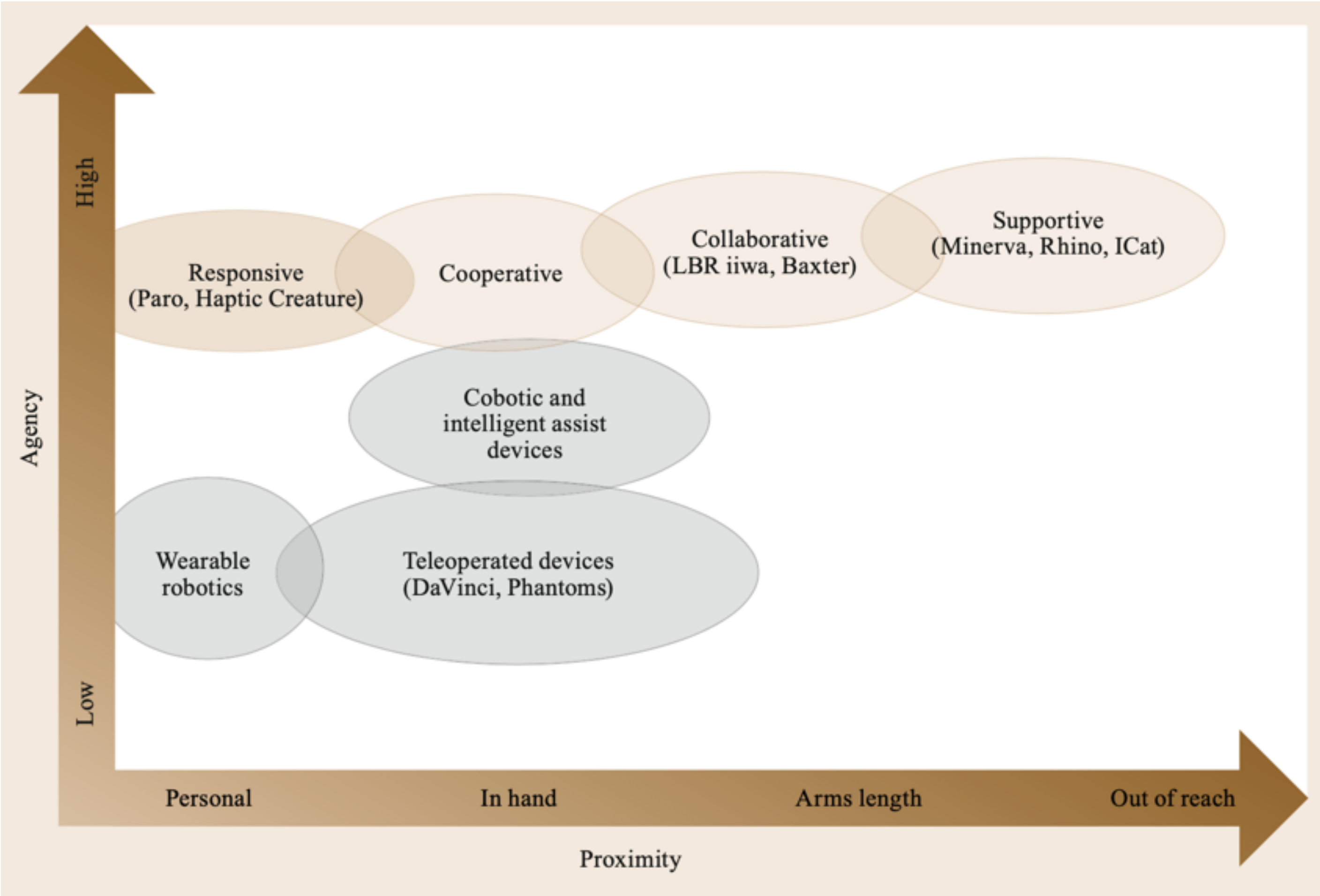


- shop floor logistics and manipulation
- professional service robots & assistive devices for the elderly or disabled
- service robots in domestic applications

Aim of this module

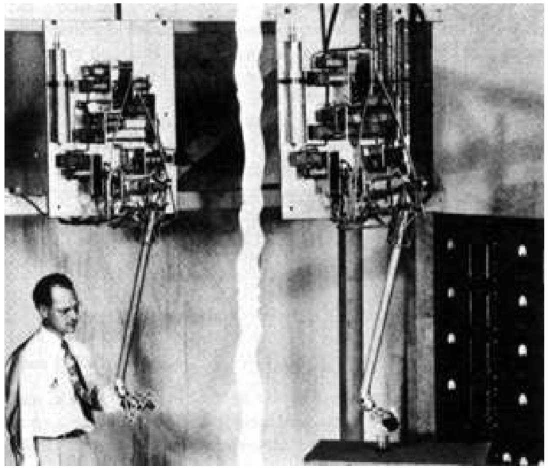
- an overview of the state of the art in pHRI
  - robot safety for humans, human injury analysis in robotics and current/future safety standards for pHRI
  - basics of human-friendly design, with lightweight and intrinsically flexible torque-controlled robots
  - perception abilities required for HR interaction and collaboration
  - motion planning techniques for human environments and human-aware (re-)planning
  - interaction control, including
    - collision avoidance and coexistence
    - collision detection, isolation and identification
    - contact force estimation
    - robot reflexes and reactive control
    - control architecture for pHRC (physical HR Collaboration)

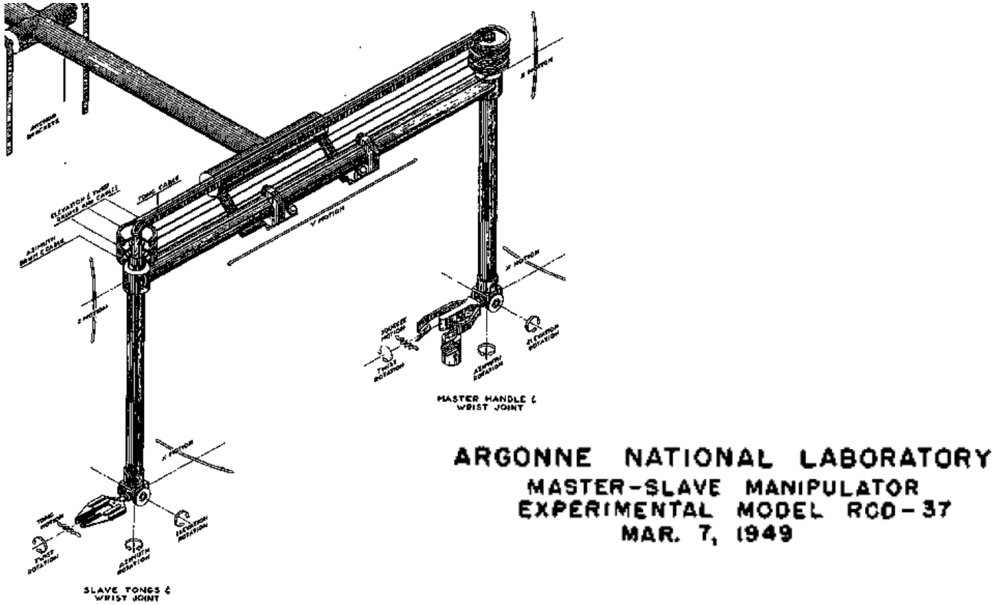
Classification



by proximity of the interaction and available autonomy (agency) of the robot

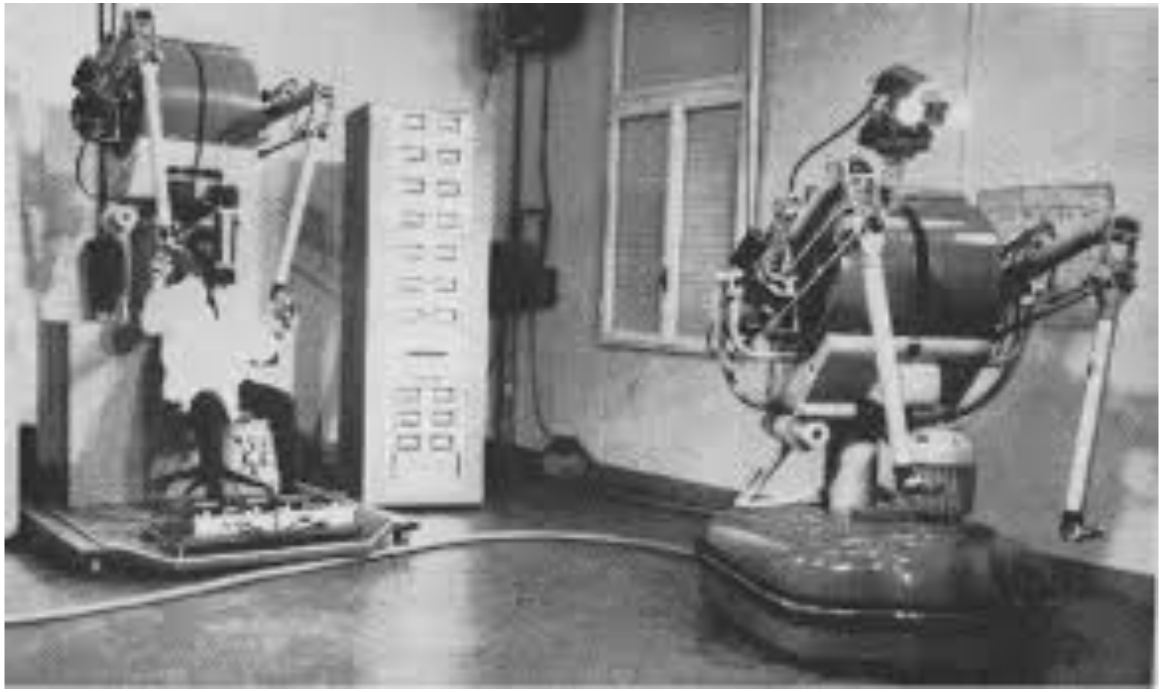
Historical pHRI in telemanipulation

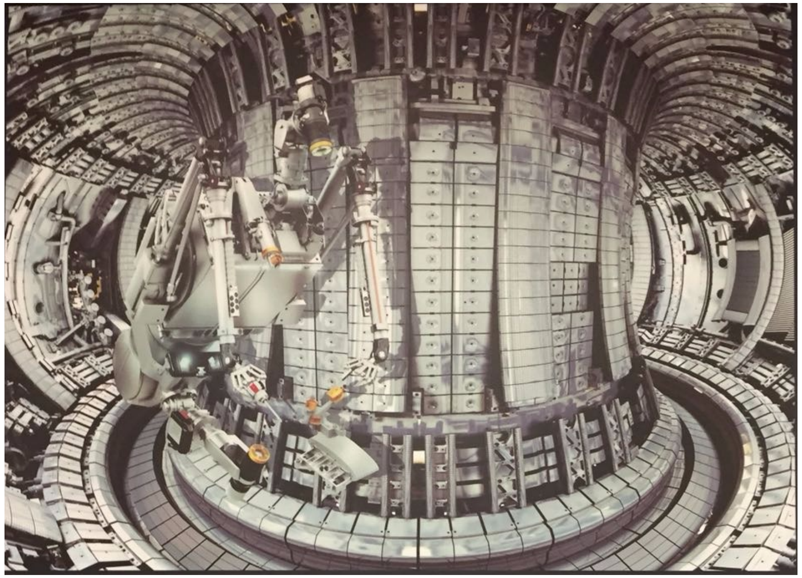


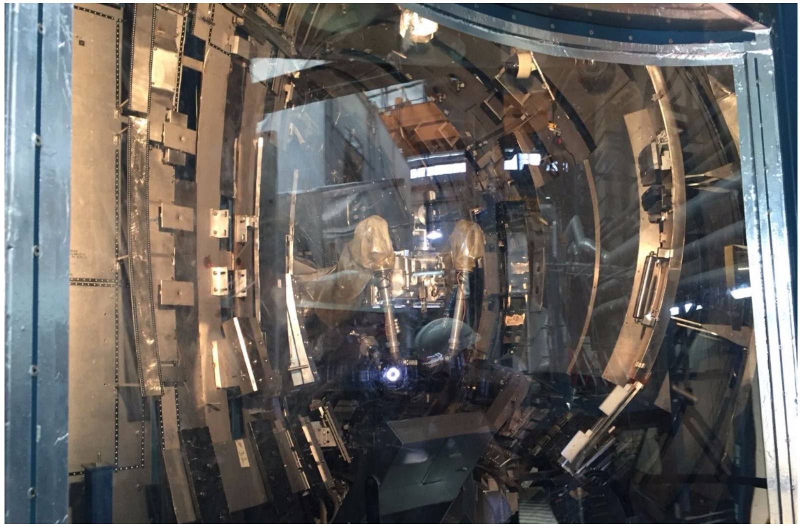


Raymond C. Goertz, Master-Slave Manipulator (MSM), 1949

Historical pHRI in telemanipulation



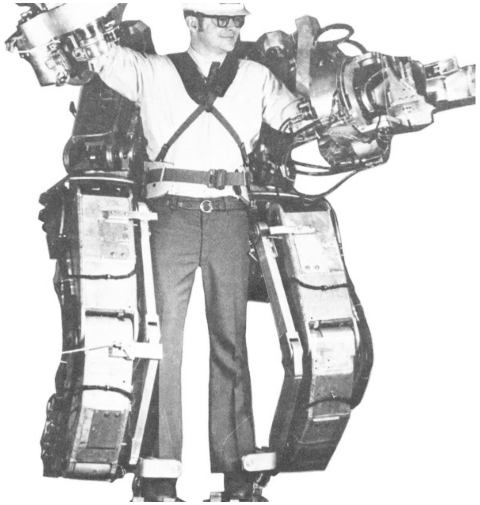




Carlo Mancini, MASCOT (CNEN/ENEA), 1959
MAnipolatore Servo COntrollato Transistorizzato

a master/slave tele-manipulator (two 6-link arms, with force feedback and controlled grippers) still in use for maintenance of the plasma facility at the Joint European Torus (JET) project in Culham, UK

Exoskeletons



General Electric, 1967

H. Kazerooni, UC Berkeley, 1985

https://youtu.be/AcfxDAklBCQ
commercial video

Wandercraft Atalante, 50 years later

self-balanced lower-limb exoskeleton with
12 actuated dofs and dynamic walk algorithms

Rehabilitation robotics

- "RUPERT" Robotic Upper Extremity Repetitive Therapy (Arizona State University + Kinetic Muscles, Inc.)
- sustains the human arm with pneumatic muscles (McKibben actuators)
- it can be programmed for the execution of cyclic exercises of rehabilitation

Wearable robots
for human augmentation

A Supernumerary Soft Robotic Hand-Arm System for Improving Worker Ergonomics

https://youtu.be/EdK2y3lphmE

video

IIT-Università Pisa, 2018

reducing load on hand-arm joints and vibration on hand-arm

ExoHiker™
(H. Kazerooni, UC Berkeley, 2005)

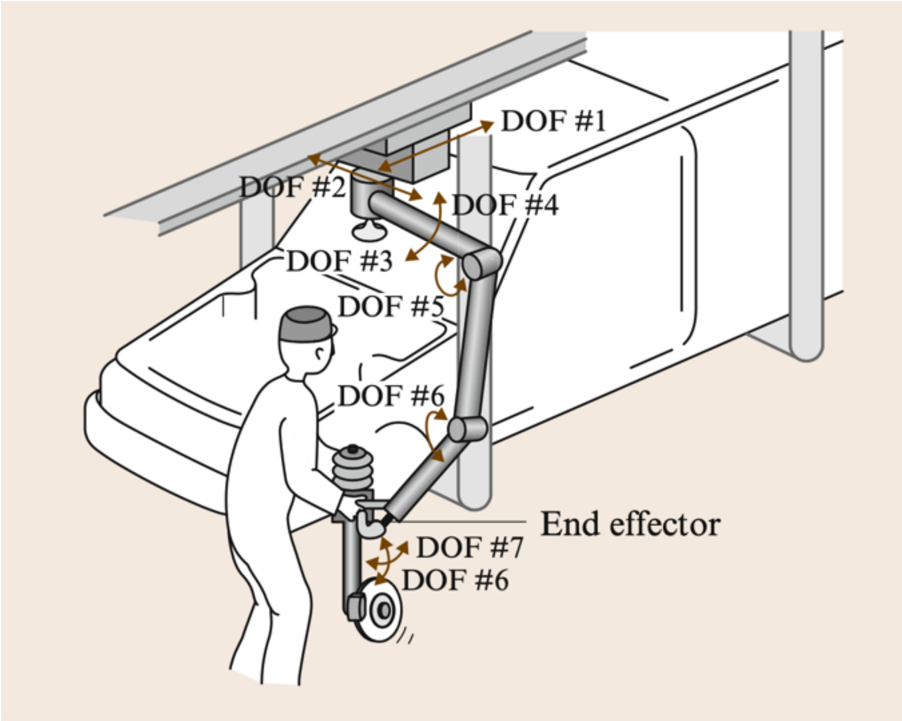
Intelligent Assistive Devices (IAD)

FANUC Intelligent Assist Device, 1995
(at Ford Motor Co.)

gantry-type robot with force-input handles for human guidance with six admittance-controlled axes

to install truck instrument panels on a moving assembly line or to load cylinder heads on top of engine blocks

Toyota Skill Assist, 1999
(Y. Yamada and Y. Umetani, Toyota Tech Inst)



dynamic behavior varies according to the task phase: inertial for moving a payload over long distances, viscous for precise positioning

task phases (start up, traversing, fine positioning) automatically determined from motion characteristics

Intelligent Assistive Devices (IAD)

http://handbookofrobotics.org/view-chapter/69/videodetails/821

video

- CoBot scooter-like robot for mounting car doors (General Motors, 1995)

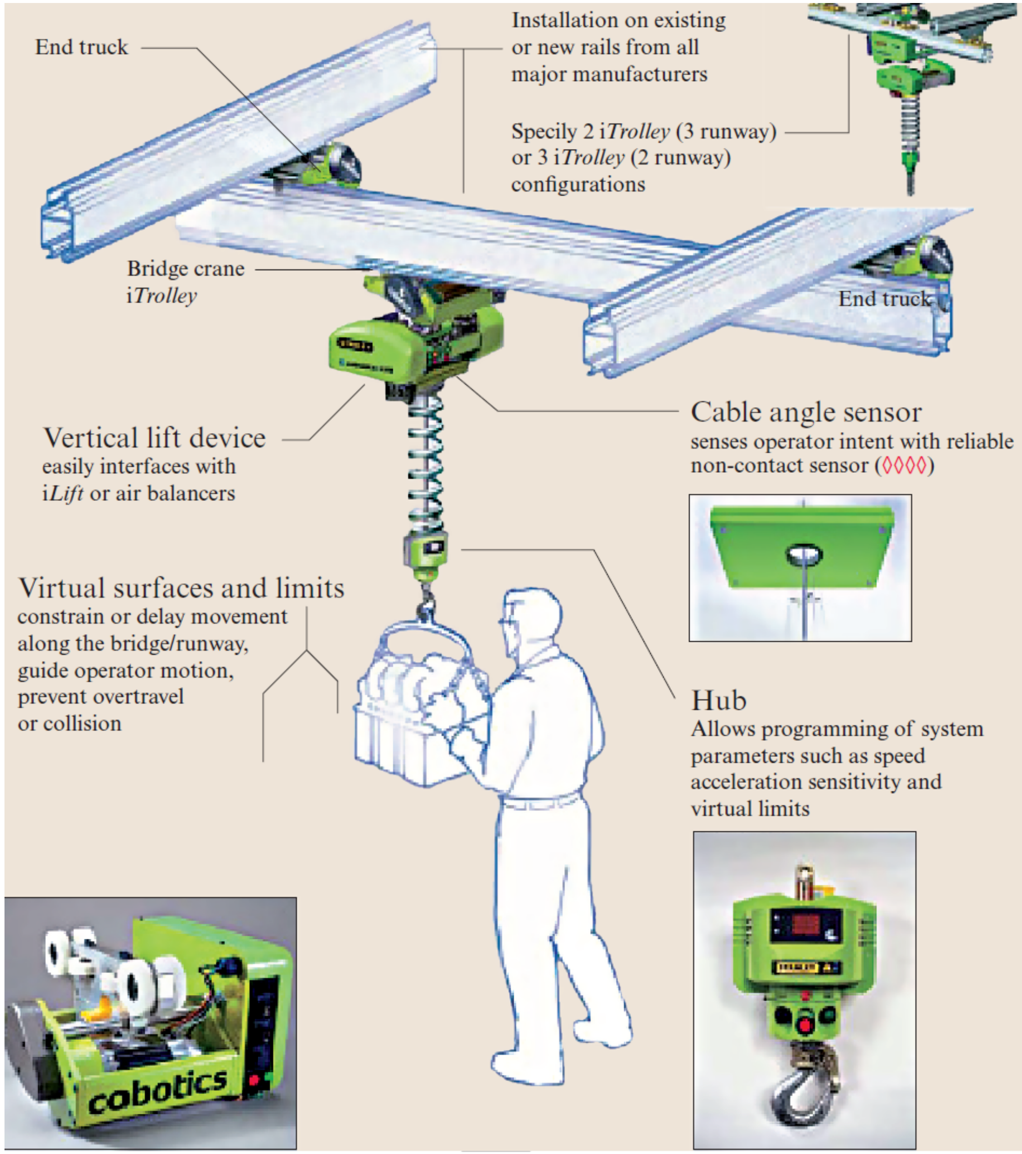
From IADs to Cobotics

1995 M.A. Peshkin and J.E. Colgate (Northwestern University) launch a spinoff for producing IADs

1997 US Patent 5,952,796 Cobots

"an apparatus and method for direct physical interaction between a person and a general purpose manipulator controlled by a computer"

iTrolley system
("hands on payload")



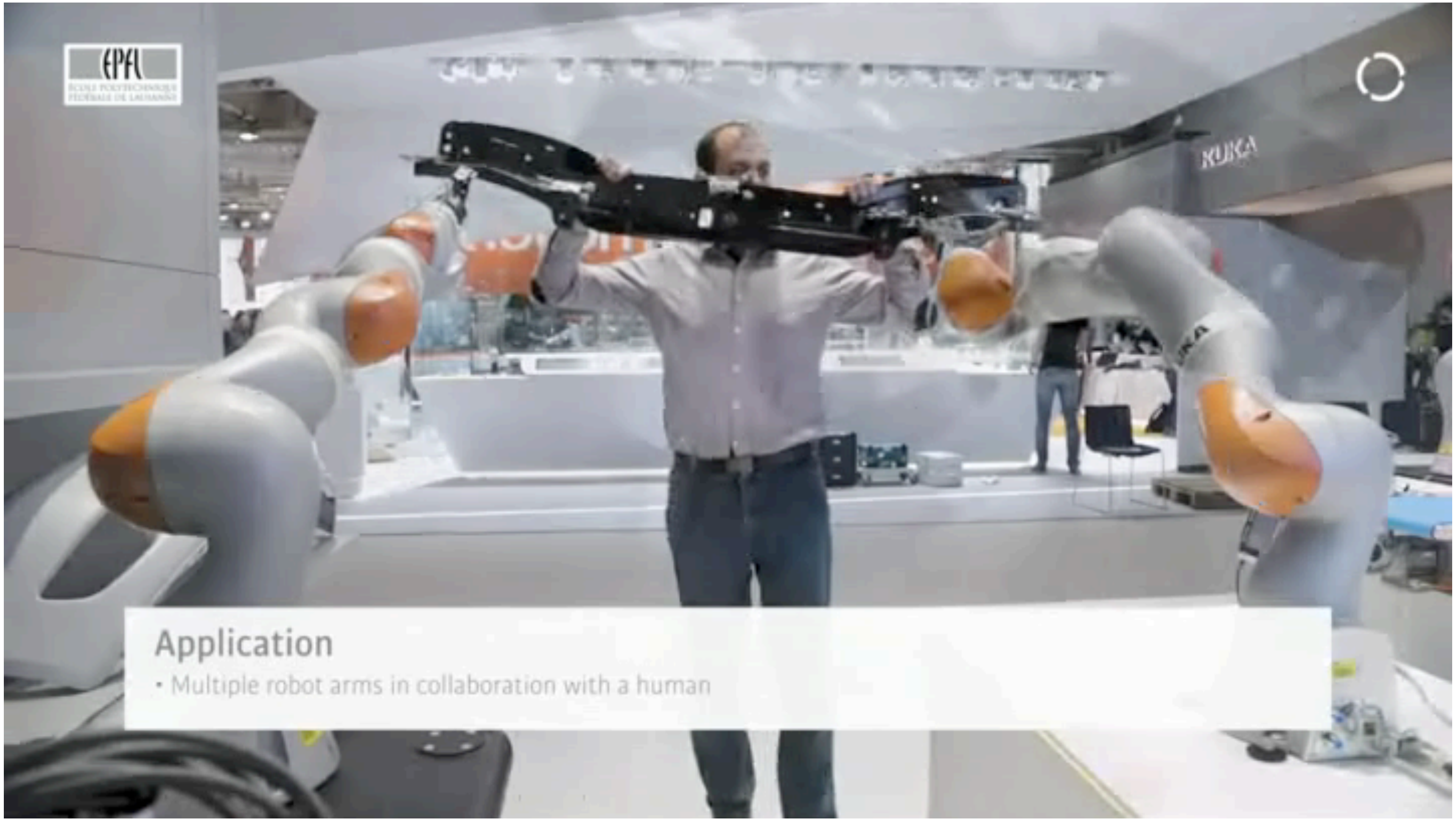
Human-robot collaboration

http://handbookofrobotics.org/view-chapter/69/videodetails/606

video

- Mr. Helper collaborates with humans in carrying large and/or heavy loads (K. Kosuge, Tohoku University, 2000)

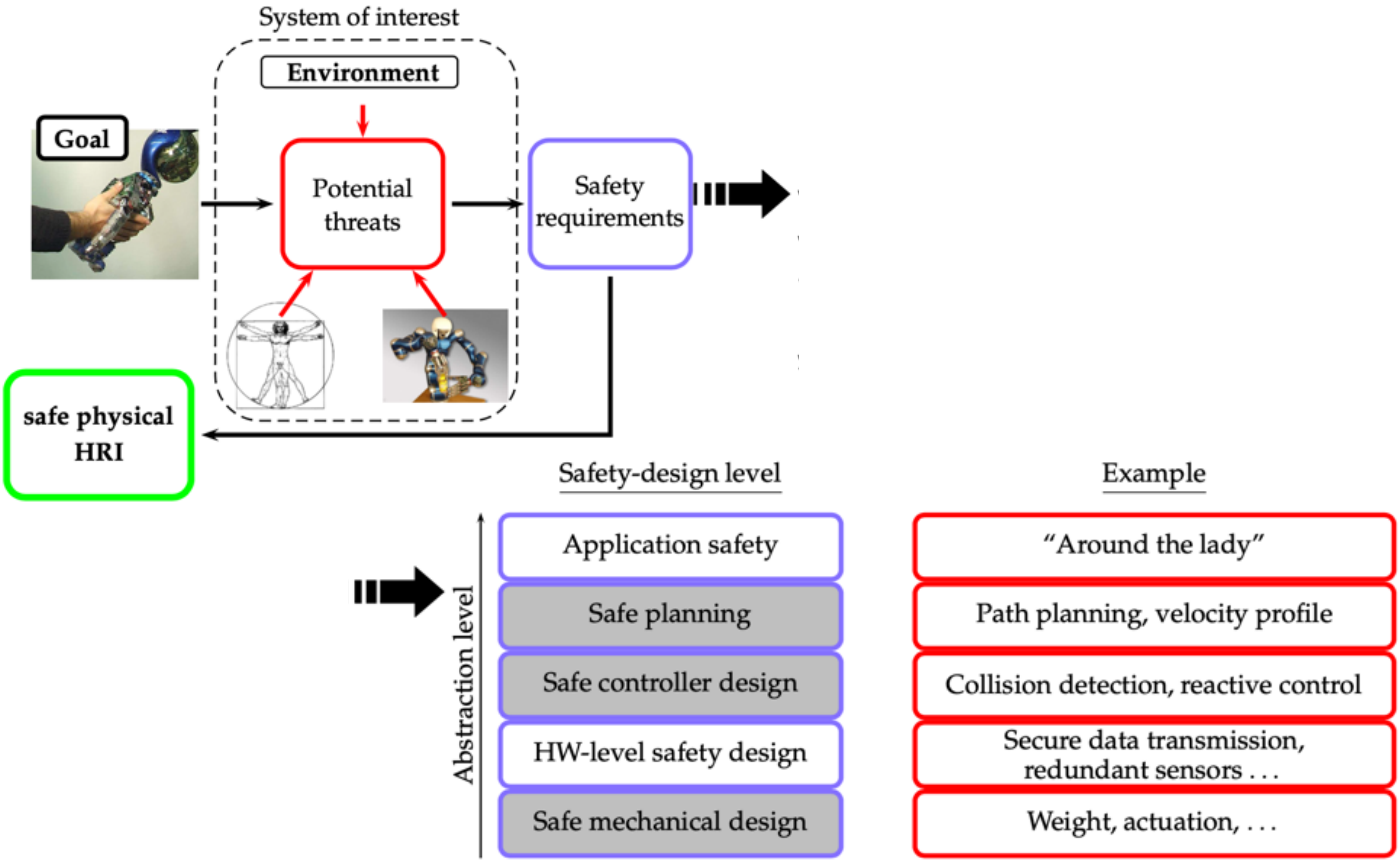
Working with humans or for humans?



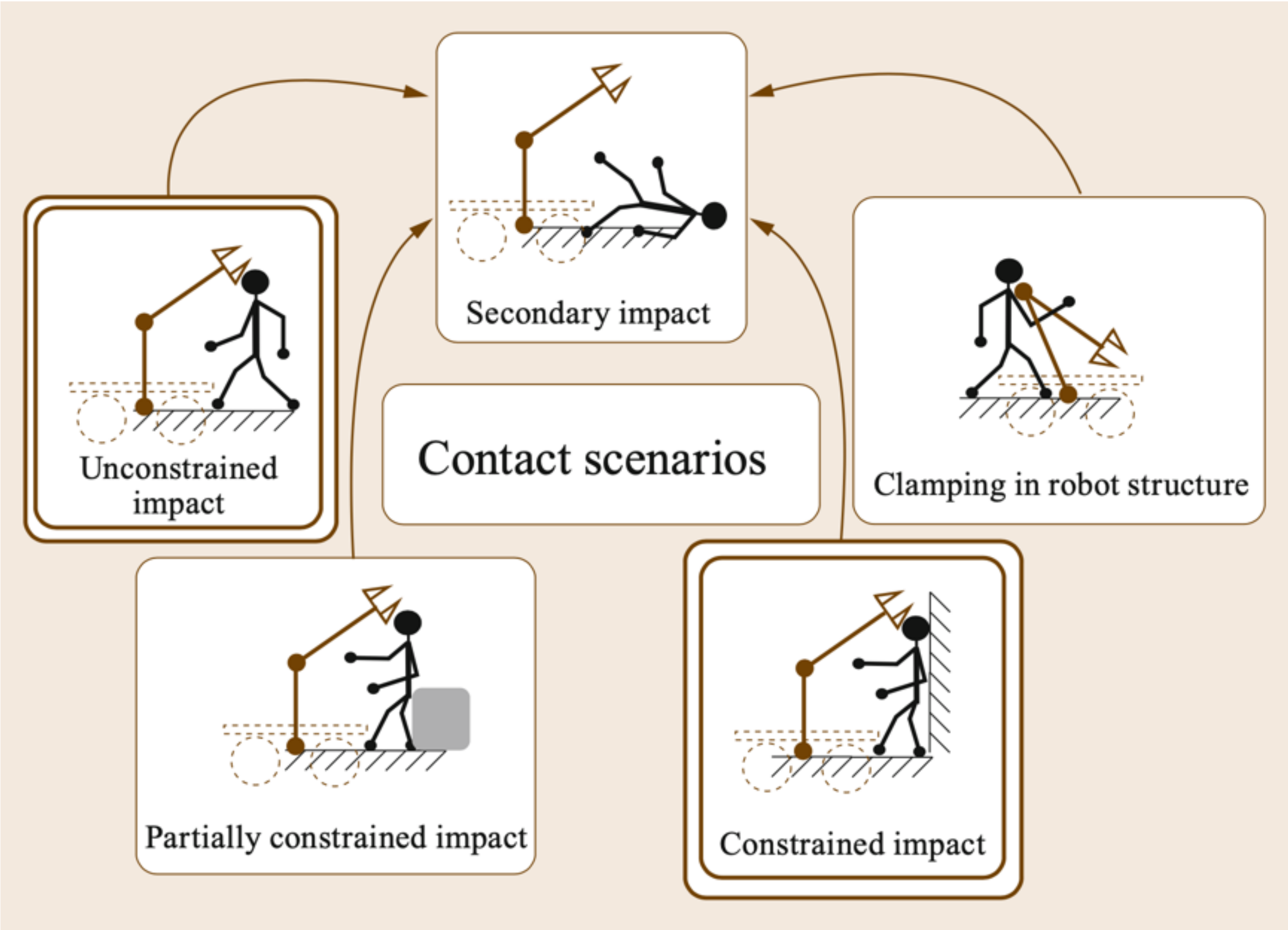
KUKA Innovation Award 2017 finalist video

https://youtu.be/SdI6lrQUa8s

Steps for safe pHRI

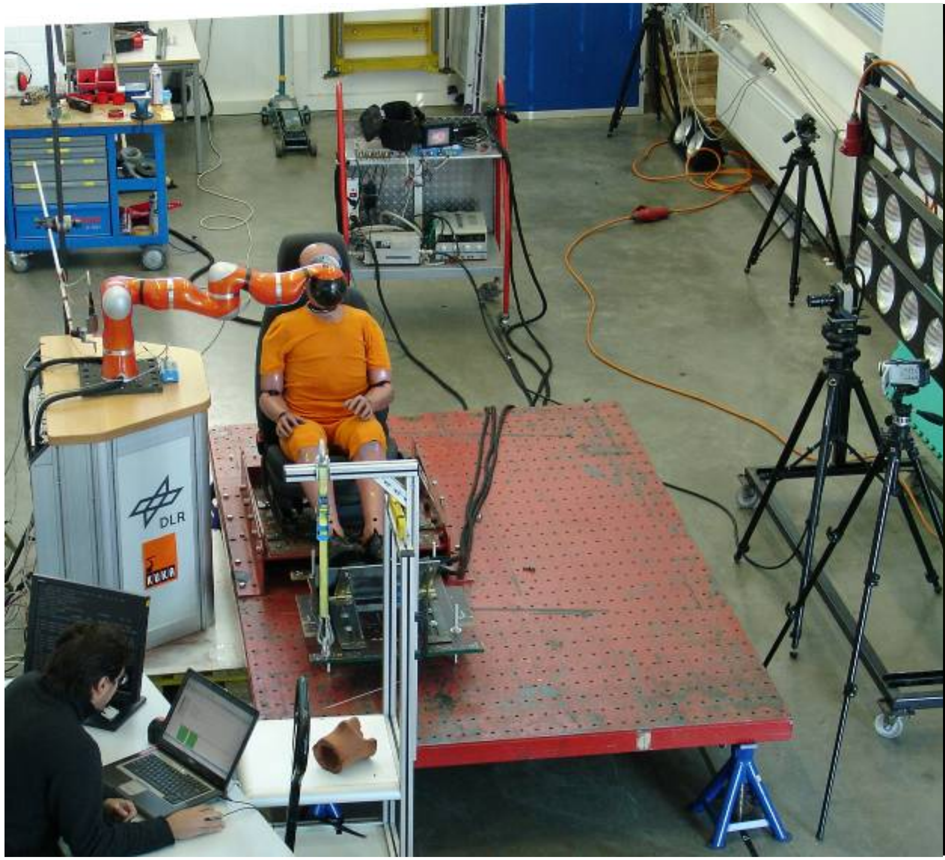


Human injury scenarios



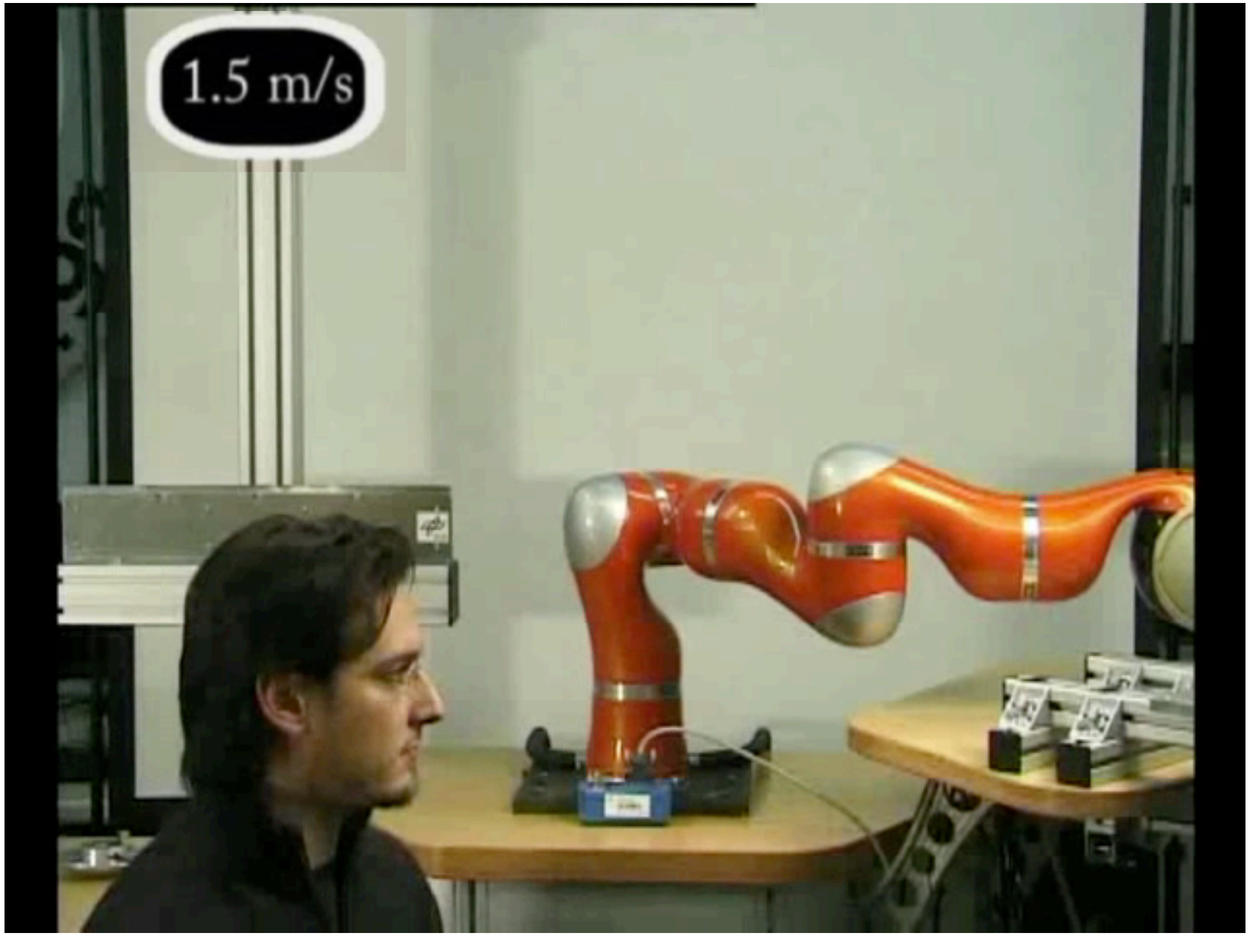
Robot-human crash

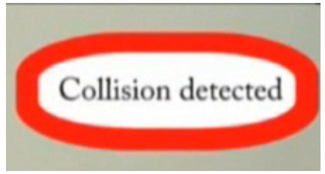
video by ADAC



First robotic crash tests with dummies worldwide (2006)

A famous test in robotics …



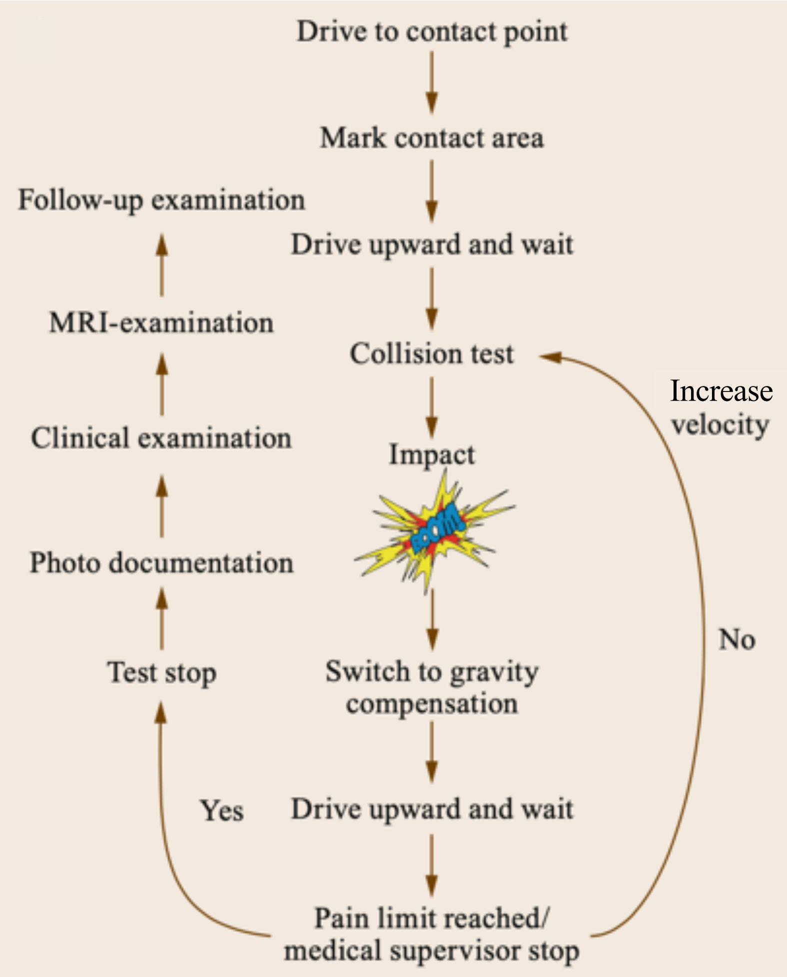


at t=1.6 s

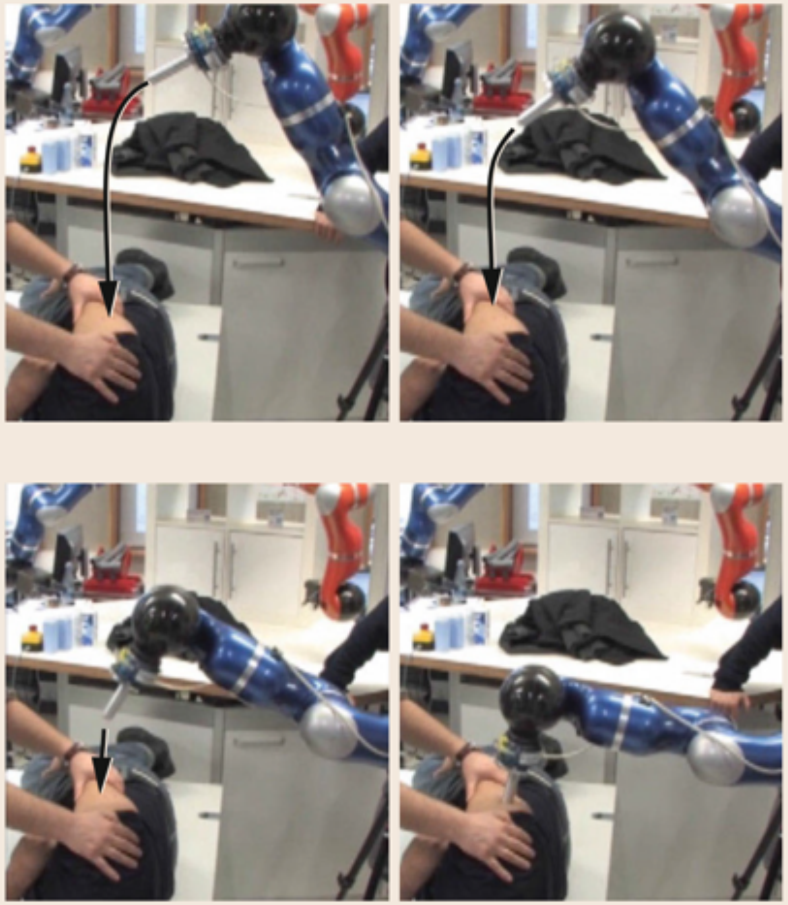
at t=1.61 s

video with Prof. Sami Haddadin (as a master student, 2006)

Biomechanics tests



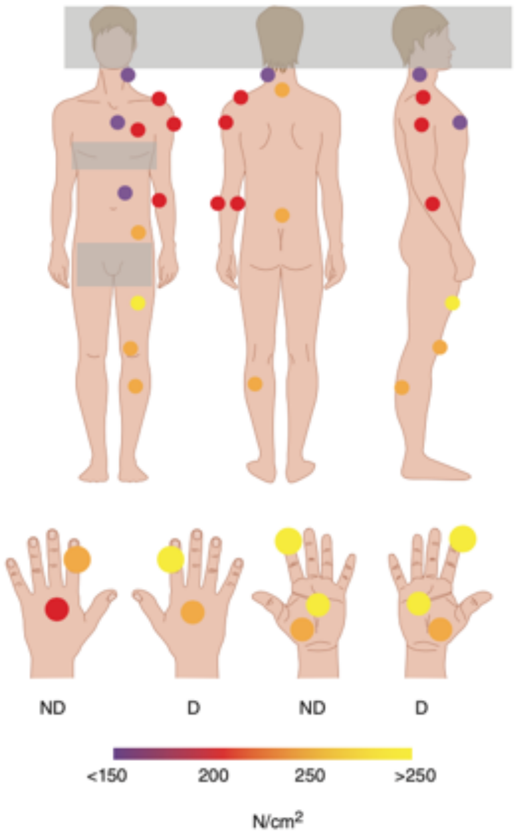
flow chart of experimental steps

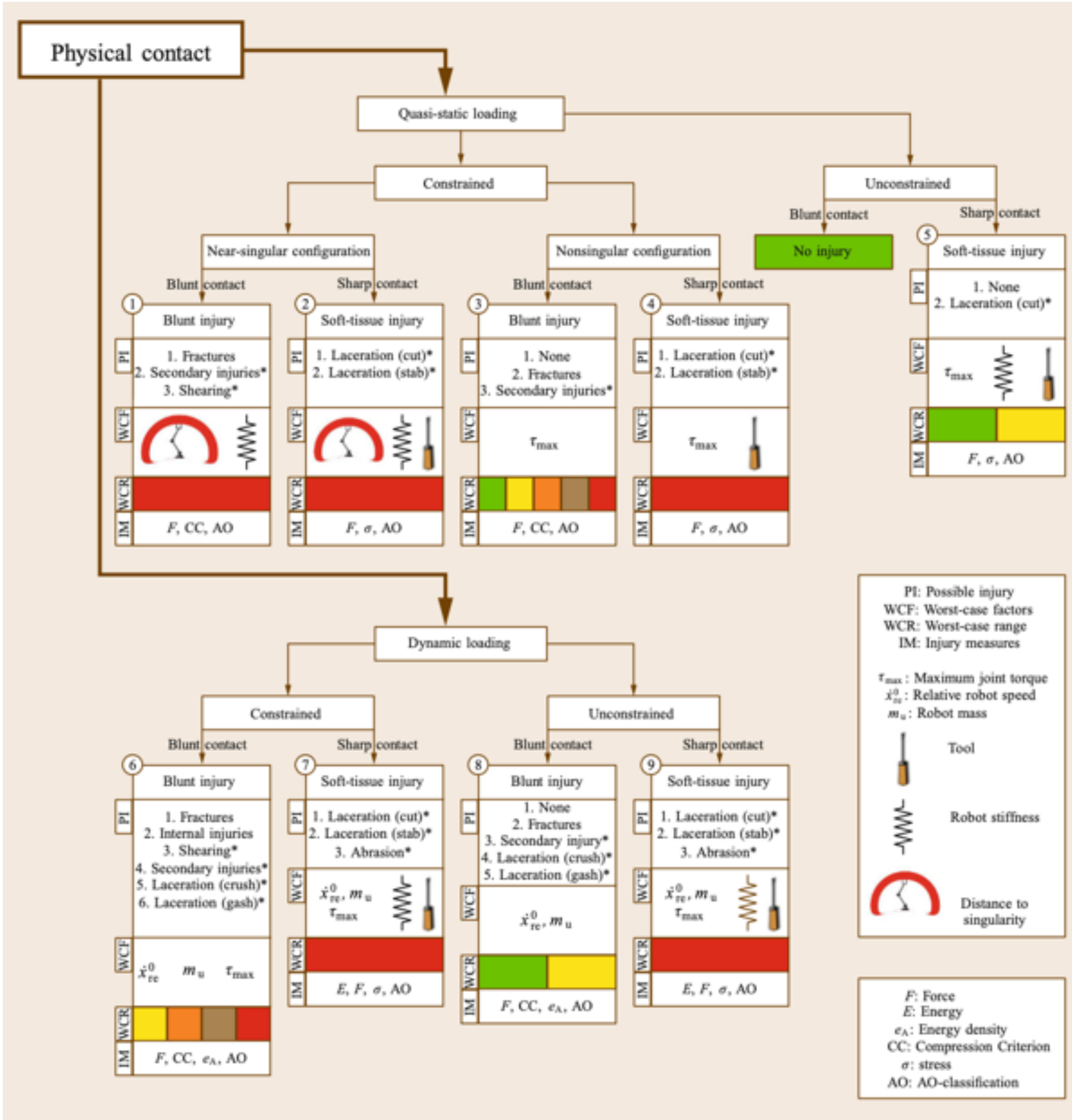


collision trajectory with subject

Safety tree

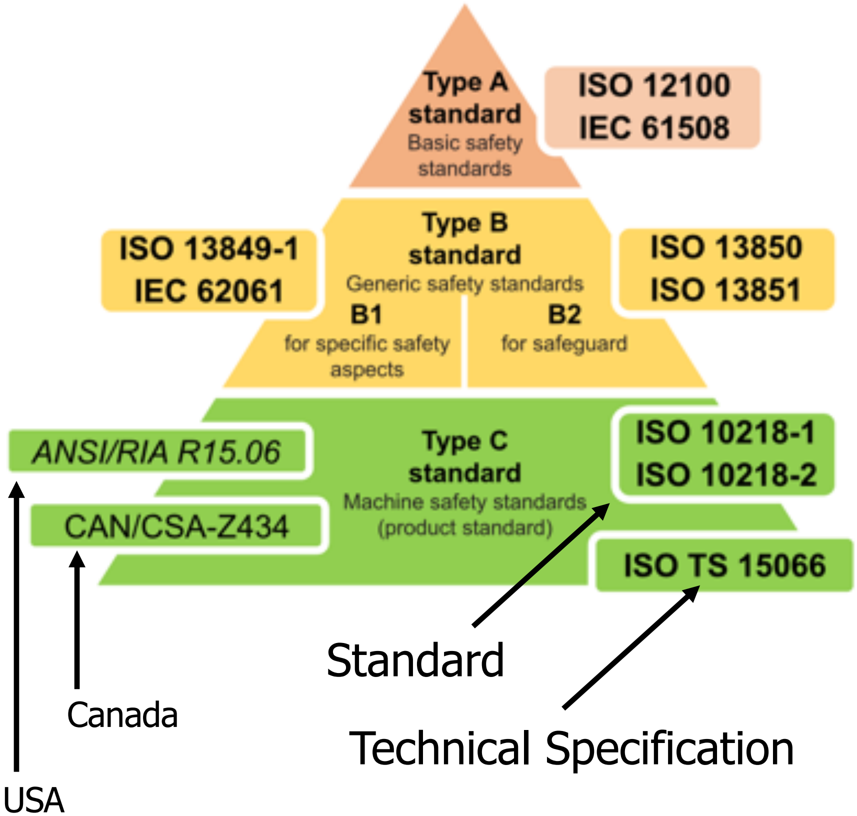
"Handbook of Injury"



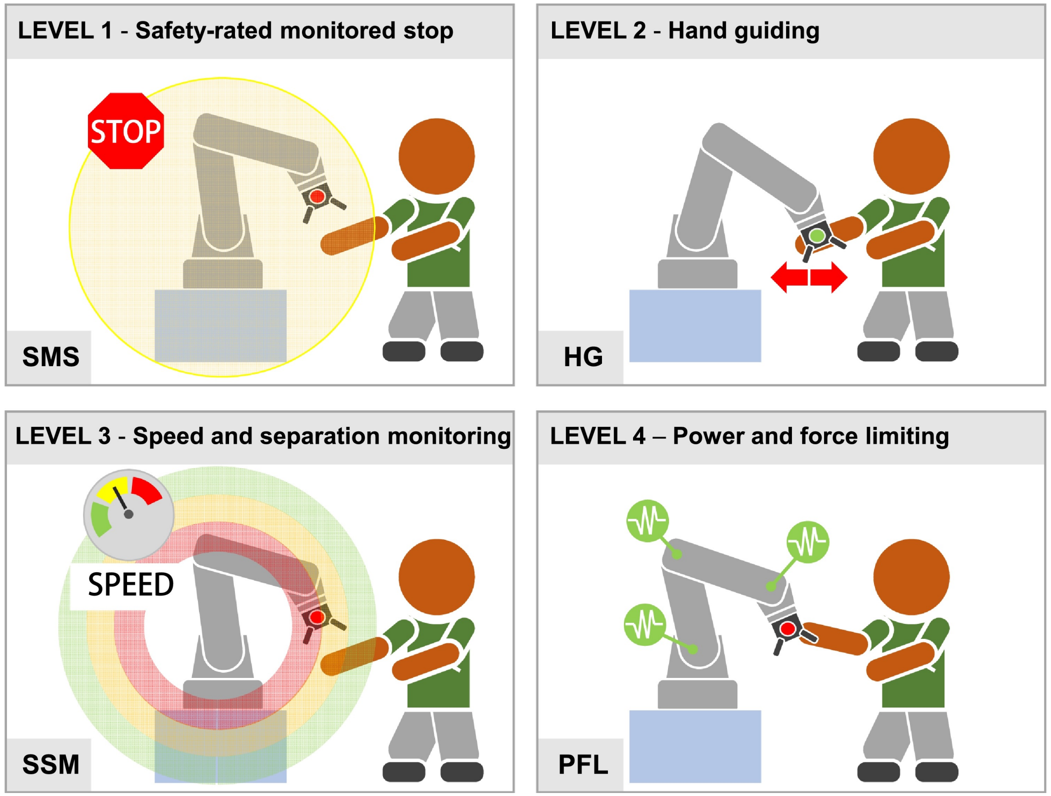


Safety standards in industrial robotics

International
Organization
for Standardization



four basic types of
collaborative operation



Villani et al.: Mechatronics, 2018

Safety standards in robotics

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN ISO 10218-1

July 2011

ICS 25.040.30

Supersedes EN ISO 10218-1:2008

English Version

Robots and robotic devices - Safety requirements for industrial robots - Part 1: Robots (ISO 10218-1:2011)

Robots et dispositifs robotiques - Exigences de sécurité pour les robots industriels - Partie 1: Robots (ISO 10218-1:2011)

Industrieroboter - Sicherheitsanforderungen - Teil 1: Roboter (ISO 10218-1:2011)

This European Standard was approved by CEN on 21 April 2011.

CEN members are bound to comply with the CEN/CENELEC Internal Regulations which stipu
Standard the status of a national standard without any alteration. Up-to-date lists and bibliogra
standards may be obtained on application to the CEN-CENELEC Management Centre or to a

This European Standard exists in three official versions (English, French, German). A version
under the responsibility of a CEN member into its own language and notified to the CEN-CEN
status as the official versions.

CEN members are the national standards bodies of Austria, Belgium, Bulgaria, Croatia, Cypru
Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxemb
Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland and United Kingdom.

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Management Centre: Avenue Marnix 17, B-1000 Br

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN ISO 10218-2

July 2011

ICS 25.040.30

English Version

Robots and robotic devices - Safety requirements for industrial robots - Part 2: Robot systems and integration (ISO 10218-2:2011)

Robots et dispositifs robotiques - Exigences de sécurité pour les robots industriels - Partie 2: Systèmes robots et intégration (ISO 10218-2:2011)

Roboter und Robotikgeräte - Sicherheitsanforderungen - Teil 2: Industrierobotersystem und Integration (ISO 10218-2:2011)

This European Standard was approved by CEN on 21 April 2011.

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TECHNICAL SPECIFICATION

ISO/TS 15066

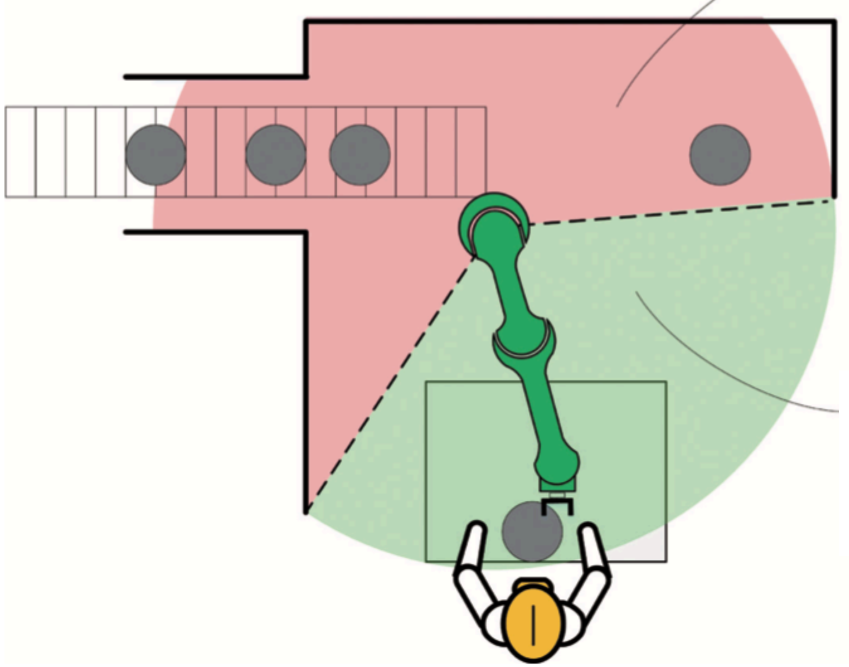
First edition
2016-02-15

Robots and robotic devices — Collaborative robots

Robots et dispositifs robotiques — Robots coopératifs

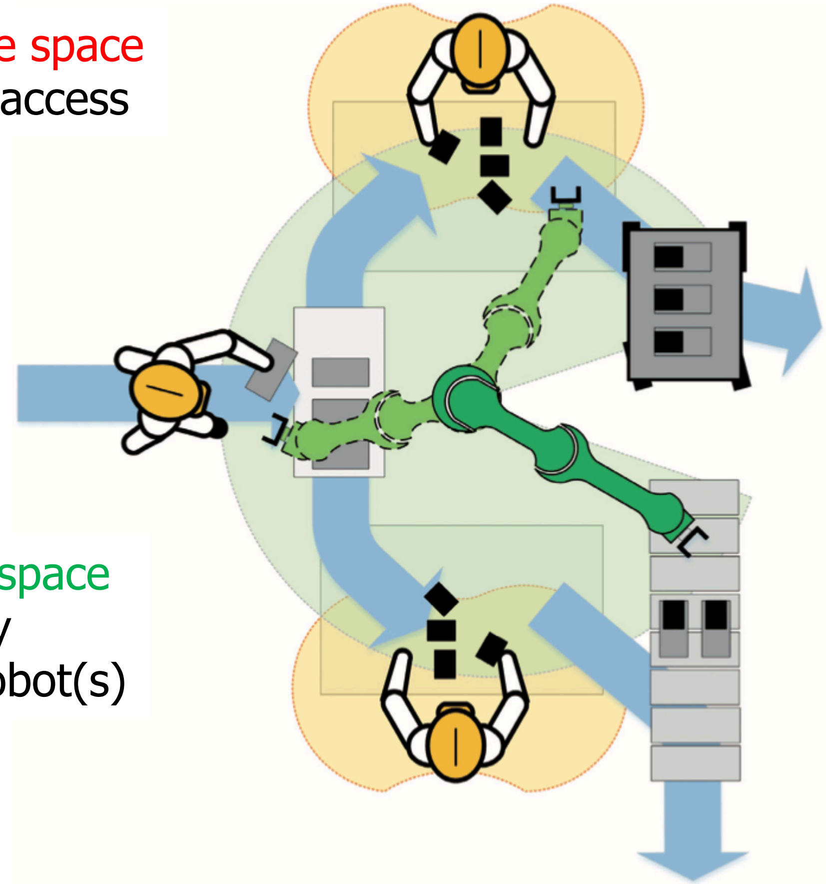
Reference number
ISO/TS 15066:2016(E)

Collaborative spaces



non-collaborative space
protected from access

collaborative space
shared by
human(s) & robot(s)



courtesy of Federico Vicentini, CNR-STIIMA

Handling of risks

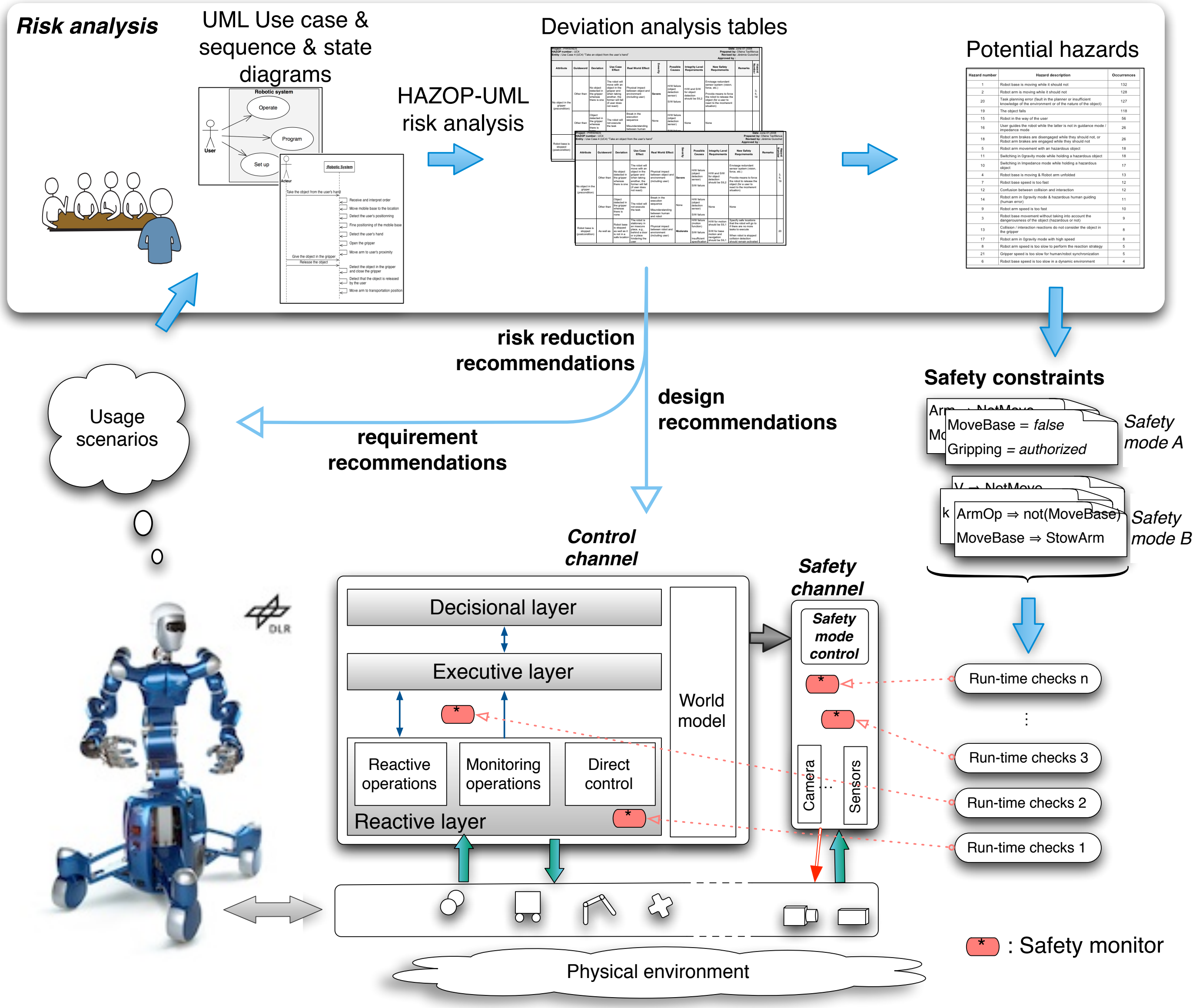
risk analysis

⇩

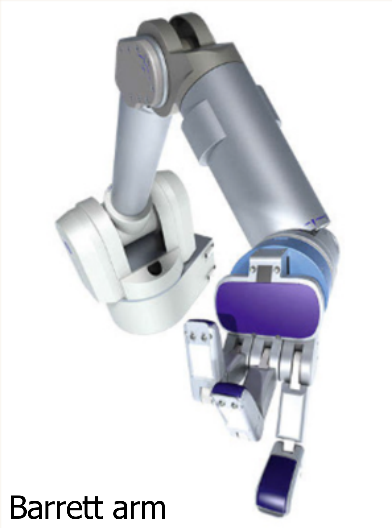
risk assessment and mitigation

⇩

safety monitoring



Human-friendly robot design


Barrett arm


Mitsubishi PA10


DLR LWR III


KUKA LBR iiwa


NASA Robonaut

DLR Rolling Justin


Rethink Robotics Baxter

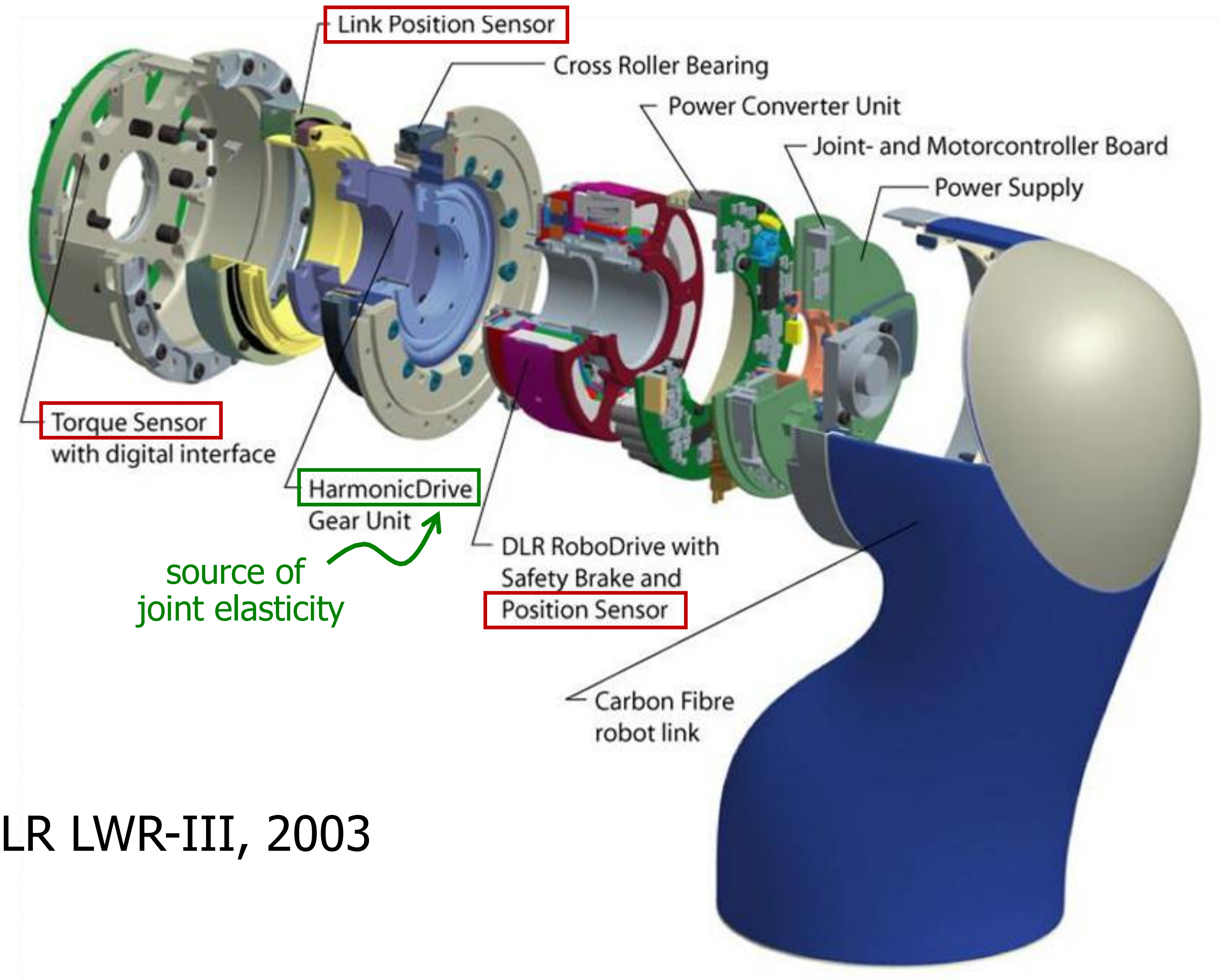


Boston Dynamics ATLAS

Intrinsically flexible design

- robots with lightweight (but rigid) links
- cable- and tendon-driven robotic systems (e.g., hands)
- robots with Serial Elastic Actuators = SEA
  - includes robots with constant joint elasticity (linear or nonlinear)
- robots with Variable Stiffness Actuation = VSA
  - simultaneous change of joint position and stiffness
  - agonistic/antagonistic cooperating motor pairs or …
  - serial macro-mini motors with separate position/stiffness tasks
- robots with Variable Impedance Actuation = VIA
  - allow the change of stiffness and/or damping (and/or even inertia)
- soft continuum robots
  - distributed deformation along the robot body, using soft materials

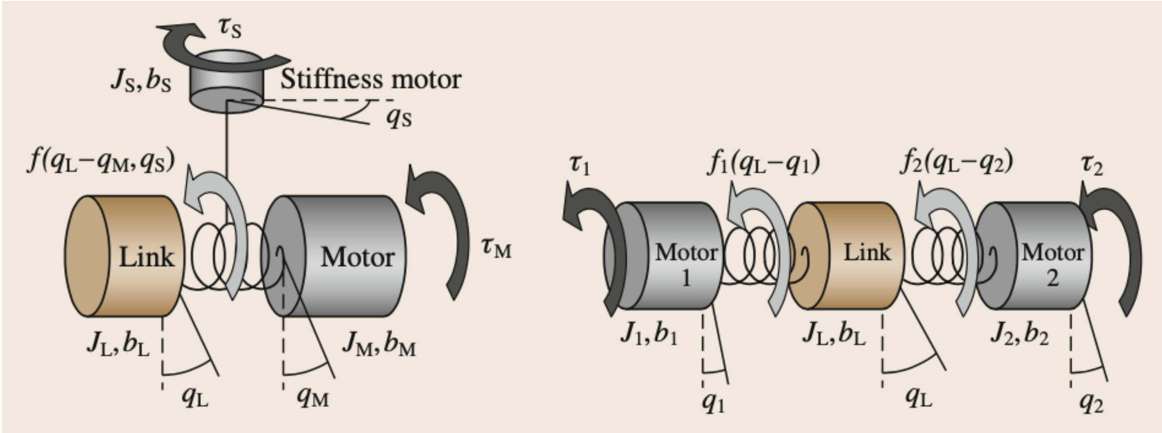
Lightweight robot with compliant joints



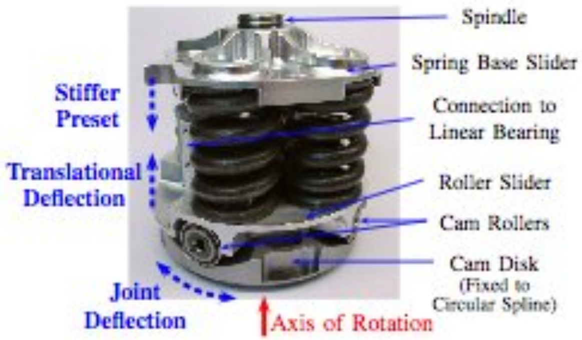
DLR LWR-III, 2003

Variable Stiffness Actuators

serial
VSA

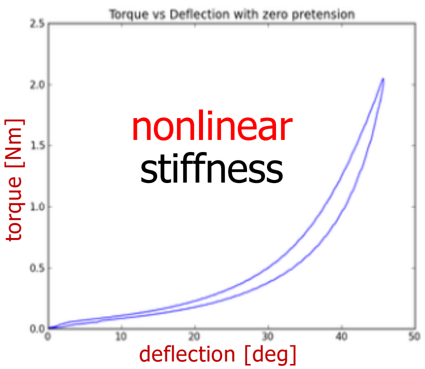


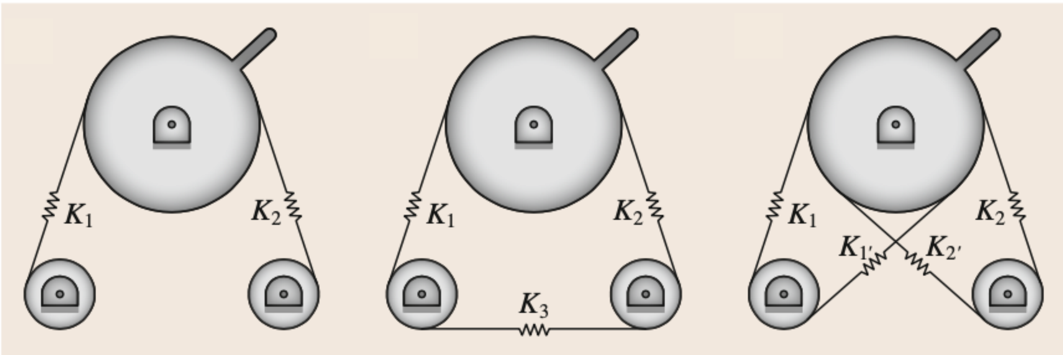
antagonistic
VSA

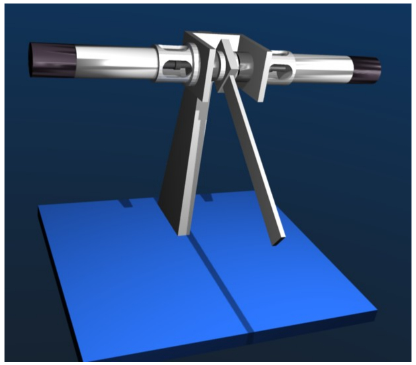


DLR
VS-Joint

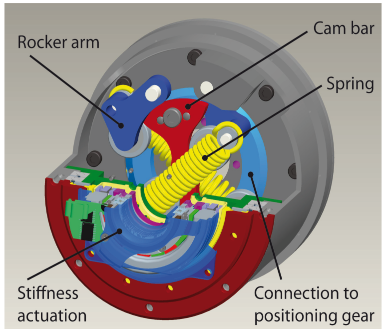
UniPisa
VSA-II

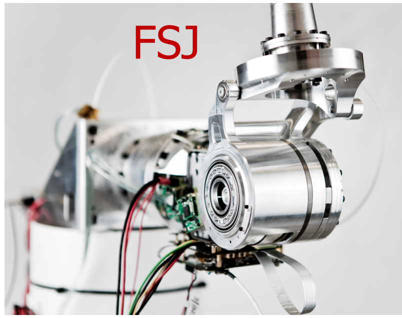






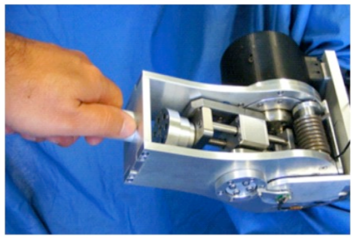
VIA developments





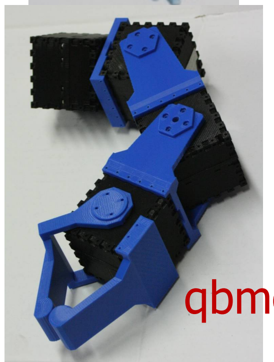
components

VSA-II



AwAS

single arms

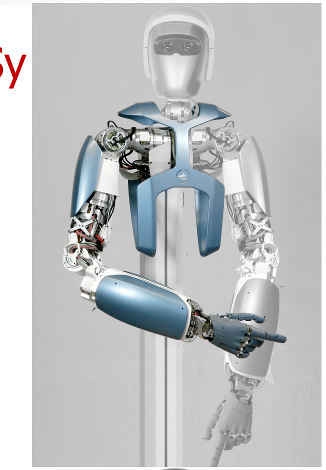


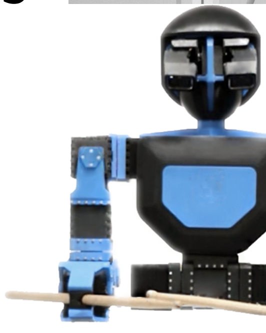
qbmove

CoAct

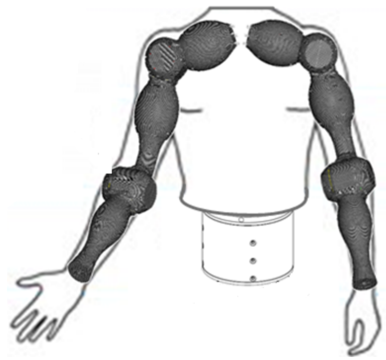
upper bodies

HASy





qbmate



Safety and Dependability

- the "holy grail" in pHRI design is intrinsic safety

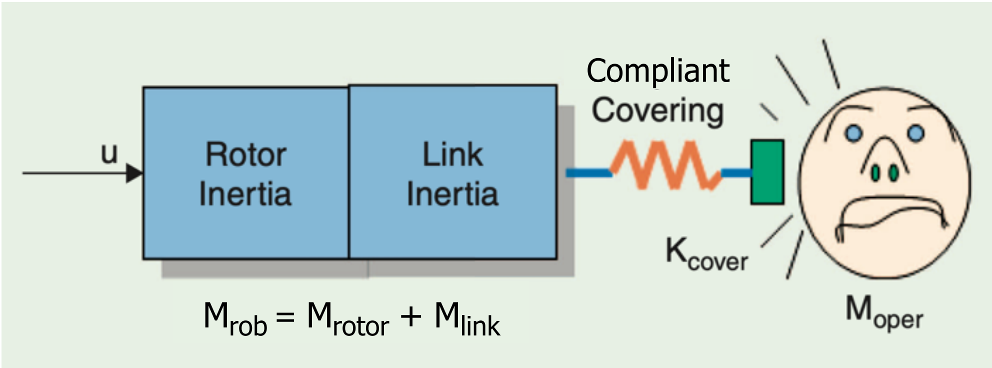
design a robot that will be safe for humans, no matter what failure, malfunctioning, or even misuse might happen

- however, perfect safety against all odds is not feasible for robots that have to deliver traditional performance in terms of payload lifting, fast motion, and accuracy
- the trade-off between safety and performance is in fact the name of the pHRI game
- it would be useful to quantify this trade-off in a neutral way
  - maximizing performance (e.g., a minimum time transfer) and …
  - minimizing risk (e.g., the Head Injury Criterion (HIC) for impacts)
  - optimal control tool: safe brachistochrone

Soft-arm tactics

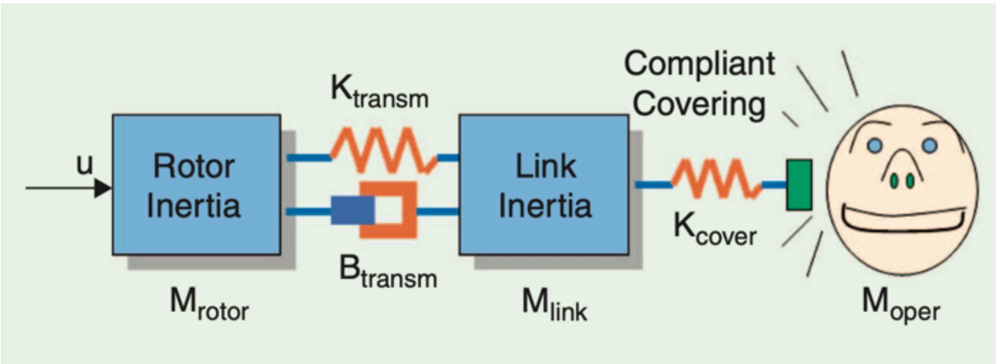
normalized rest-to-rest motion
$$\begin{cases} x_{rob}(0) = 1, x_{rob}(T) = 0 \\ \dot{x}_{rob}(0) = \dot{x}_{rob}(T) = 0 \end{cases}$$

rigid robot



$$\min T = \int_0^T dt$$
$$M_{rob}\ddot{x}_{rob} = u$$
$$|\dot{x}_{rob}| \leq v_{safe}$$
$$|u| \leq U_{max}$$
$$v_{safe} = \left(\frac{HIC_{max}}{\beta(M_{rob}, M_{oper}, K_{cover})}\right)^{2/5}$$

elastic joint robot



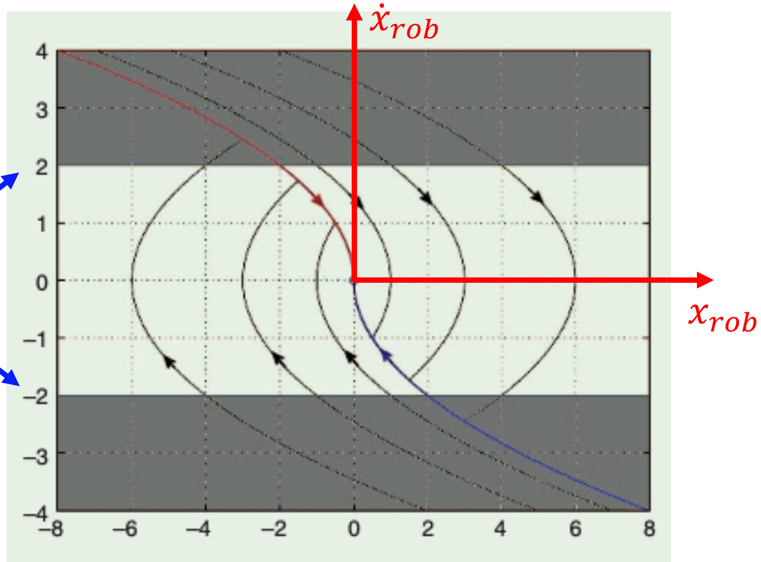
$$\min T = \int_0^T dt$$
$$M_{rot}\ddot{x}_{rot} + K_{transm}(x_{rot} - x_{link}) = u$$
$$M_{link}\ddot{x}_{link} + K_{transm}(x_{link} - x_{rot}) = 0$$
$$|\dot{x}_{link}| \leq v_{safe}(K_{transm})$$
$$|u| \leq U_{max}$$

Bicchi, Tonietti: IEEE Robotics and Automation Magazine, 2004

Soft-arm tactics

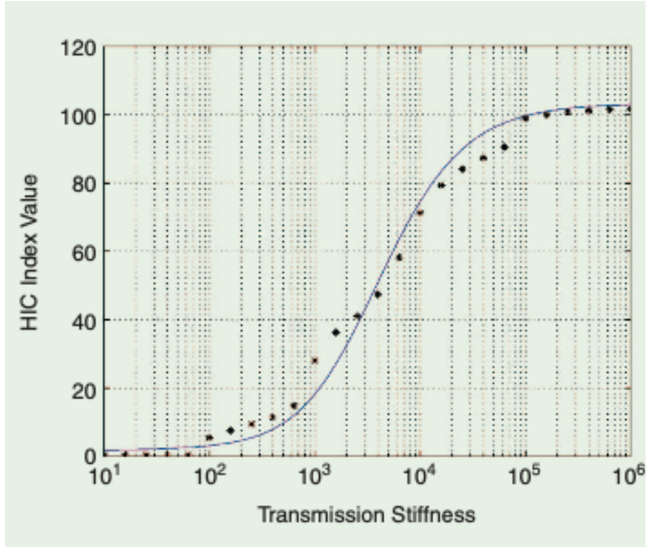
rigid robot

$\pm v_{safe}$



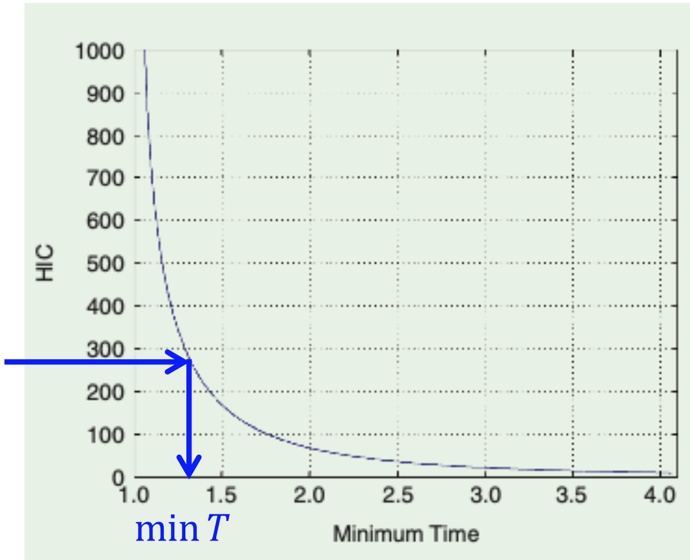
safe brachistochrone: analytic solution

elastic joint robot



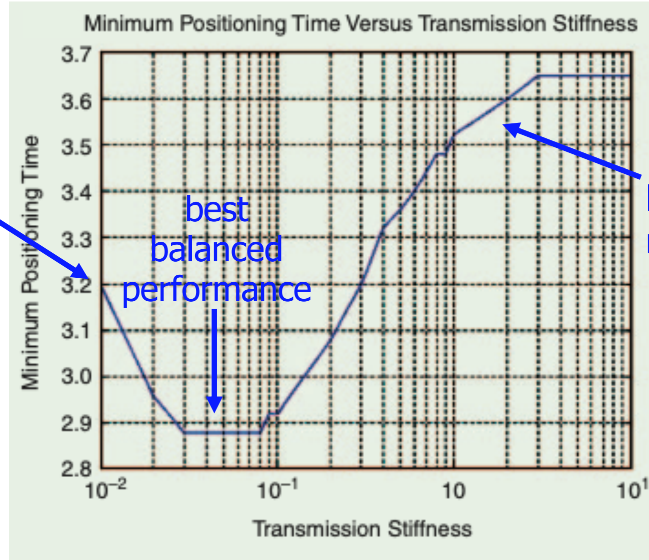
all the rest being equal, HIC increases with K_{transm}

HIC_{max}



$\min T$

low due to reduced mechanical bandwidth



low due to reduced v_{safe}

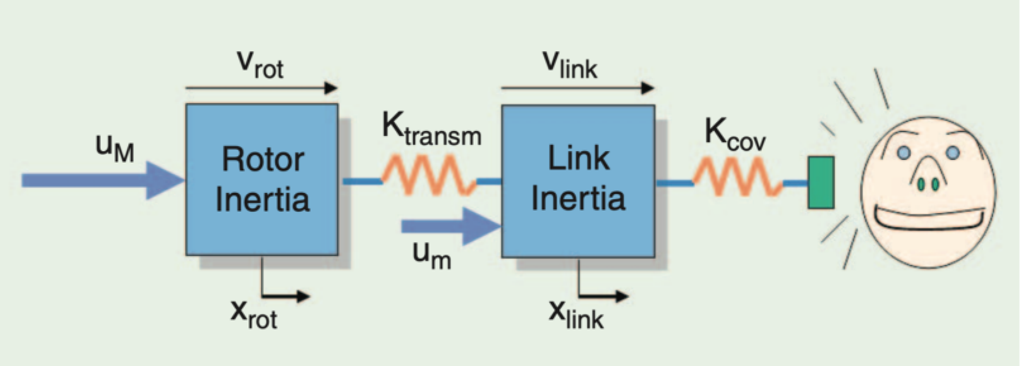
change of performance with K_{transm}

Soft-arm tactics

normalized rest-to-rest motion

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

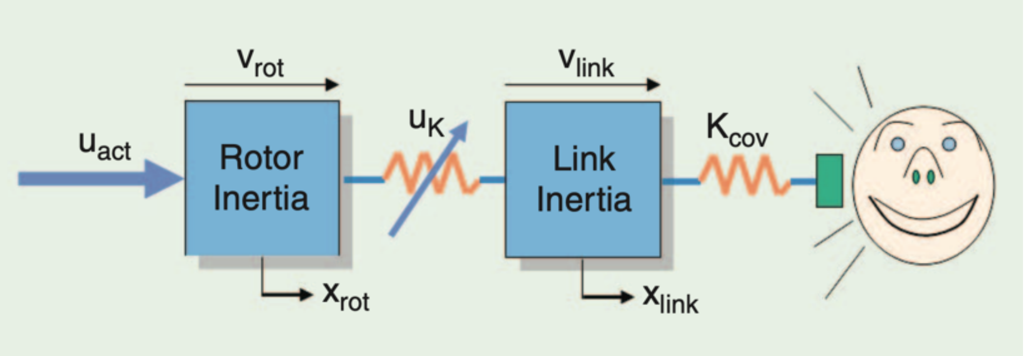
DM[2] robot



$$\min T = \int_0^T dt$$

$$M_{rot}\ddot{x}_{rot} + K_{transm}(x_{rot} - x_{link}) = u_M$$
$$M_{link}\ddot{x}_{link} + K_{transm}(x_{link} - x_{rot}) = u_m$$
$$|\dot{x}_{link}| \le v_{safe}(K_{transm})$$
$$|u_m| \le U_{m,max} \quad |u_M| \le U_{M,max}$$

VSA joint

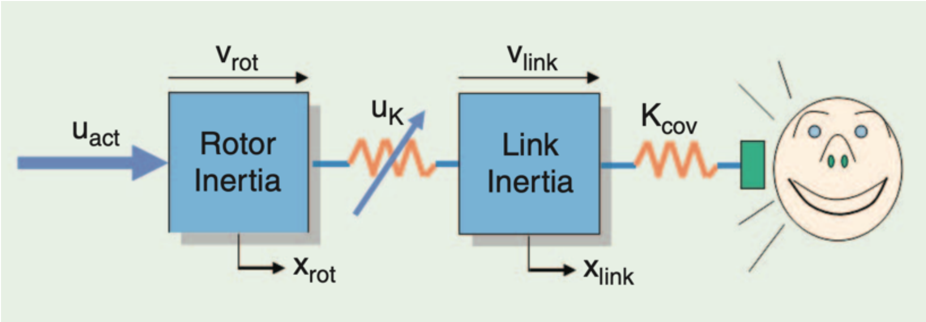


$$\min T = \int_0^T dt$$

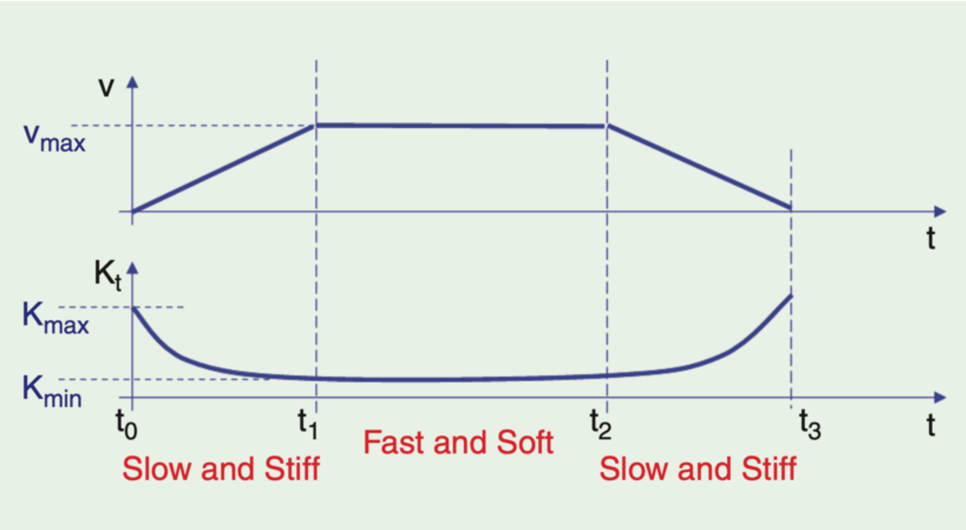
$$M_{rot}\ddot{x}_{rot} + u_K(x_{rot} - x_{link}) = u_{act}$$
$$M_{link}\ddot{x}_{link} + u_K(x_{link} - x_{rot}) = 0$$
$$|\dot{x}_{link}| \le v_{safe}(u_K)$$
$$u_{K,min} \le u_K \le u_{K,max} \quad |u_{act}| \le U_{max}$$

VSA soft-arm tactics and applications

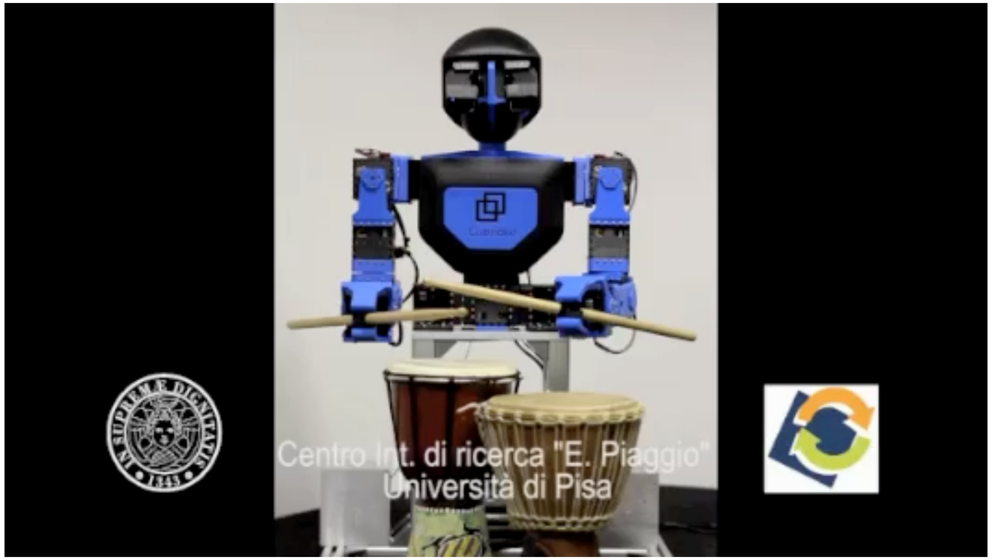
VSA joint



video



qualitative optimal control solution of brachistochrone problem for the VSA



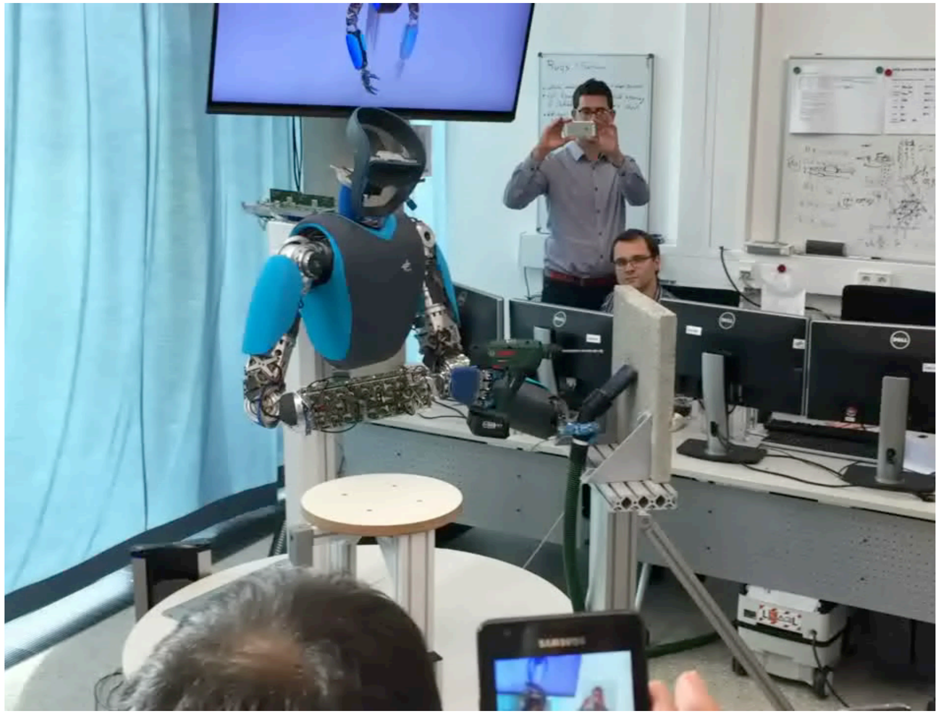
Uni Pisa VSA-Cube
low-cost modular system:
adaptive, energy efficient, robust

Absorbing vibrations!

https://youtu.be/Z2gMFtHb6Y8

video from web

video

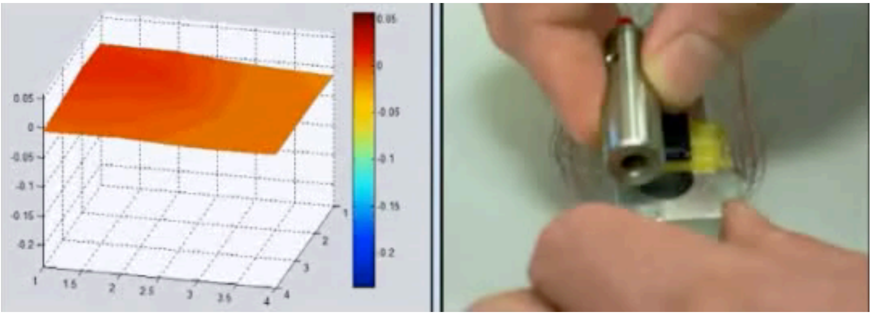


SAPHARI
Safe and Autonomous Physical Human-Aware Robot Interaction

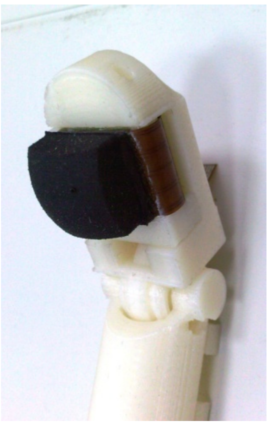
DLR HASy VSA-based robot drilling a hole on a concrete (@ final project meeting, Dec 2015)

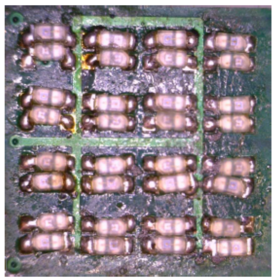
Perception for interaction

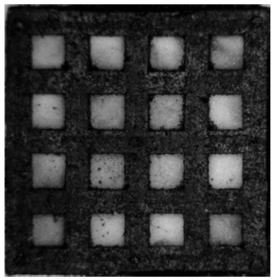
- proprioceptive and contact sensing
  - joint torque and tendon force sensing, stiffness sensing (indirect or by estimation), Force/Torque (F/T) sensors (in fingers and at the tip)
  - tactile sensing for distributed contact measurement

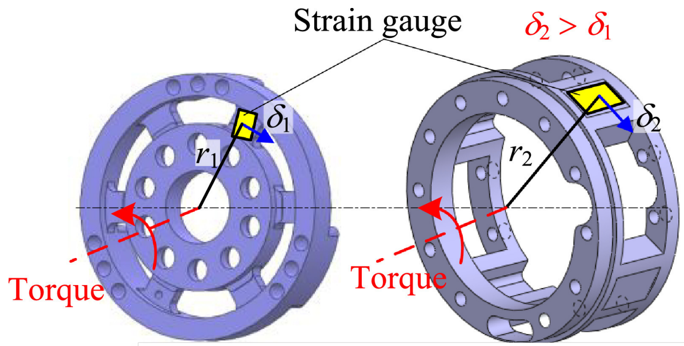


video

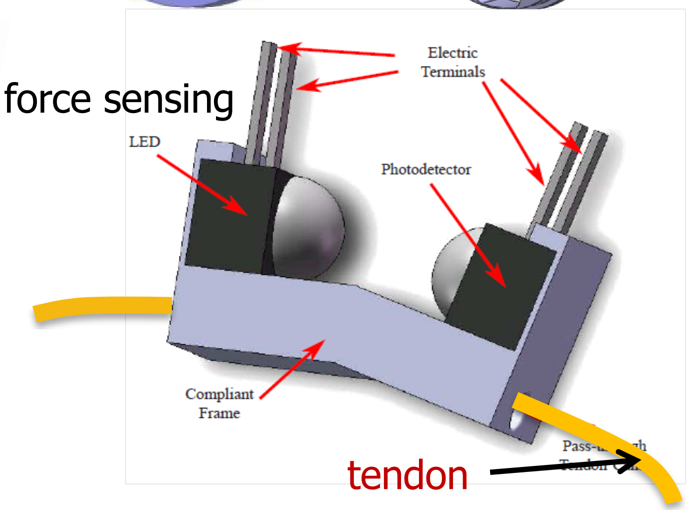






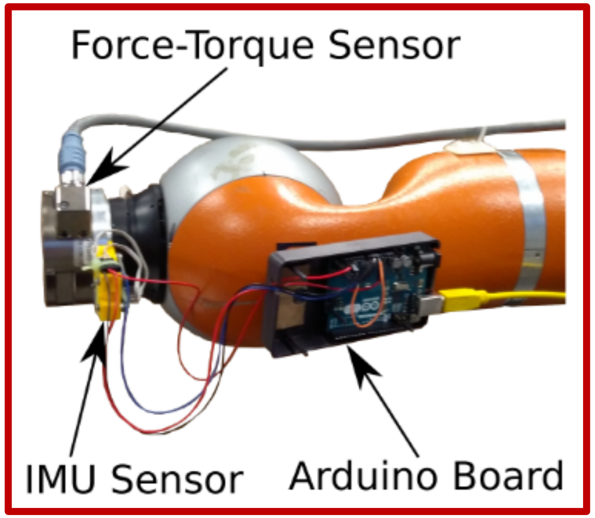


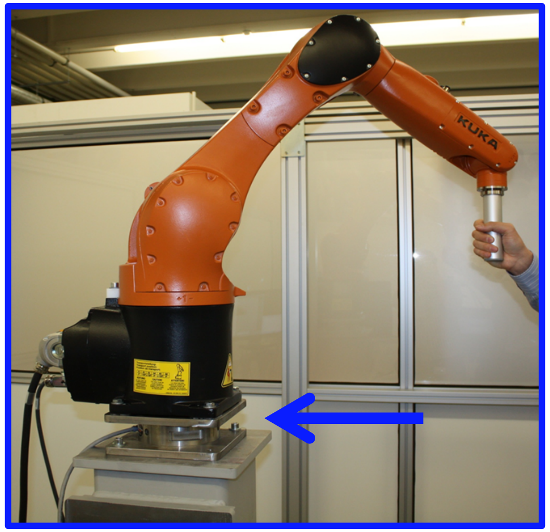
force sensing

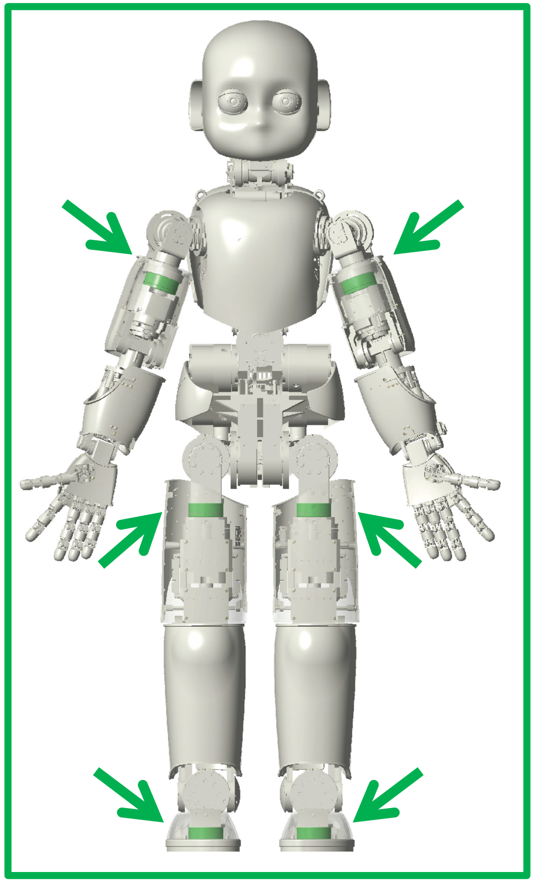


Perception for interaction

- F/T sensors at the end-effector, link, and/or base levels







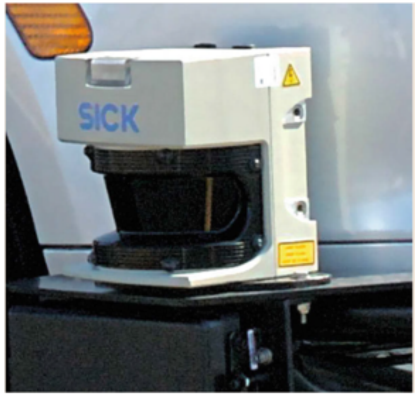
pHRI based on a F/T sensor

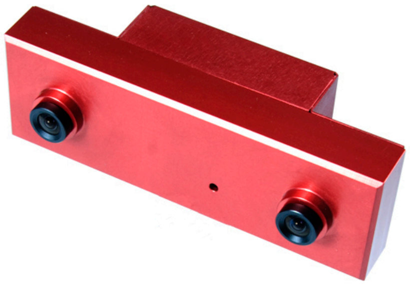
video

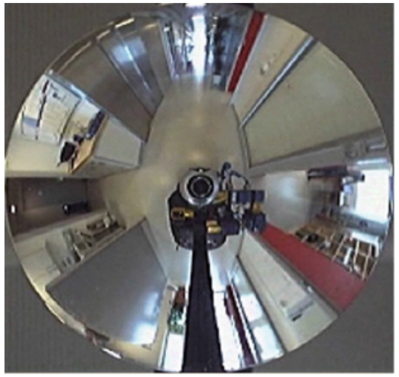
Robotiq 6D F/T sensor + gripper

Perception for interaction

- exteroceptive sensing
  - laser scanners, proximity sensors (magnetic, ultrasound, …)
  - cameras (single, stereo, catadioptric, event-based, …), Vicon system

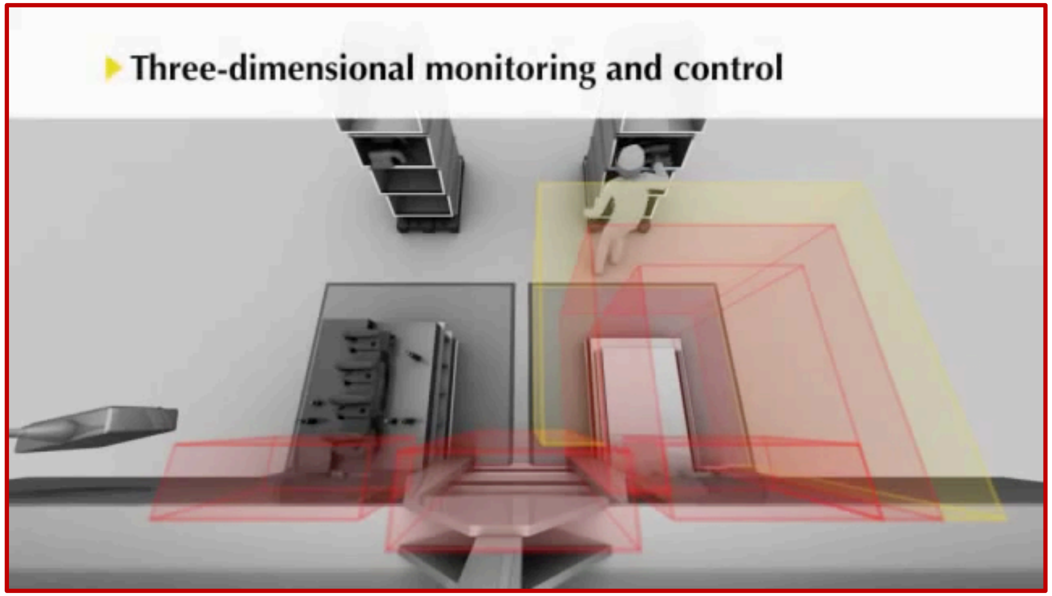






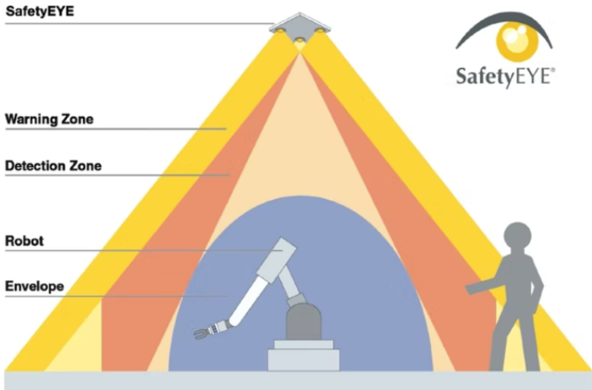


Perception for interaction



SafetyEYE commercial animation by Pilz

https://youtu.be/YHEEeBerqUk



- 3D monitoring camera(s) with safety zones

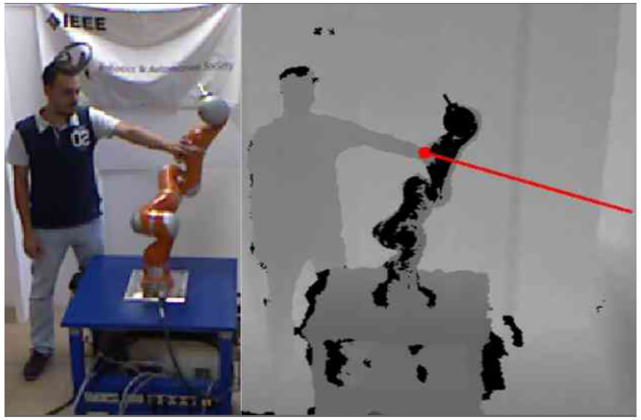
https://youtu.be/dVVvoxDDkT8

video

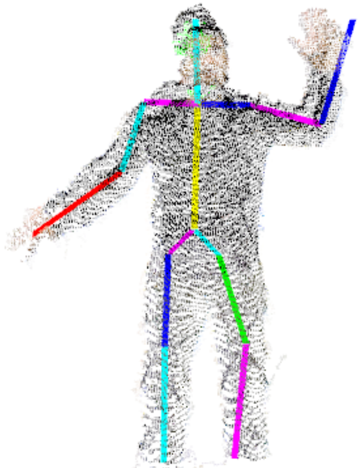
Politecnico Milano

Perception for interaction

- exteroceptive sensing
  - depth and RGB-D sensing (Kinect, Asus)

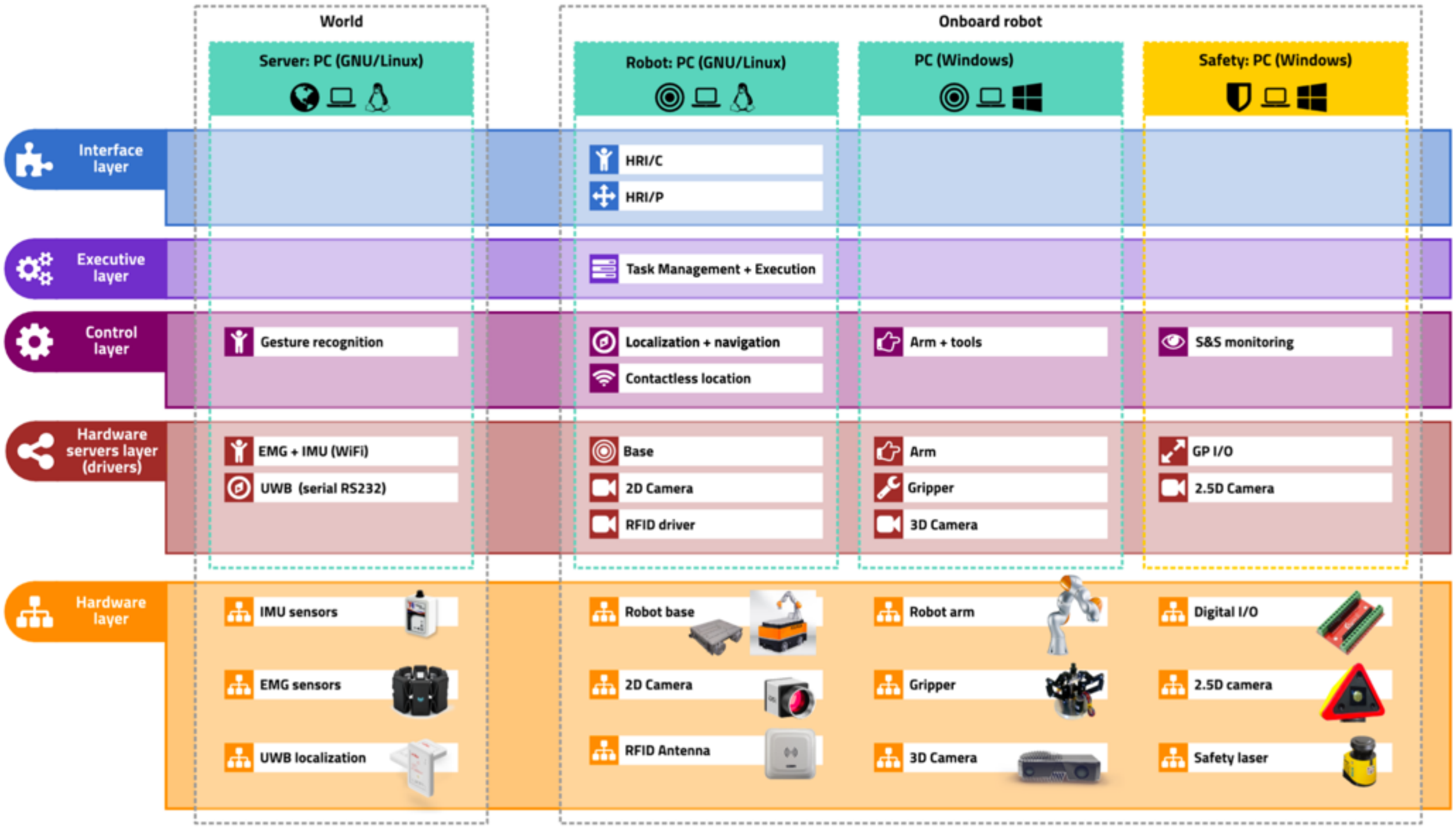


depth image and human-robot distance computation



Point Cloud Library and human skeleton reconstruction

Software integration for HRI

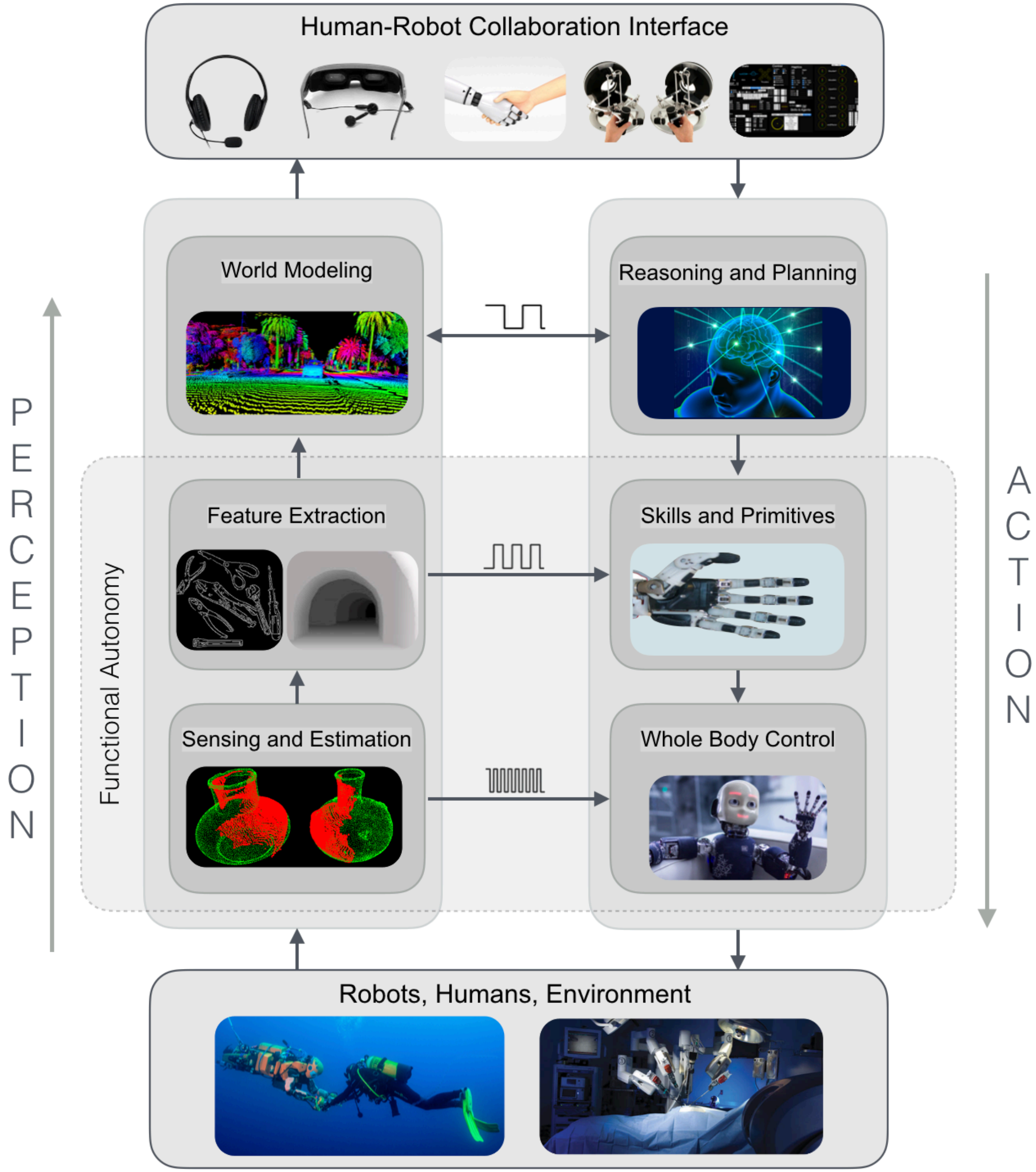


An architecture for perception-to-action

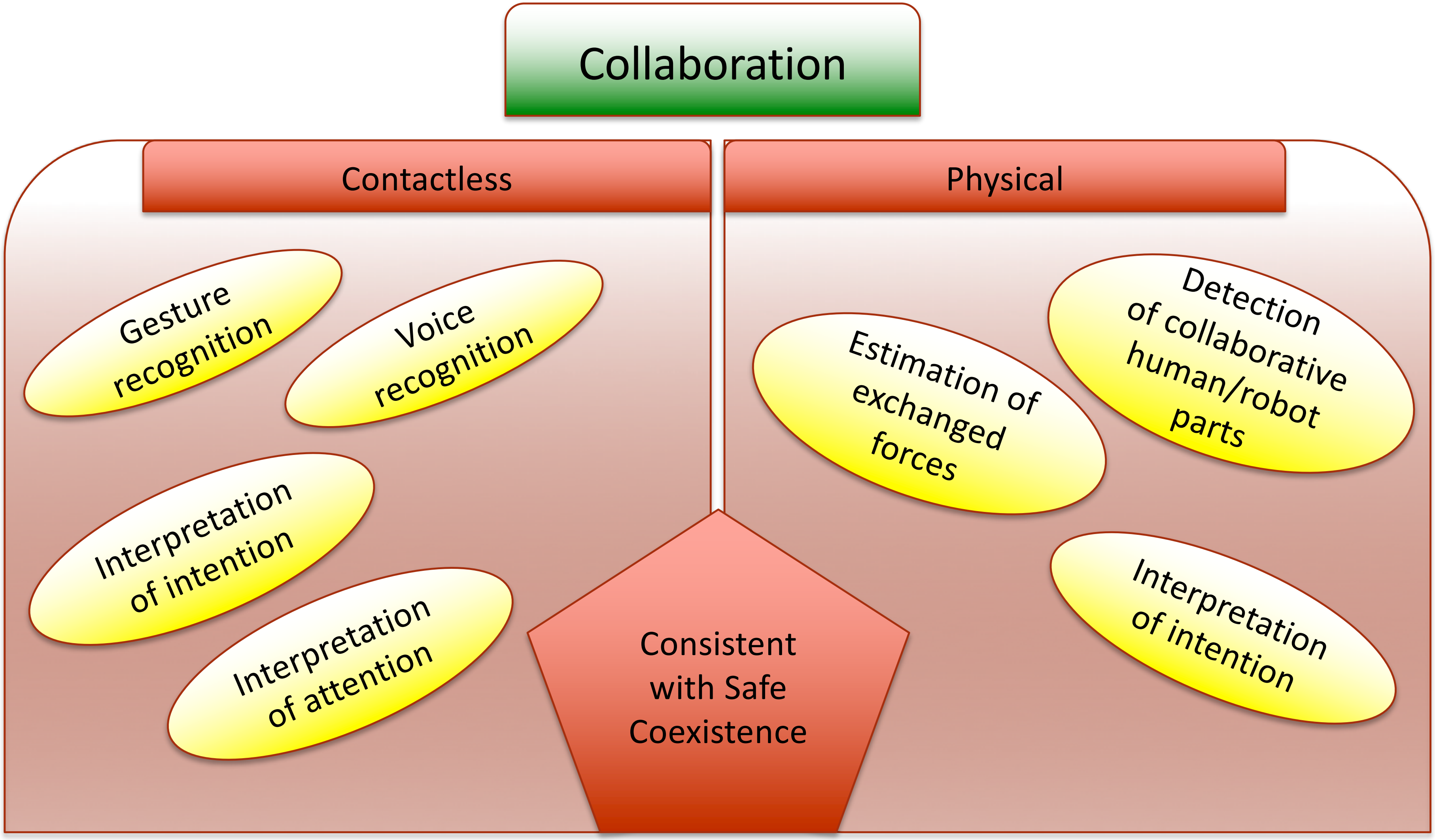
Connecting
Perception-to-Action
and
Human-to-Robot

Collaborative
Multi-Layered
Robot Control Architecture

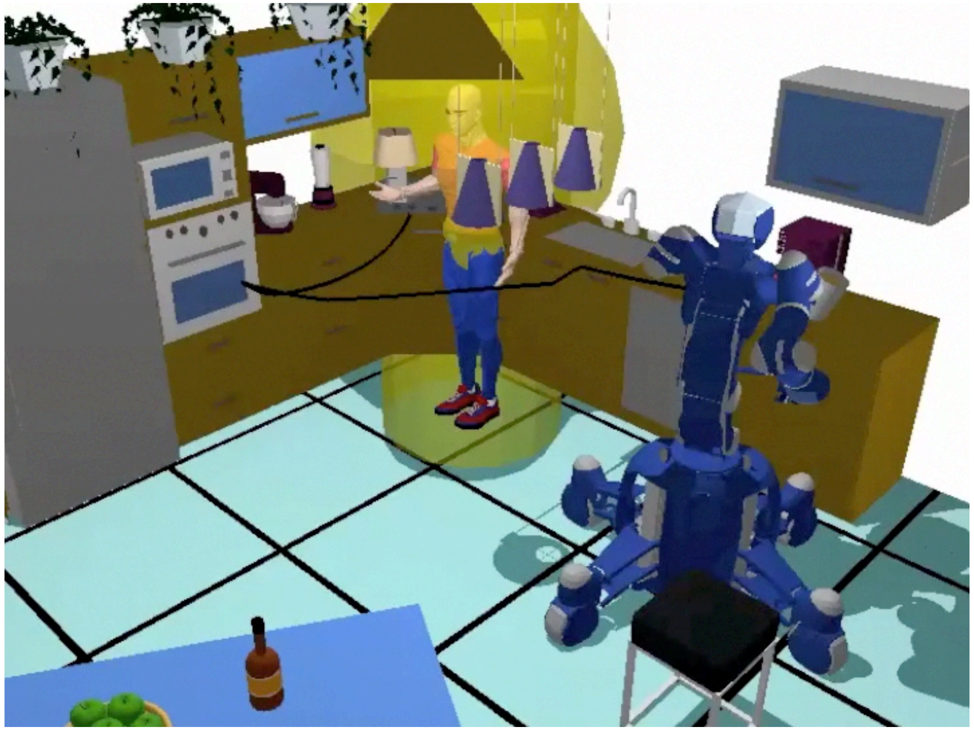
courtesy of Oussama Khatib, Stanford



A control architecture for collaboration



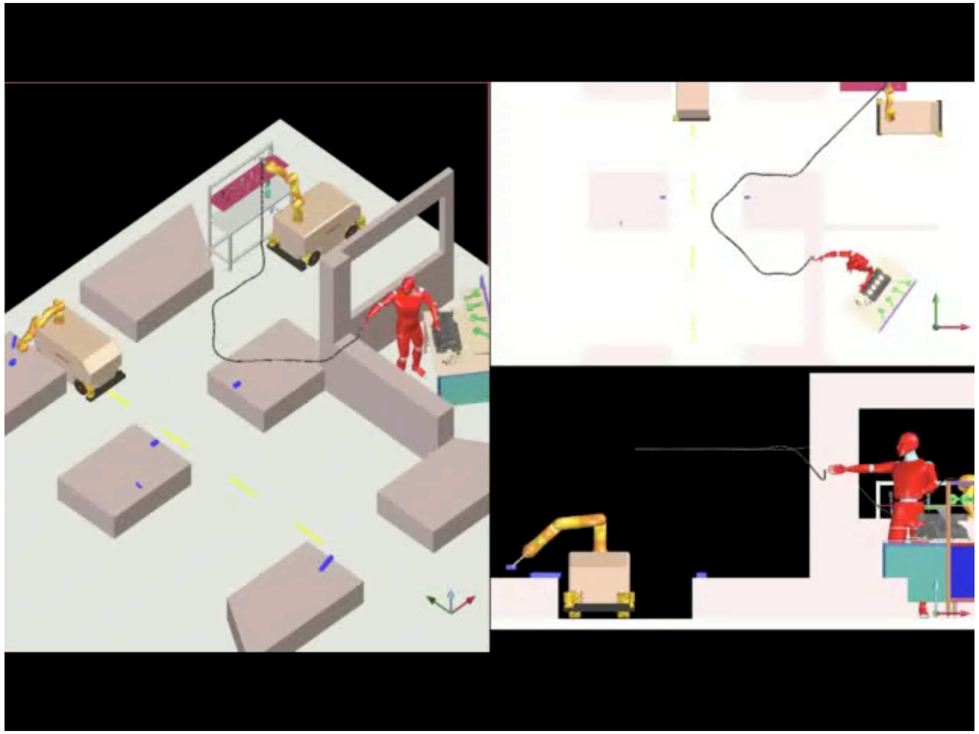
Human-aware motion planning



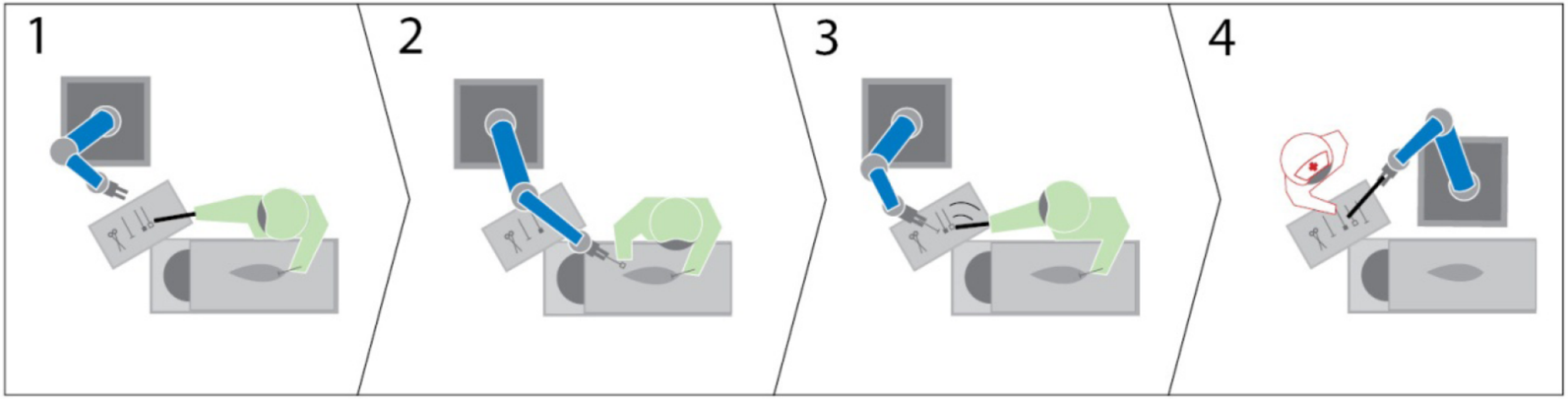
video of DLR wheeled Justin
@CNRS-LAAS, Toulouse

both are **randomized**
motion planners

video of two KUKA OmniRob
mobile manipulators @DIAG, Roma



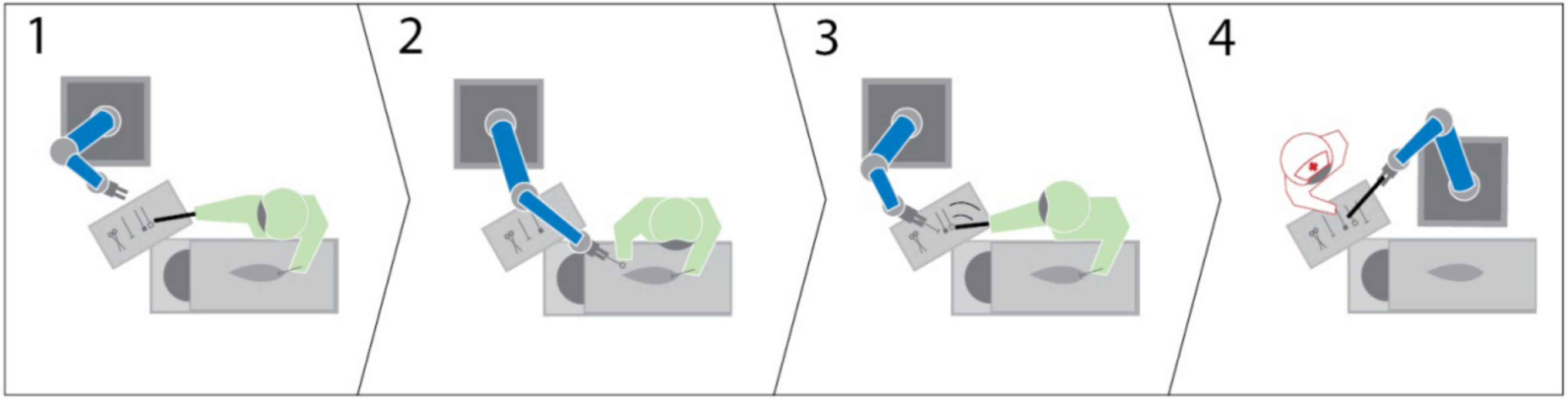
Handover of surgical instrument



learning

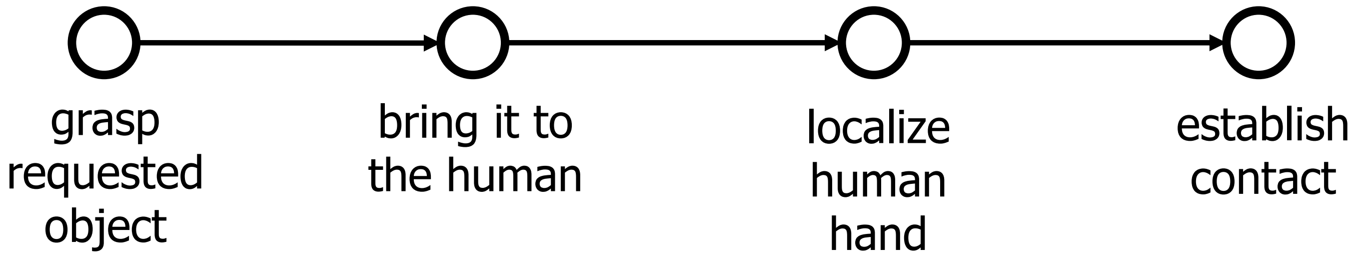
- learning subtask structures
- learning trajectories
- learning contact force/stiffness profiles

Handover of surgical instrument

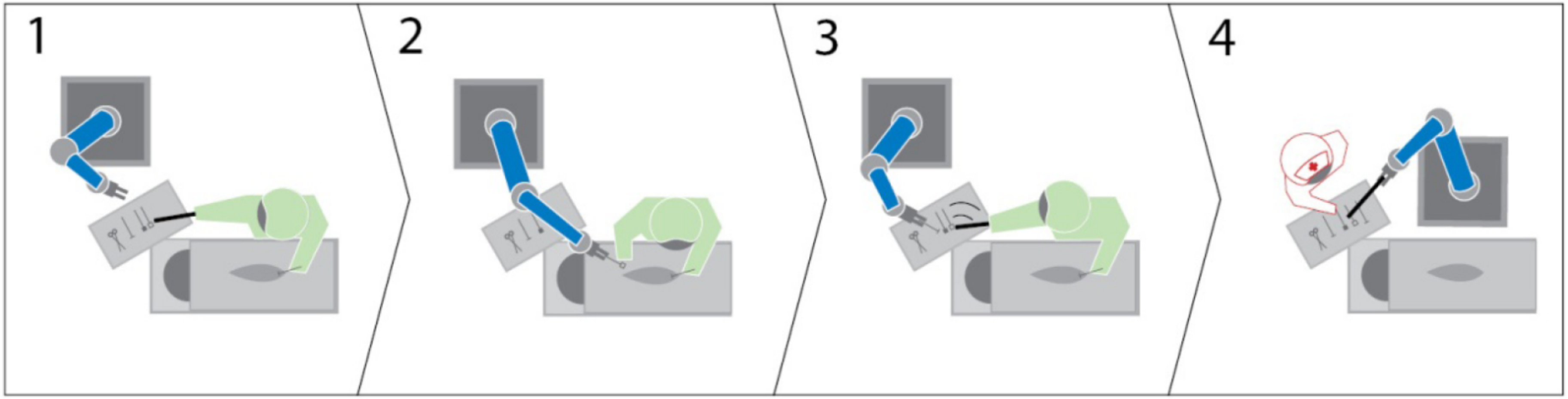


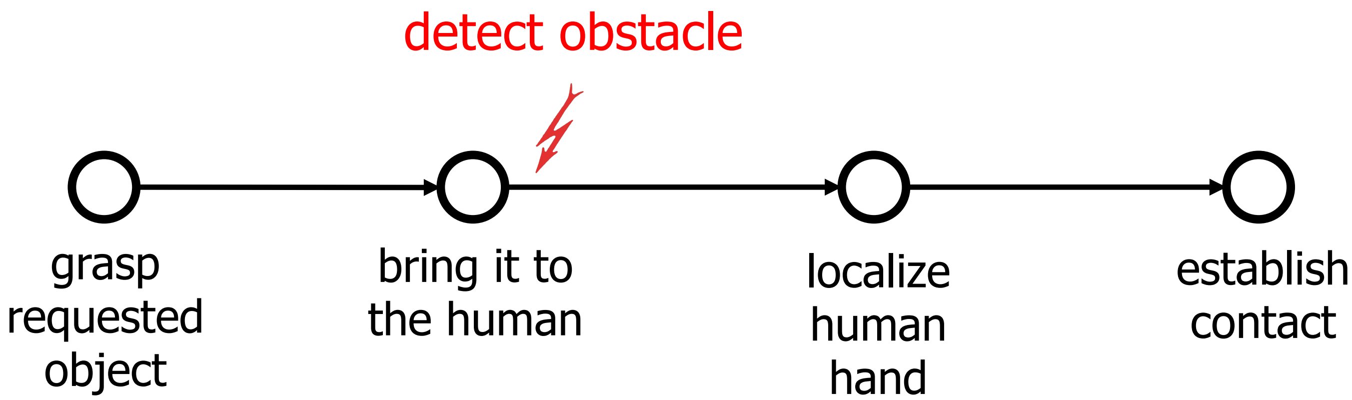
task and motion planning

- global nominal plan
- global nominal trajectories

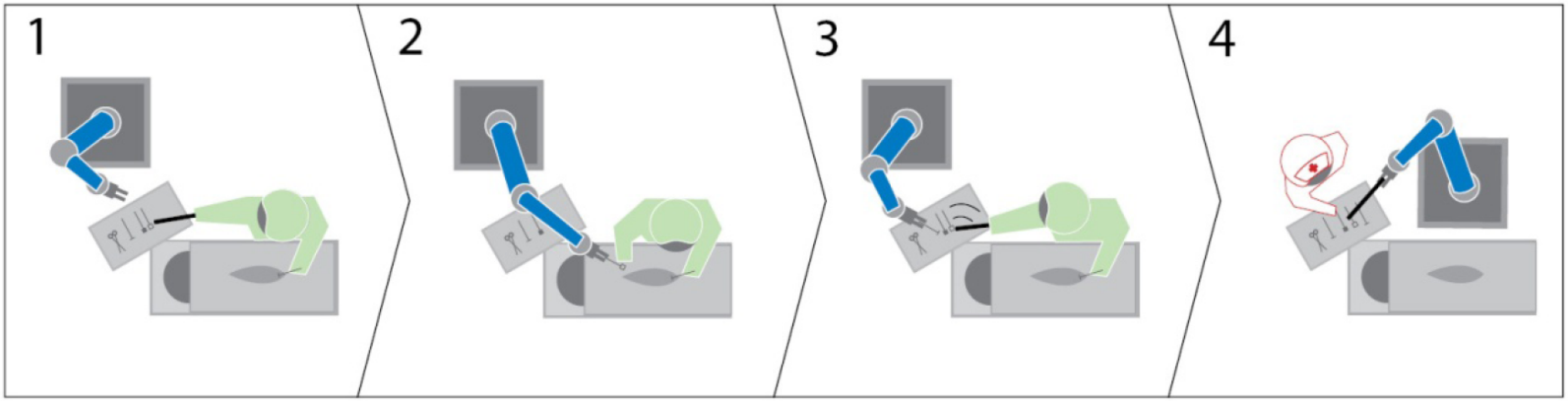


Handover of surgical instrument

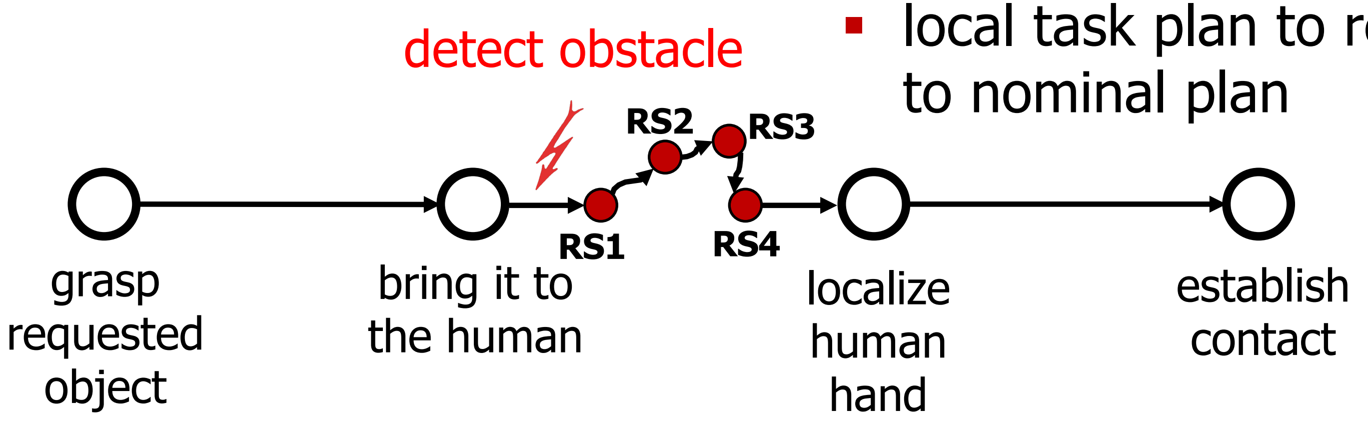




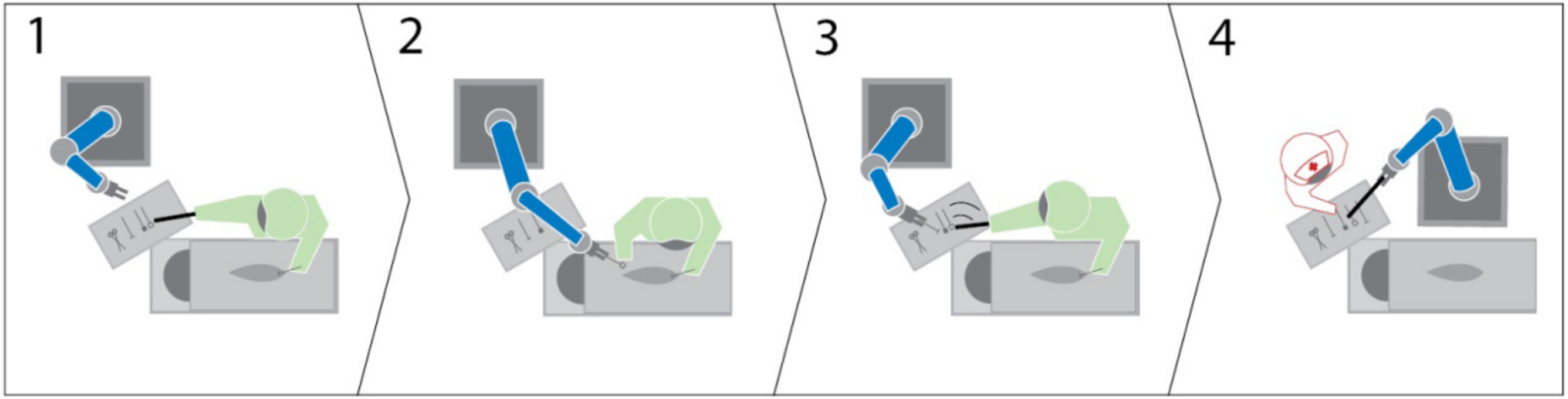
Handover of surgical instrument



- re-plan trajectory locally
- local task plan to return to nominal plan

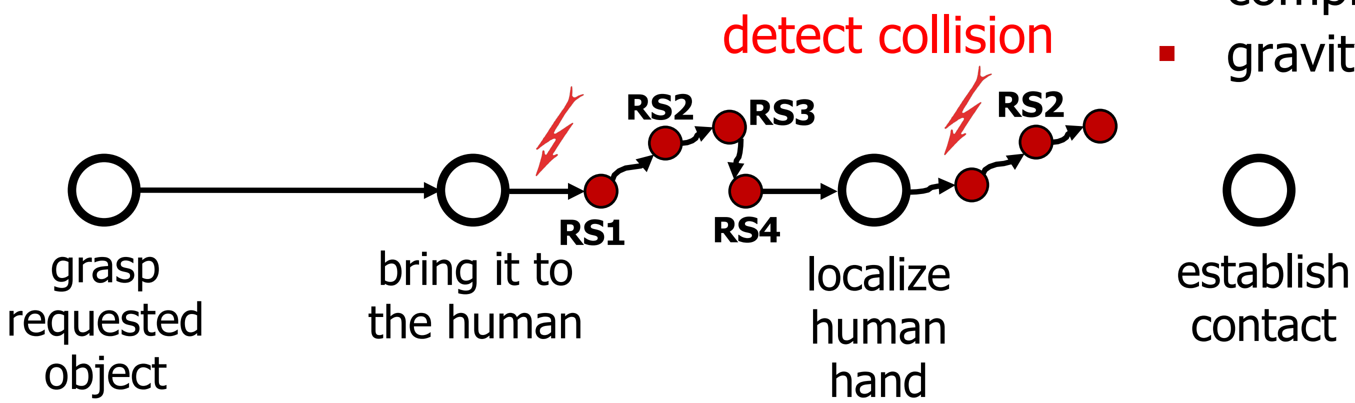


Handover of surgical instrument

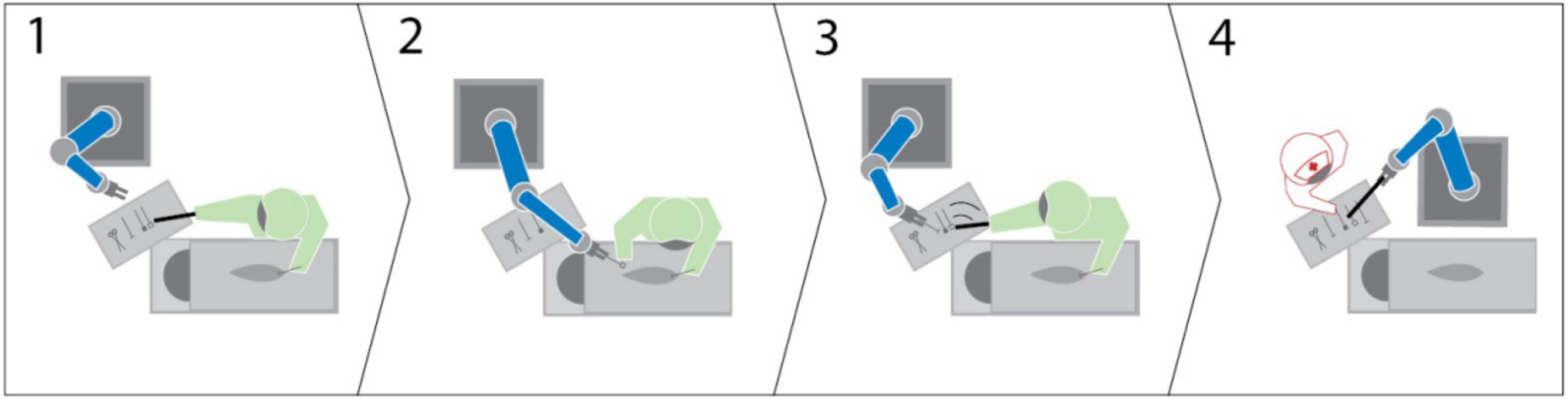


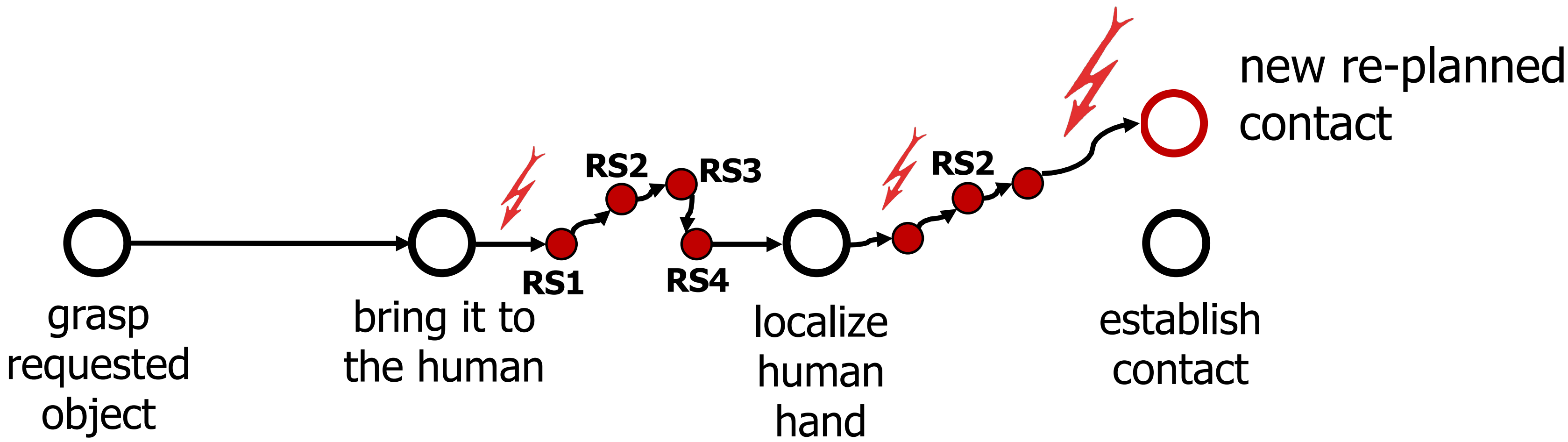
situation-dependent switching to

- trajectory scaling
- compliant mode
- gravity compensation

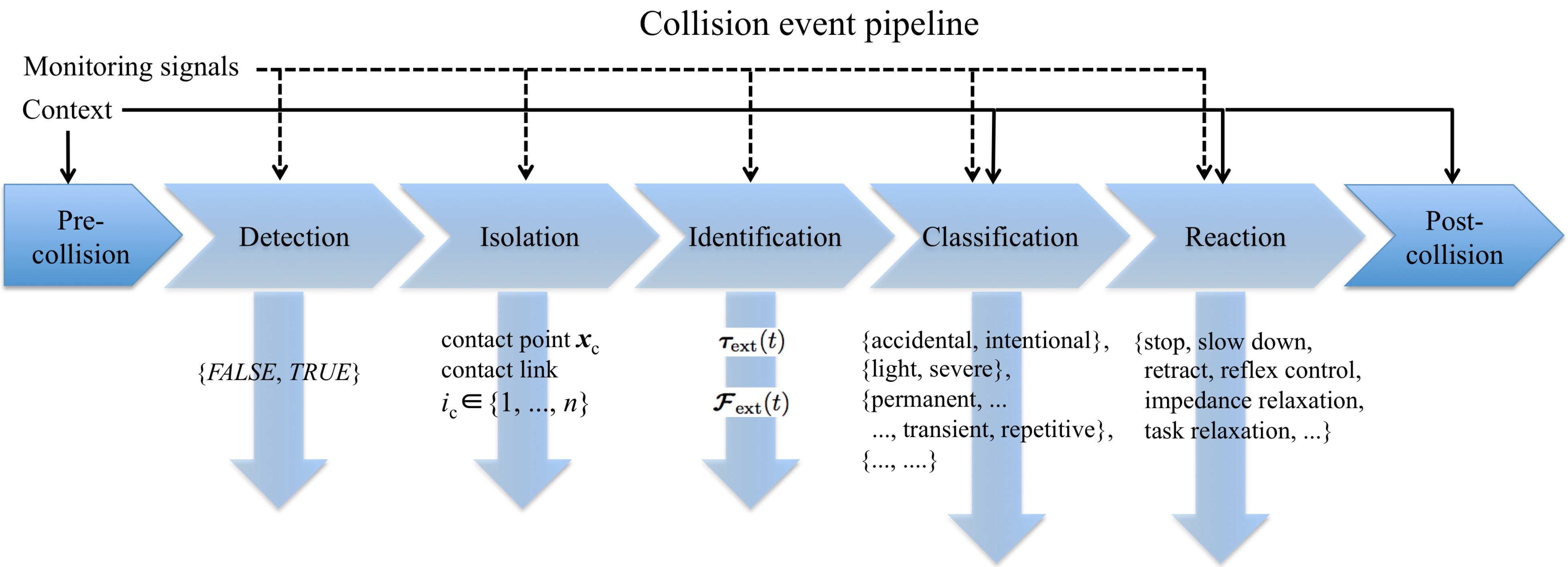


Handover of surgical instrument





Collision event pipeline

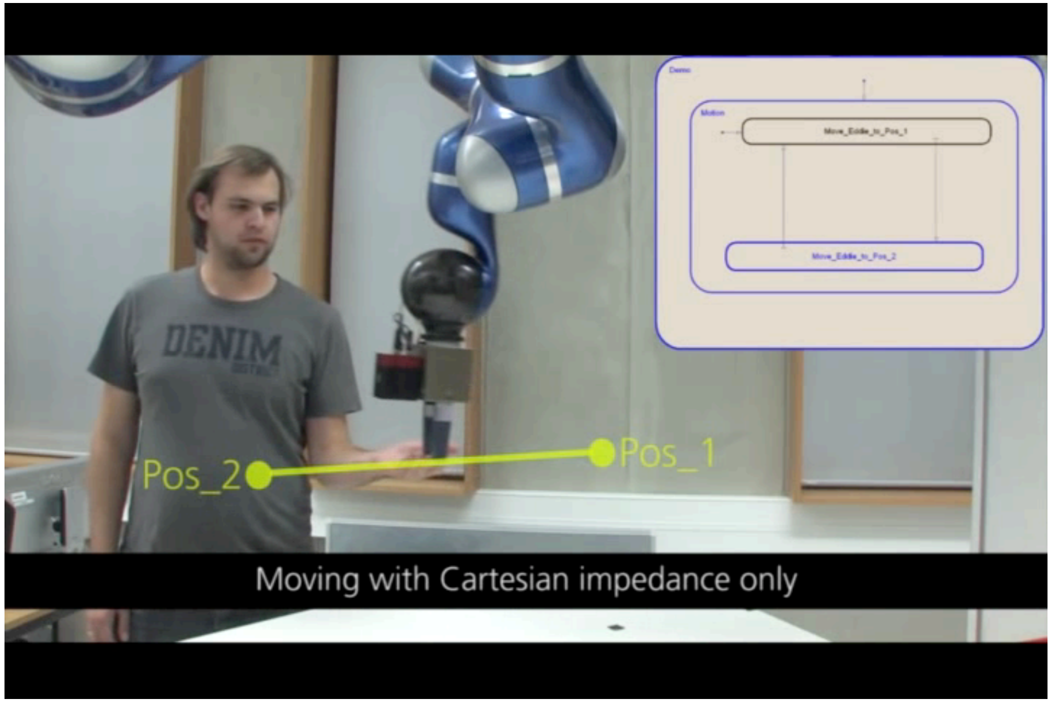


Haddadin, De Luca, Albu-Schäffer: IEEE Trans. on Robotics, 2017

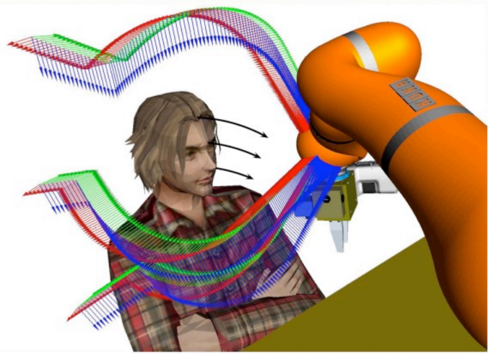
Collision detection and reaction

video

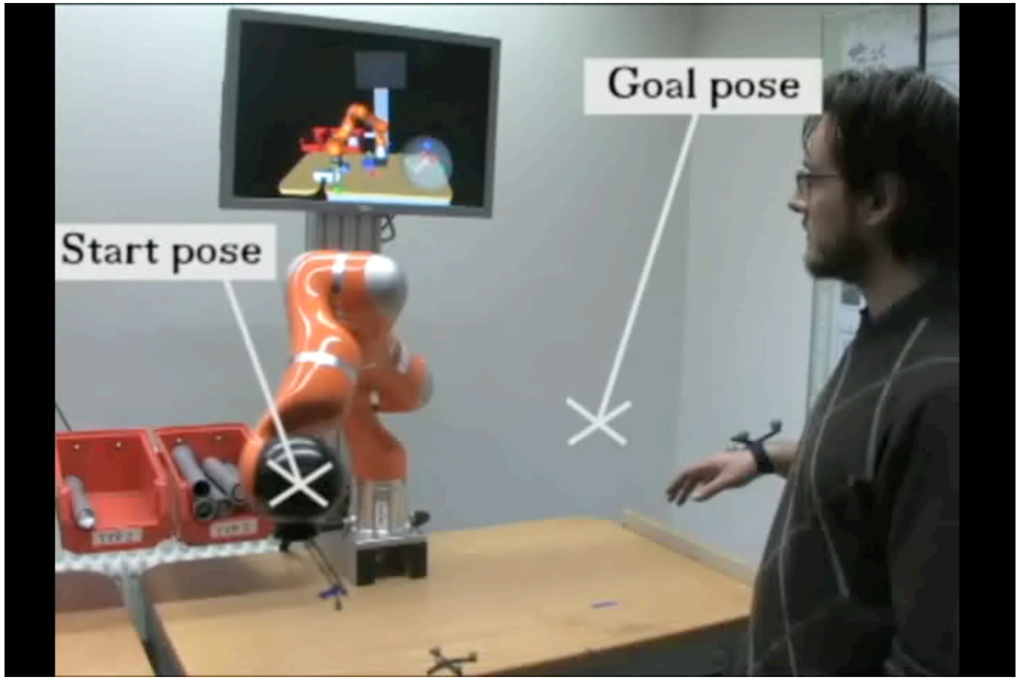
video



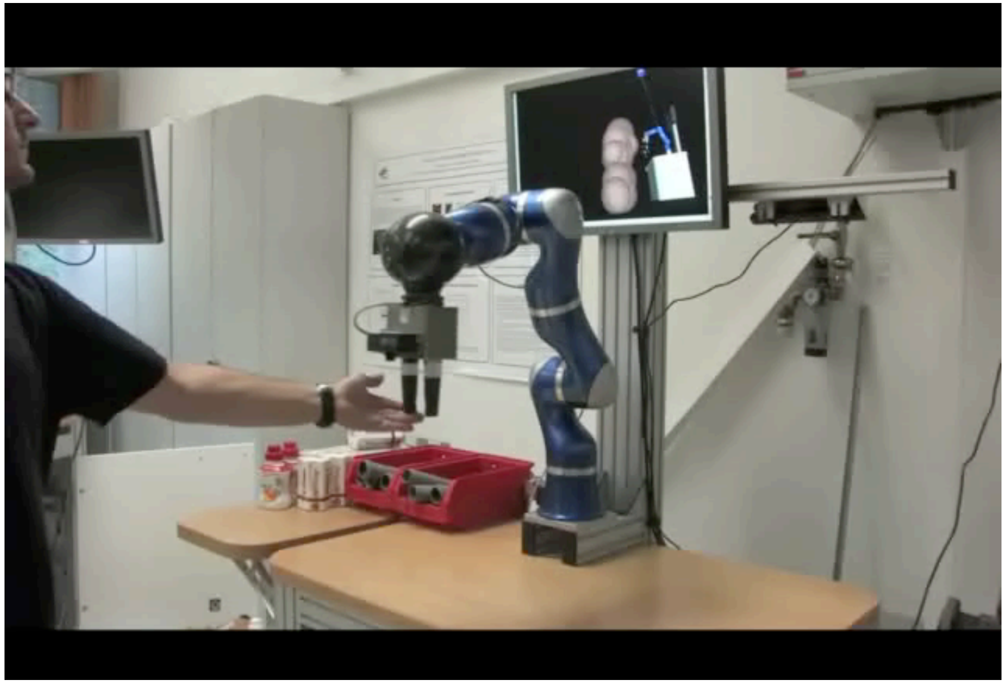
Collision avoidance and coexistence



video



video



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