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*IROS 2018 Workshop on Robot Safety:*

*Filling the Gap Between Technology Offer and Industry Needs for a Fully Deployable Human Robot Collaboration*

# Experiences with a control architecture enabling safe human-robot collaboration

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SAPIENZA
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Madrid, October 5, 2018

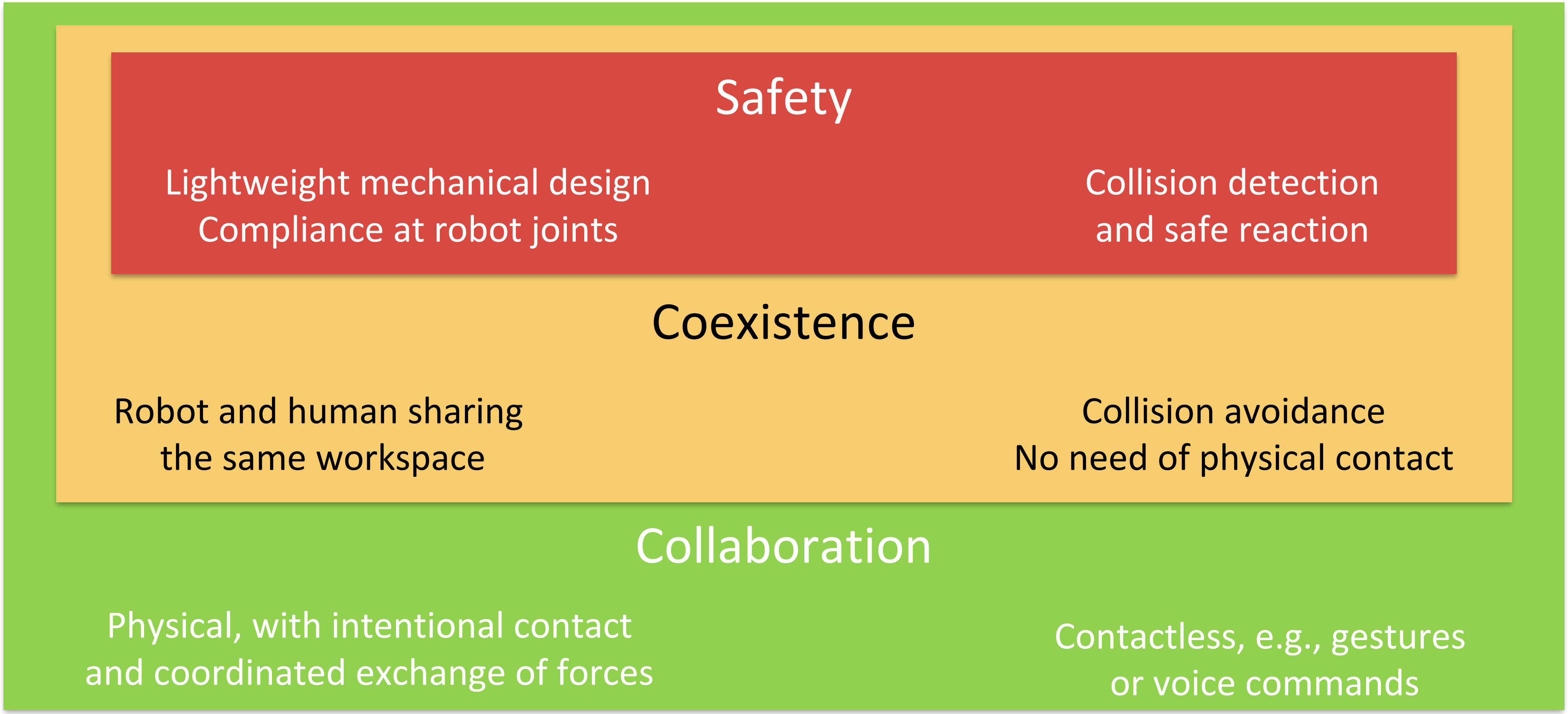
# Summary

- physical Human-Robot Interaction (pHRI)
  - safety, coexistence, and collaboration
- control architecture handling pHRI through consistent robot behaviors
- methods and results with
  - lightweight research manipulators (DLR LWR-III, KUKA LBR 4+)
  - lightweight commercial manipulator (Universal Robots UR10)
  - full-size industrial robot in a cell (ABB IRB 4600)
  - medium-size robot with closed control architecture (KUKA KR5 Sixx)
- lessons learned

SAPHARI
SAFE AND AUTONOMOUS PHYSICAL HUMAN-AWARE ROBOT INTERACTION

SYMPLEXITY

# Hierarchical control architecture of consistent behaviors for safe pHRI



## Safety

Lightweight mechanical design
Compliance at robot joints

Collision detection
and safe reaction

## Coexistence

Robot and human sharing
the same workspace

Collision avoidance
No need of physical contact

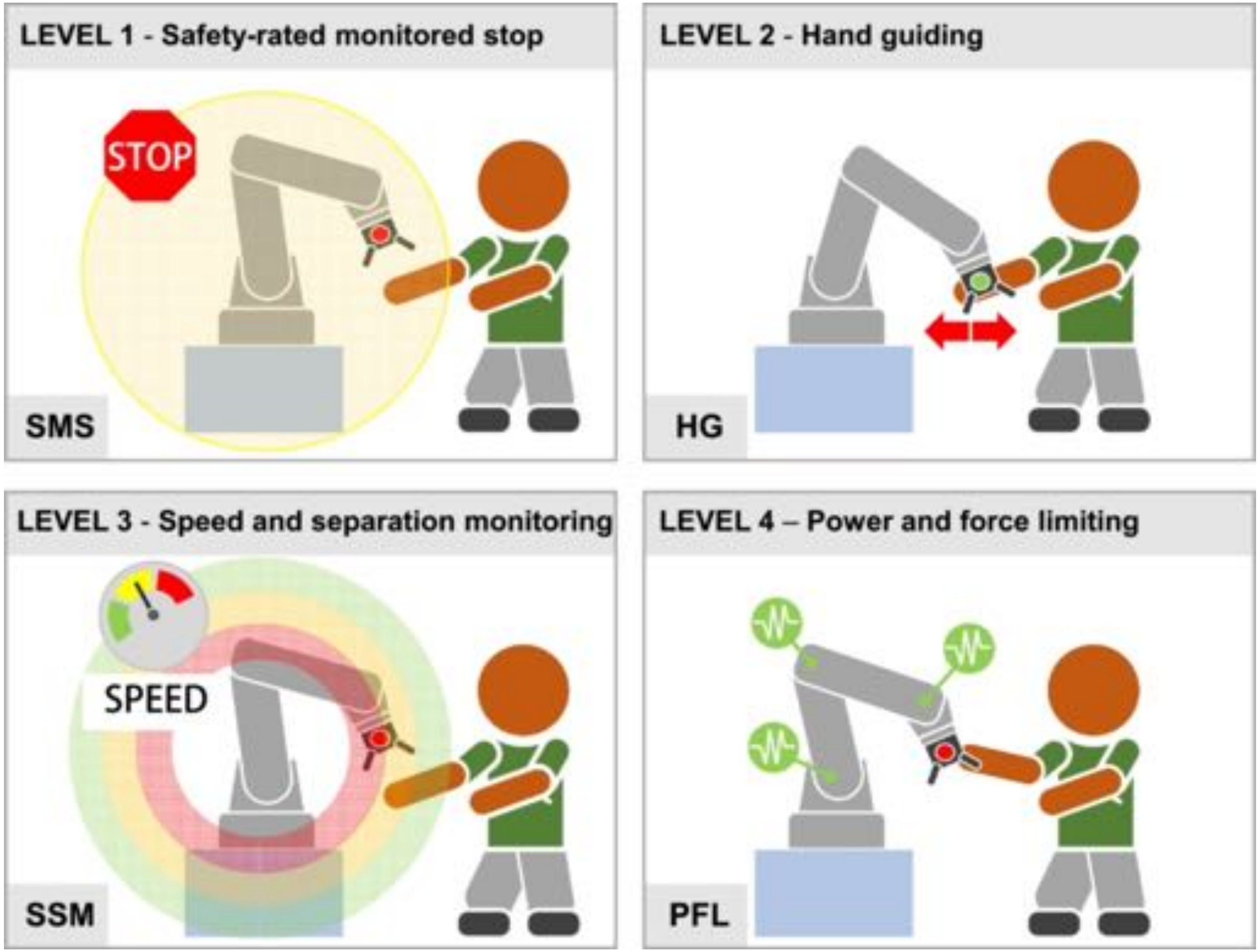
## Collaboration

Physical, with intentional contact
and coordinated exchange of forces

Contactless, e.g., gestures
or voice commands

*(A. De Luca, F. Flacco: BioRob 2012)*

# Types of collaborative operations (ISO 10218-1 & -2, and more in TS 15066)



*(V. Villani et al.: Mechatronics 2018)*

# Relation of our control architecture with the ISO collaborative operations

| | Speed | Separation Distance | Torques | Operator controls | Main risk reduction |
|---|---|---|---|---|---|
| SAFETY<br>**Safety-rated monitored stop**<br>COEXISTENCE | Zero while operator in Collaborative WS | Small or zero | Gravity + load compensation only | None while operator in Collaborative WS | No motion in presence of operator |
| **Hand guiding**<br>COLLABORATION | Safety-rated monitored speed | Small or zero | As by direct operator input | E-stop;<br>Enabling device;<br>Motion input | Motion only by direct operator input |
| **Speed and separation monitoring**<br>COEXISTENCE | Safety-rated monitored speed | Safety-rated monitored distance | As required to execute application and maintain min separation distance | None while operator in Collaborative WS | Contact between robot and operator prevented |
| **Power and force limiting**<br>COLLABORATION | Max determined by RA to limit impact forces | Small or zero | Max determined by RA to limit static forces | As required by application | By design or control, robot cannot impart excessive force |

# Implementation of Safety, Coexistence, and Collaboration layers - 1

❶ sensorless collision **detection** (use this if everything else fails!): robot stops and is gravity compensated

❷ **distinguishing** accidental (hard) collisions from intentional (soft) contacts: robot reacts then differently

DLR LWR-III

*IROS 2006 & 2008*

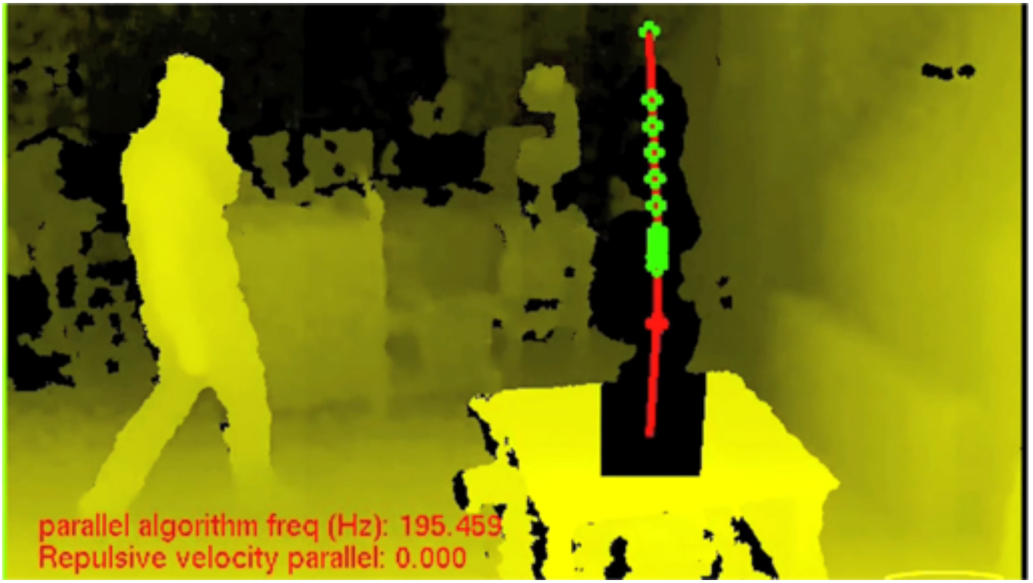
KUKA LBR 4+

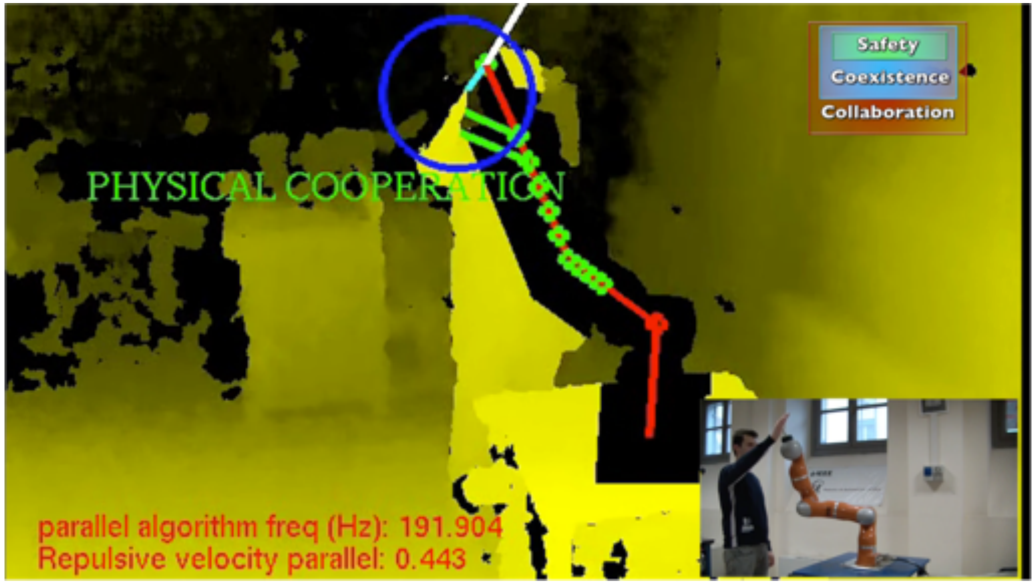
*IROS 2014, ICRA 2015*

# Implementation of Safety, Coexistence, and Collaboration layers - 2

❶ **continuous coexistence:** external sensors to avoid contact and modify robot motion or reduce speed

❷ **coexistence** dominates **collaboration** (with a designated body part) when both actions are inconsistent





SAPHARI
Safe and Autonomous Physical Human-Aware Robot Interaction

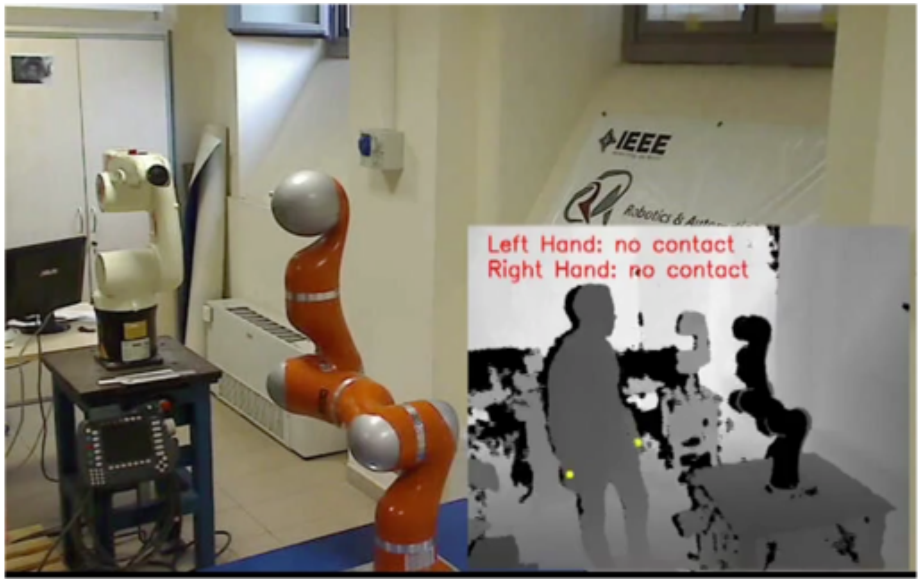
KUKA LBR 4+

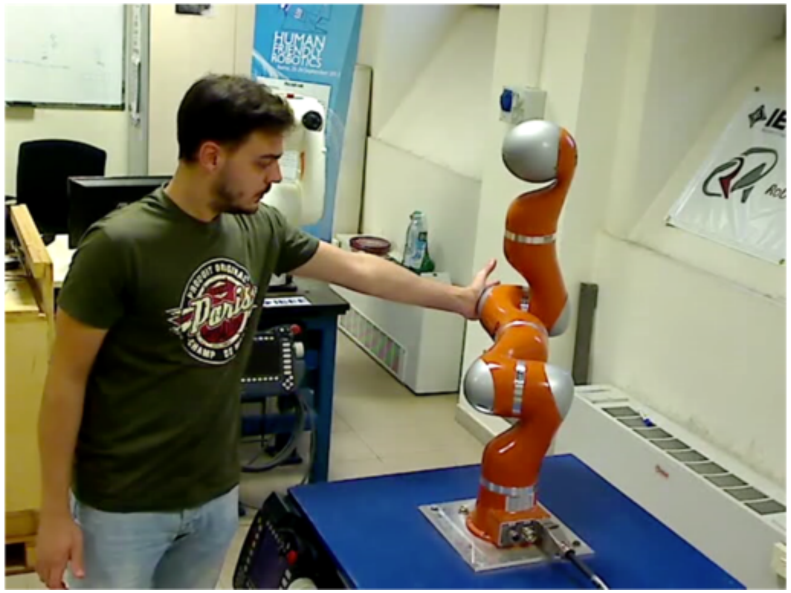
*ICRA 2012, IROS 2013, J Intell Rob Syst 2015*

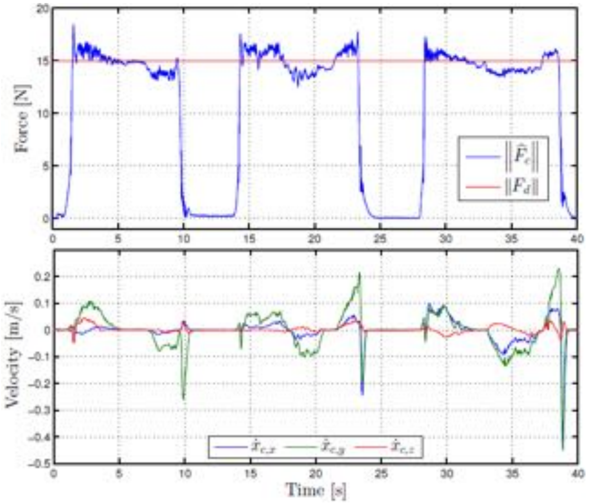
# Implementation of Safety, Coexistence, and Collaboration layers - 3

❶ **physical collaboration:** contact force estimation combining internal signals and external depth sensing (**virtual force sensor**)

❷ **collaboration: force**, admittance or impedance control laws at the **contact** for holding, pushing, ...







SAPHARI
Safe and Autonomous Physical Human-Aware Robot Interaction

KUKA LBR 4+
*IROS 2014,*
*ICRA 2016*

# RGB–D sensors and efficient distance monitoring in the depth space

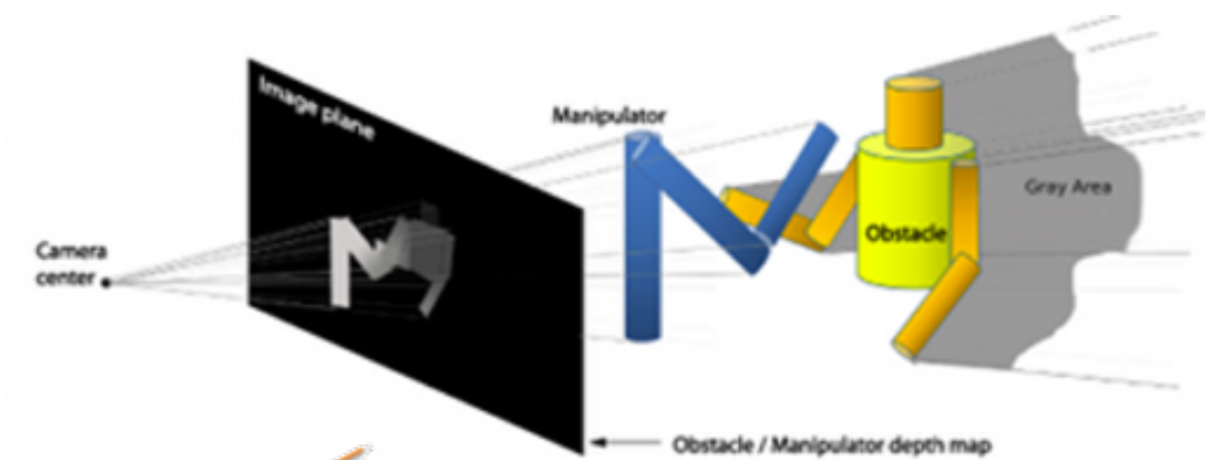
$$p_x = \frac{x_C f s_x}{z_C} + c_x$$

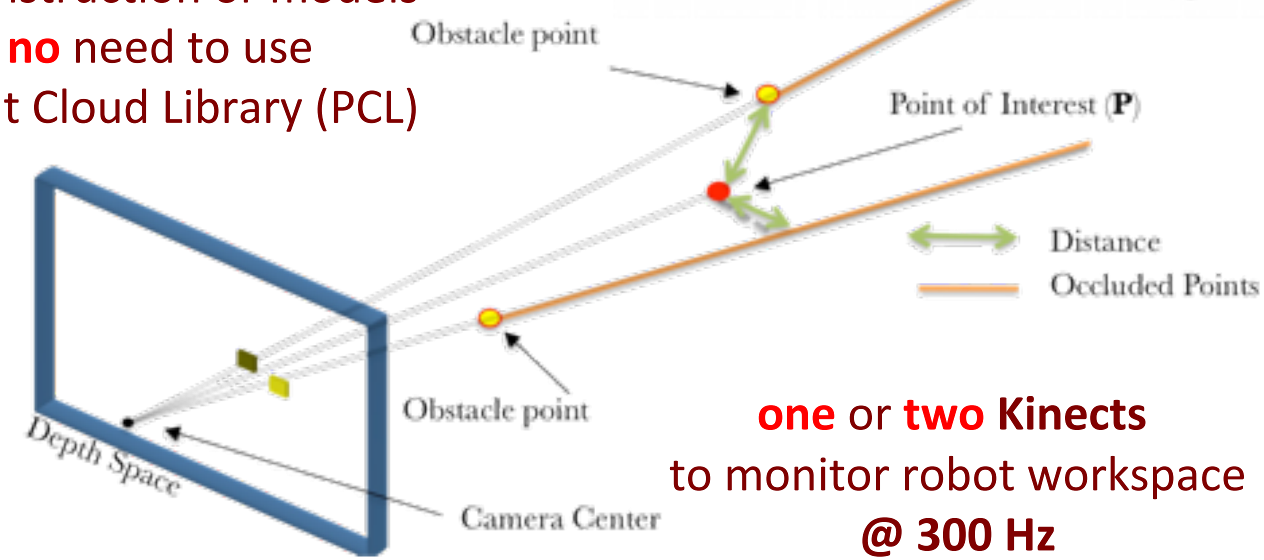
$$p_y = \frac{y_C f s_y}{z_C} + c_y$$

$$d_p = z_C$$

**no** 3D-Cartesian reconstruction or models

**no** need to use Point Cloud Library (PCL)

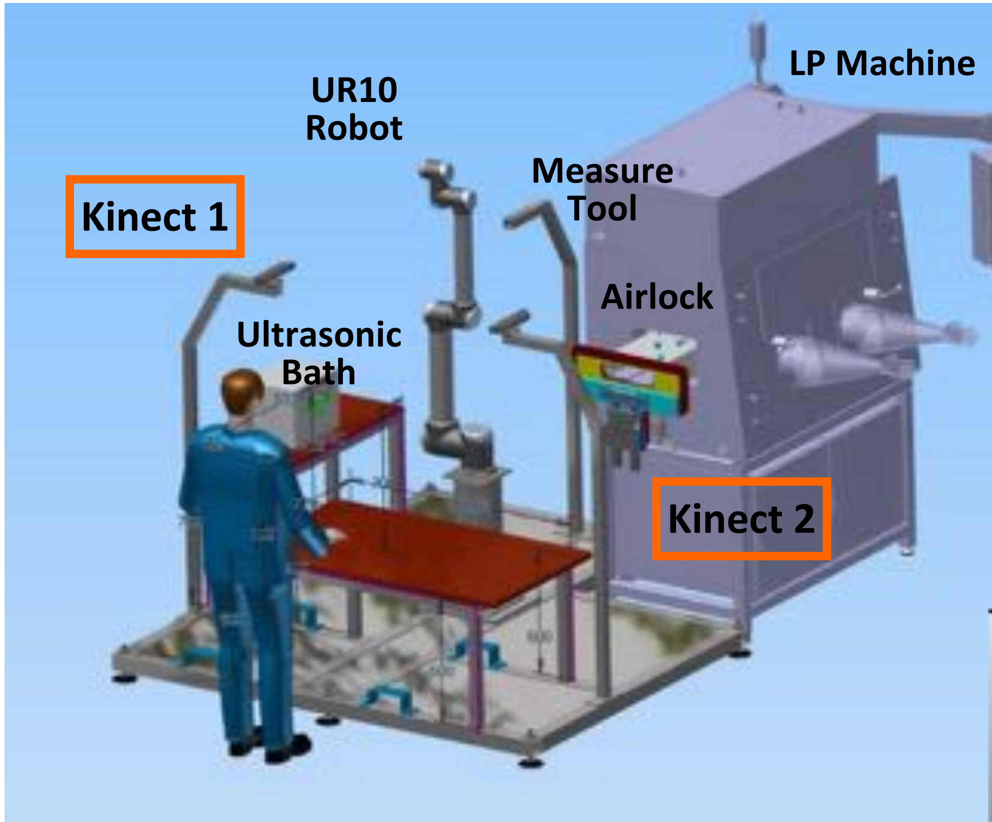




use distance, e.g., with artificial potentials, for **collision avoidance** during motion or **to slow down/stop** the robot

**one** or **two Kinects**
to monitor robot workspace
**@ 300 Hz**
with minimal gray areas

# SYMPLEXITY Laser cell with robotized Manual Polishing (MP) substation



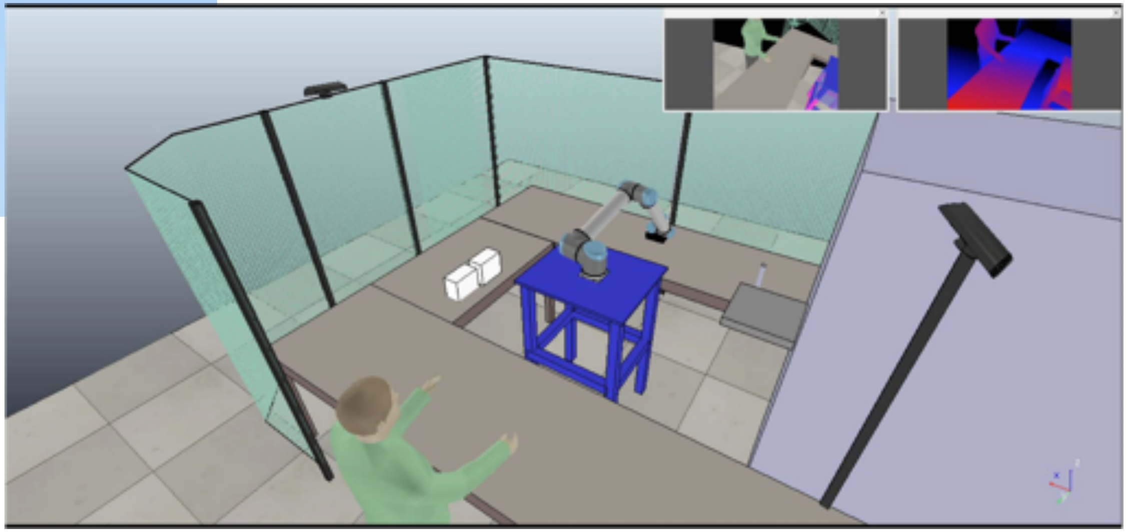
WS **monitoring** with 2 Kinects

⇒

**UR10** automatic **speed scaling** based on sensed H-R distance (**zero** for physical human-robot collaboration)

ISO/TS15066:2016

RGB & D views from the right Kinect

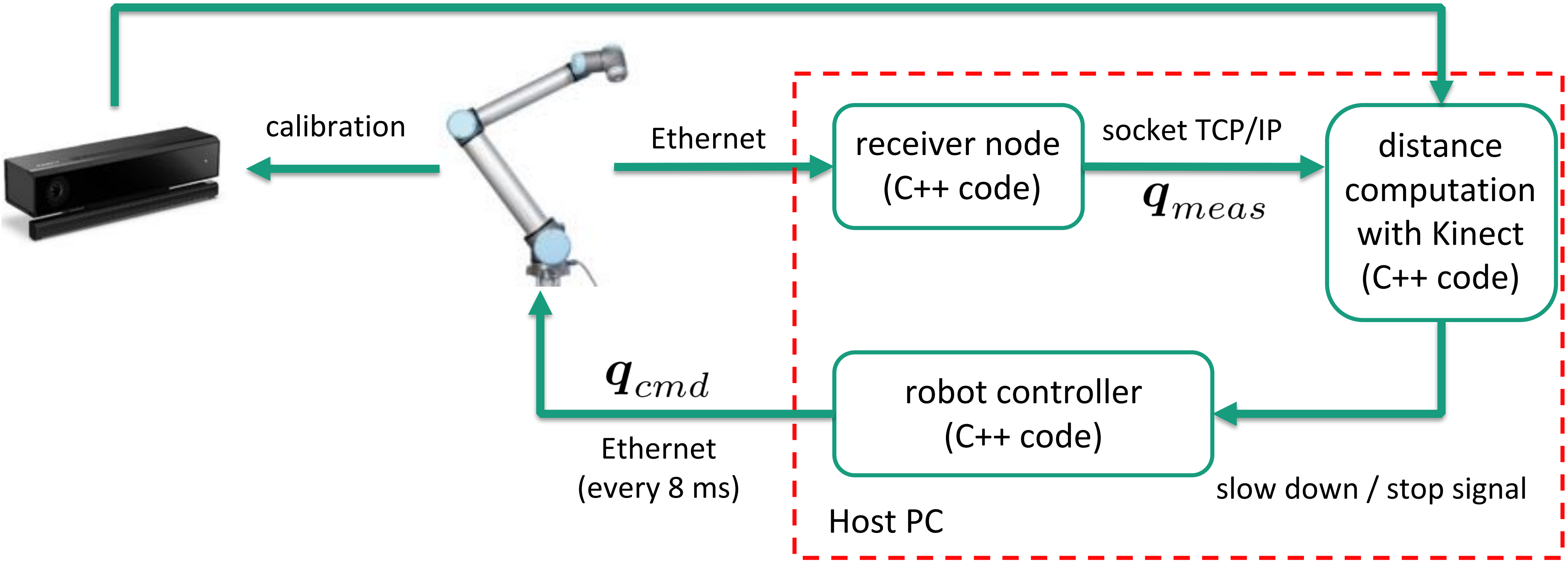


SYMPLEXITY

Fraunhofer

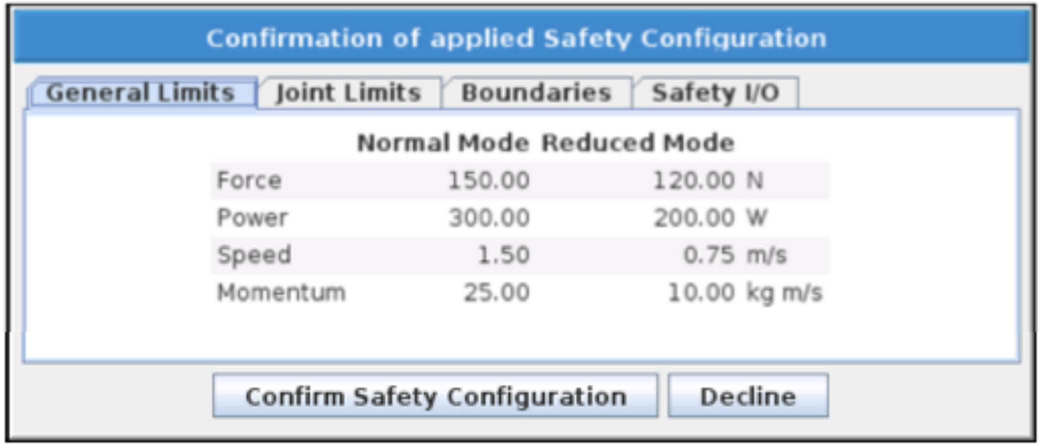
GIZELIS ROBOTICS

# SYMPLEXITY robotized MP cell with UR10 – control framework



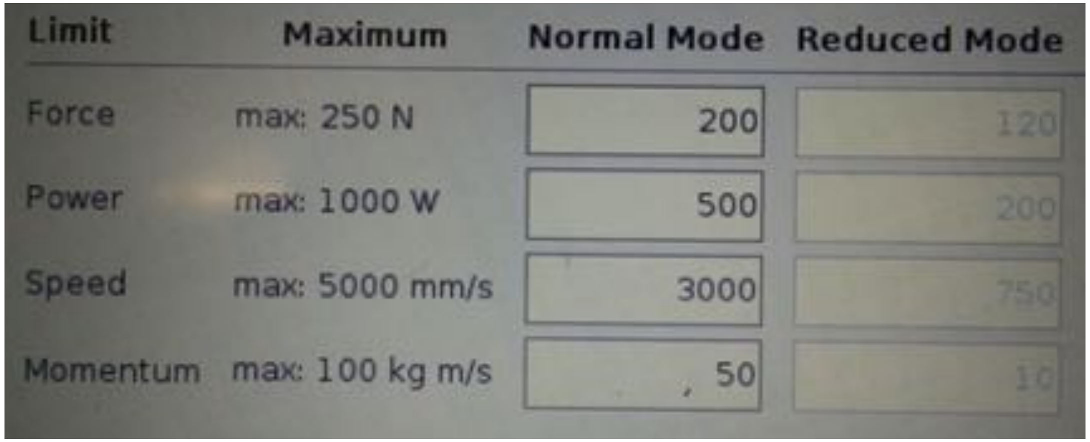
- potential safety-related issues
  - Kinect failure or severe occlusions ⇒ no or wrong distance computed
  - distance computation algorithm failure ⇒ no control signals provided
  - robot control algorithm failure ⇒ unpredictable robot motion
- first two handled separately; last relies on **UR10 safe low-level control**

# SYMPLEXITY robotized MP cell – UR10 safe low-level control



| | Normal Mode | Reduced Mode |
|---|---|---|
| Force | 150.00 | 120.00 N |
| Power | 300.00 | 200.00 W |
| Speed | 1.50 | 0.75 m/s |
| Momentum | 25.00 | 10.00 kg m/s |

from the manual

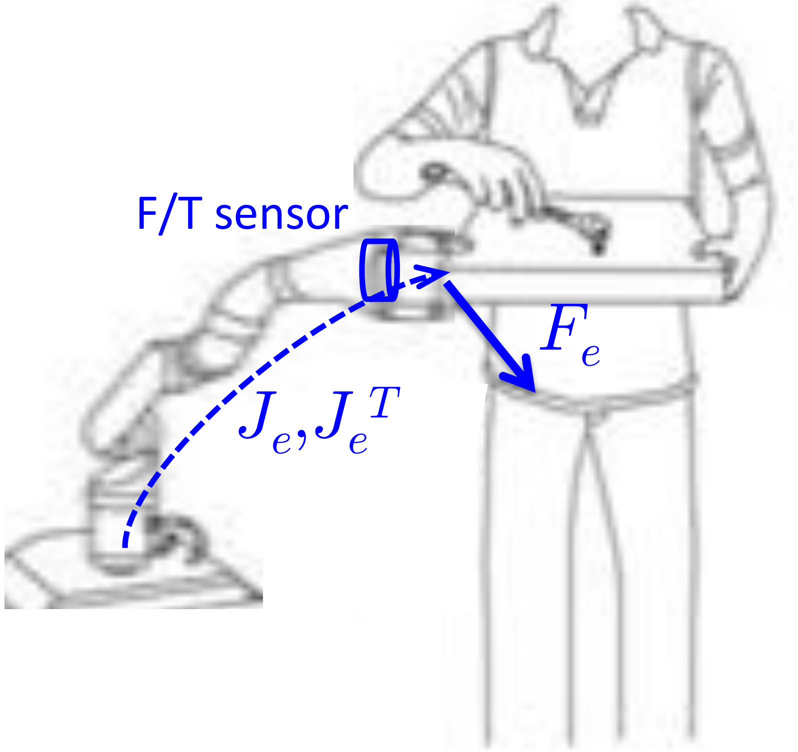


| Limit | Maximum | Normal Mode | Reduced Mode |
|---|---|---|---|
| Force | max: 250 N | 200 | 120 |
| Power | max: 1000 W | 500 | 200 |
| Speed | max: 5000 mm/s | 3000 | 750 |
| Momentum | max: 100 kg m/s | 50 | 10 |

in use: a screenshot..

- **category 0 protective stop**
  - robot motion is stopped by immediate removal of power
  - each joint brakes as fast as possible
  - used if a safety-related limit is exceeded or a fault occurs in the safety-related HW of the control system (EN ISO13850:2008 or IEC60204-1:2006)
  - user can define limits to be used in Normal Mode
  - enforced **also when** an external high-level control software is being used...

# Human-Robot Collaboration (HRC) for Manual Polishing

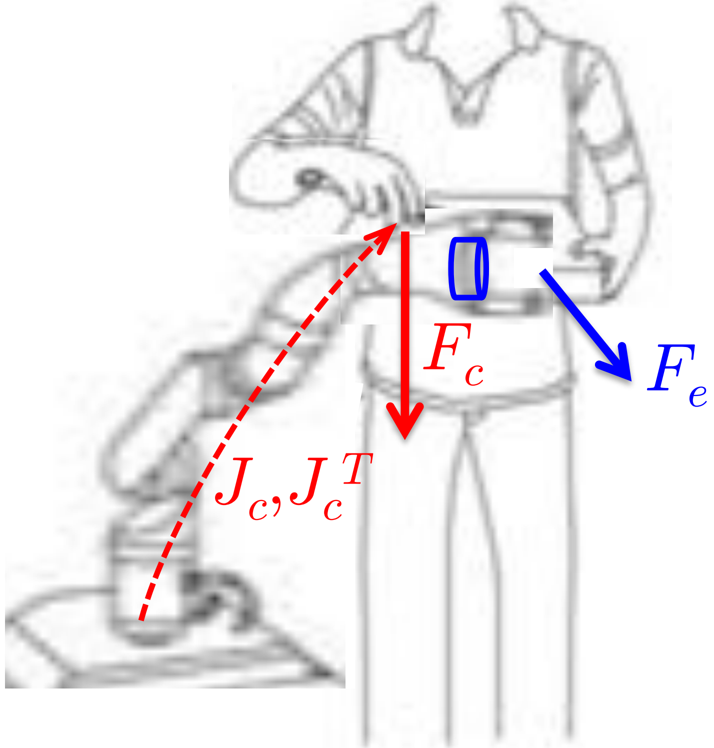


Force/Torque (F/T) sensor at wrist

- manual polishing force is **measured**
- end-effector Jacobian is **known**

contact force at unknown location

- **not** measurable by the F/T sensor
- possibly applied by the human **while** manipulating the work piece held by robot
- contact Jacobian is **not** known



# Dynamic model of a robot with contacts and residual computation

- robot **dynamic model** takes the form

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{C}(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau} + \boldsymbol{J}_e^T(\boldsymbol{q})\boldsymbol{F}_e + \boldsymbol{J}_c^T(\boldsymbol{q})\boldsymbol{F}_c$$

- joint torques resulting from different contacts
  - (measured) at the end-effector level
  - at a generic point along the structure

$$\boldsymbol{\tau}_e = \boldsymbol{J}_e^T(\boldsymbol{q})\boldsymbol{F}_e \qquad\qquad \boldsymbol{\tau}_c = \boldsymbol{J}_c^T(\boldsymbol{q})\boldsymbol{F}_c$$

- monitor the robot generalized momentum $\boldsymbol{p} = \boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{q}}$

- (model-based) **residual vector signal** to detect and isolate the generic contacts

$$\boldsymbol{r}(t) = \boldsymbol{K}_i\left(\boldsymbol{p} - \int_0^t \left(\boldsymbol{C}^T(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} - \boldsymbol{g}(\boldsymbol{q}) + \boldsymbol{\tau} + \boldsymbol{J}_e^T(\boldsymbol{q})\boldsymbol{F}_e - \boldsymbol{r}\right) ds\right)$$

$$\boxed{\boldsymbol{K}_i \to \infty \text{ (sufficiently large)} \quad \Rightarrow \quad \boldsymbol{r} \simeq \boldsymbol{\tau}_c}$$

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# Position/Admittance control during collaborative manual polishing

- when there is no extra contact along the structure, **position and orientation** of the end-effector are both held **fixed** by a **stiff kinematic control law**

$$\dot{q} = J_e^{\#} K_e \begin{pmatrix} v_r \\ \omega_r \end{pmatrix} = J_e^{\#} K_e \begin{pmatrix} I & 0 \\ 0 & T(\phi) \end{pmatrix} \begin{pmatrix} p_d - p \\ \phi_d - \phi \end{pmatrix}$$

as large as possible

constant values

- the controller counterbalances all forces/torques applied by the operator **during manual polishing**
- when the human intentionally pushes on the robot body, control of the end-effector **orientation** is **relaxed**

3×6 for UR10

$$J_e(q) = \begin{pmatrix} J_p(q) \\ J_o(q) \end{pmatrix}$$

$$\boxed{\dot{q} = J_p^{\#} K_p (p_d - p) + \overbrace{\left(I - J_p^{\#} J_p\right) K_r r}^{\text{residual-based reaction to extra contacts}}}$$

- human can reconfigure the arm, thus **reorient the work piece** held by the robot

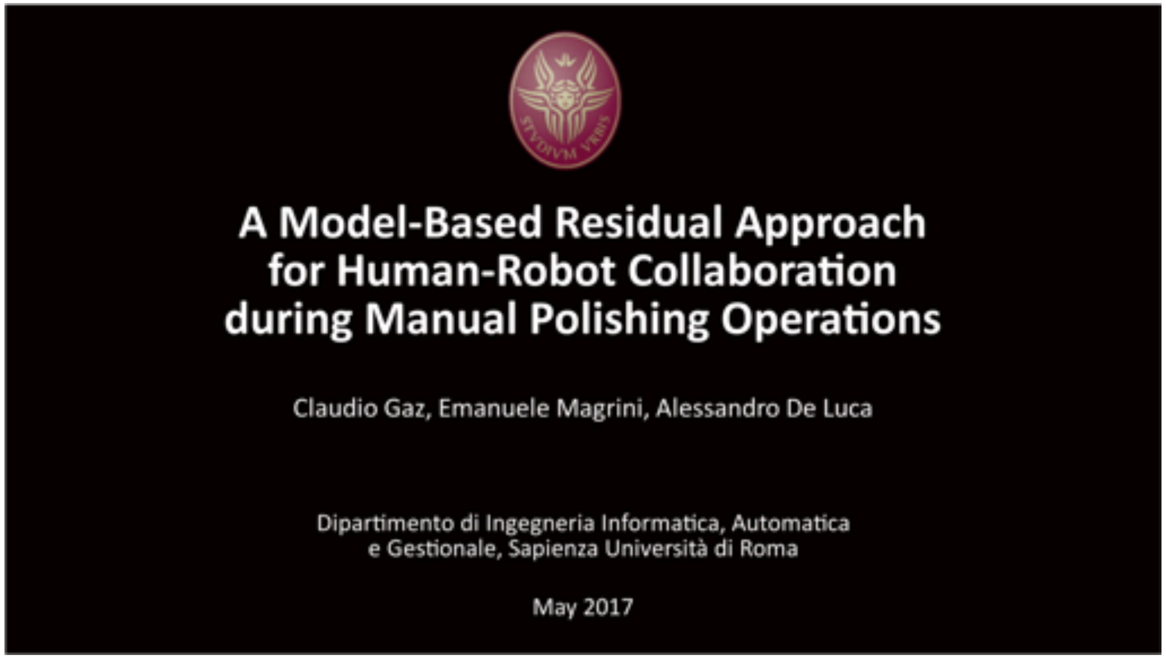
# Emulation of MP: HRC phase – experiments with UR10 at DIAG

no F/T sensor, switching to Freedrive mode

Universal Robots UR10

*Mechatronics 2018*

with F/T sensor, using residual method
tuned by accurate dynamic identification



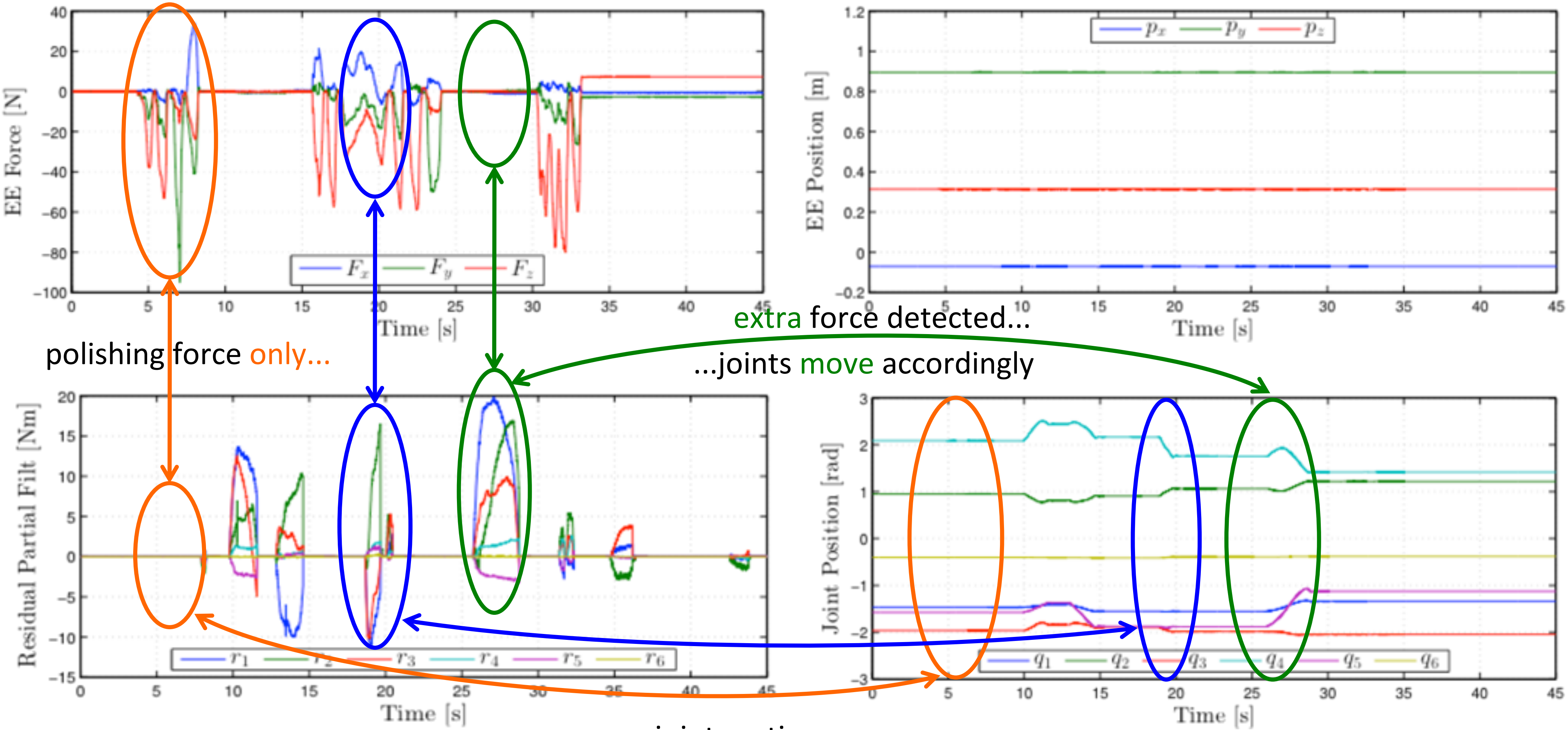
**A Model-Based Residual Approach
for Human-Robot Collaboration
during Manual Polishing Operations**

Claudio Gaz, Emanuele Magrini, Alessandro De Luca

Dipartimento di Ingegneria Informatica, Automatica
e Gestionale, Sapienza Università di Roma

May 2017

# Emulation of MP: HRC phase – experimental results with UR10



both forces at the same time...

in all cases, **no linear motion** of EE position!

polishing force only...

extra force detected...

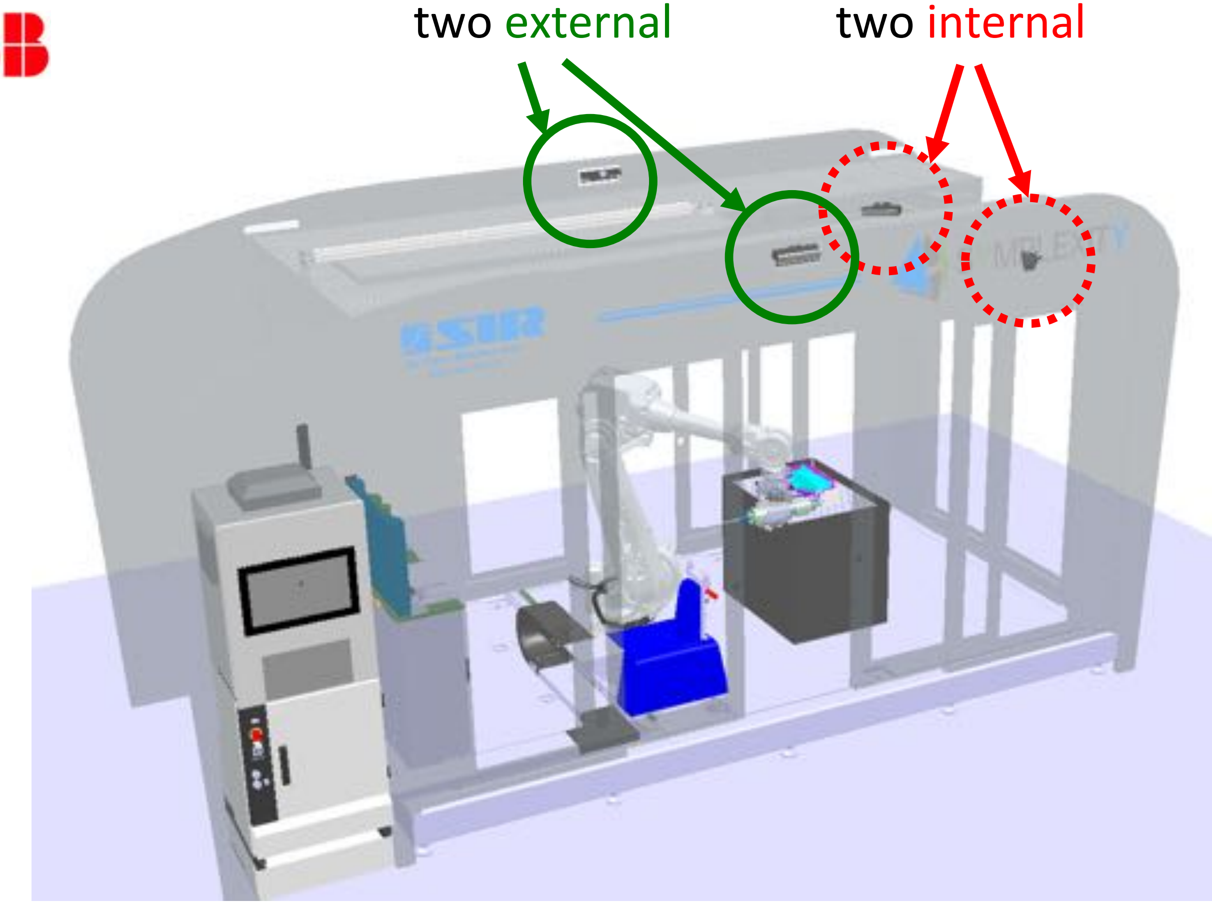
...joints move accordingly

...no joint motion

...joints move due to extra force only

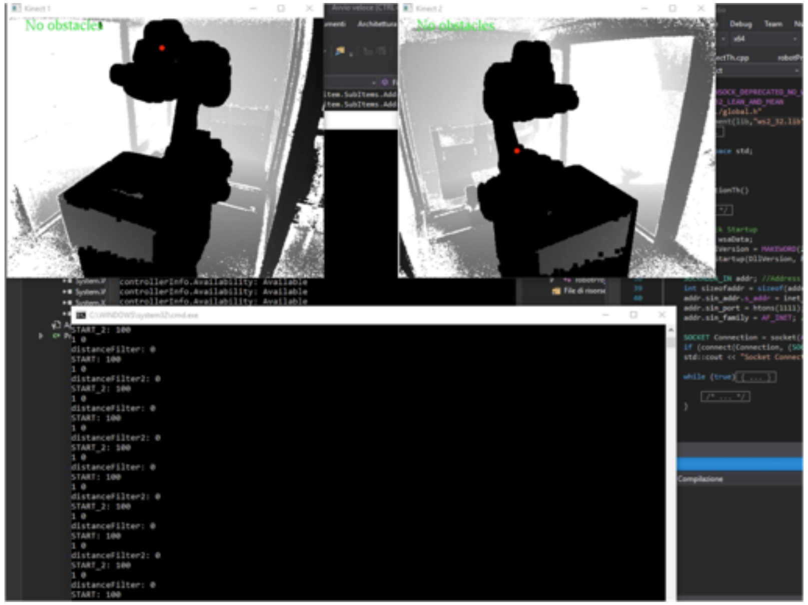
# SYMPLEXITY cell for
# Abrasive Finishing (AF) & Quality Assessment (QA) of Metallic Surface of Workpieces

- robot ABB IRB 4600-60, with integrated SafeMove option
- certified communication with cell PLC, using ProfiSAFE protocol
- due to intrinsic risks in the technological process, only **contactless collaboration** or **HR coexistence** during visual check or measuring phases of the task
- 2 external Kinects to recognize human gestures (e.g., automatic doors opening, …)
- **initially...** only 2 internal Kinects at the top corners of the cabin for monitoring human-robot distances



# Coexistence and contactless collaboration in the SYMPLEXITY industrial cell

External view of the cell



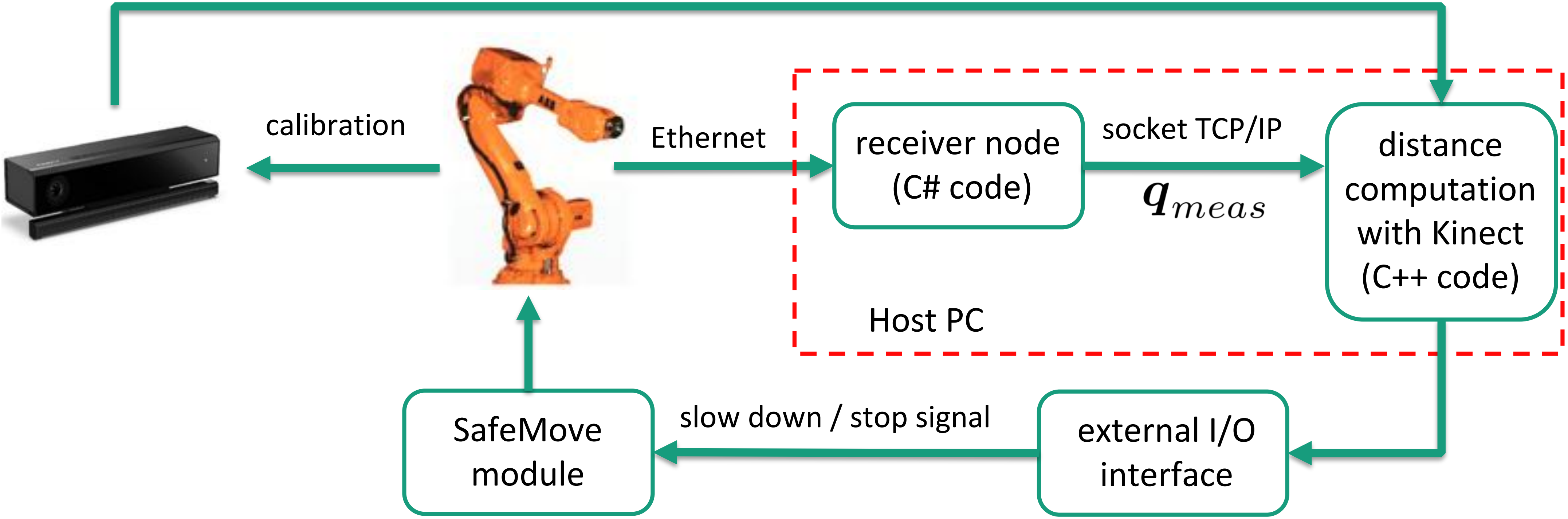
```
controllerInfo.Availability: Available
controllerInfo.Availability: Available
controllerInfo.Availability: Available
```

```
START_2: 100
1 0
distanceFilter: 0
START: 100
1 0
distanceFilter2: 0
START_2: 100
1 0
distanceFilter: 0
START: 100
1 0
distanceFilter2: 0
START_2: 100
1 0
distanceFilter: 0
START: 100
1 0
distanceFilter2: 0
START_2: 100
1 0
distanceFilter: 0
START: 100
1 0
distanceFilter2: 0
START_2: 100
1 0
distanceFilter: 0
START: 100
```

Kinect views of the real-time distance computation

Recognition of human gesture commands by an external Kinect

# SYMPLEXITY AF/QA cell with ABB IRB 4600 – control framework



- SafeMove + external I/O modules are considered “safe” (industrial certification)
- potential safety-related issues
  - Kinect failure or severe occlusions ⇒ no or wrong distances computed
  - distance computation algorithm failure ⇒ no control signals provided
  - ⇒ **risk** analysis and assessment ⇒ **mitigation** strategies

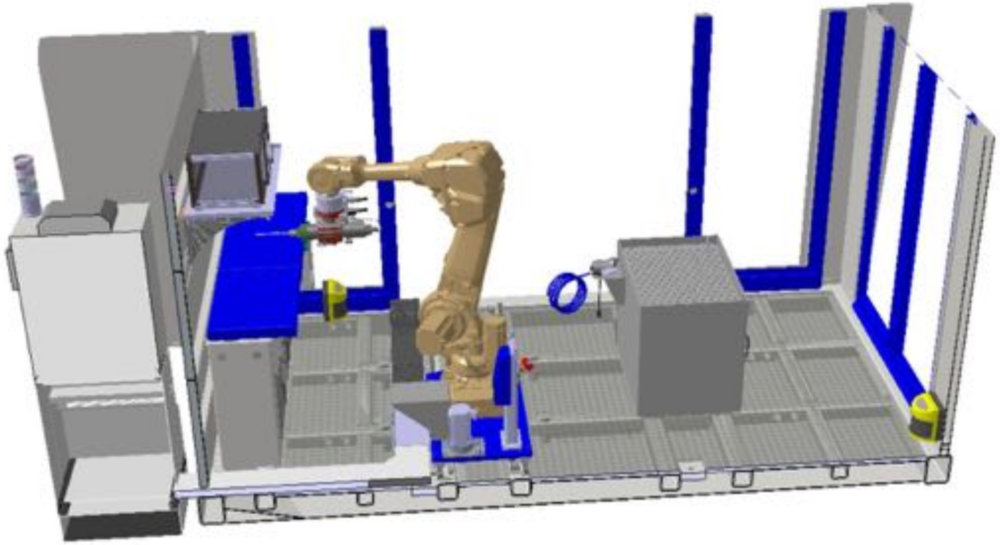
# Risk assessment and mitigation – Kinect failure

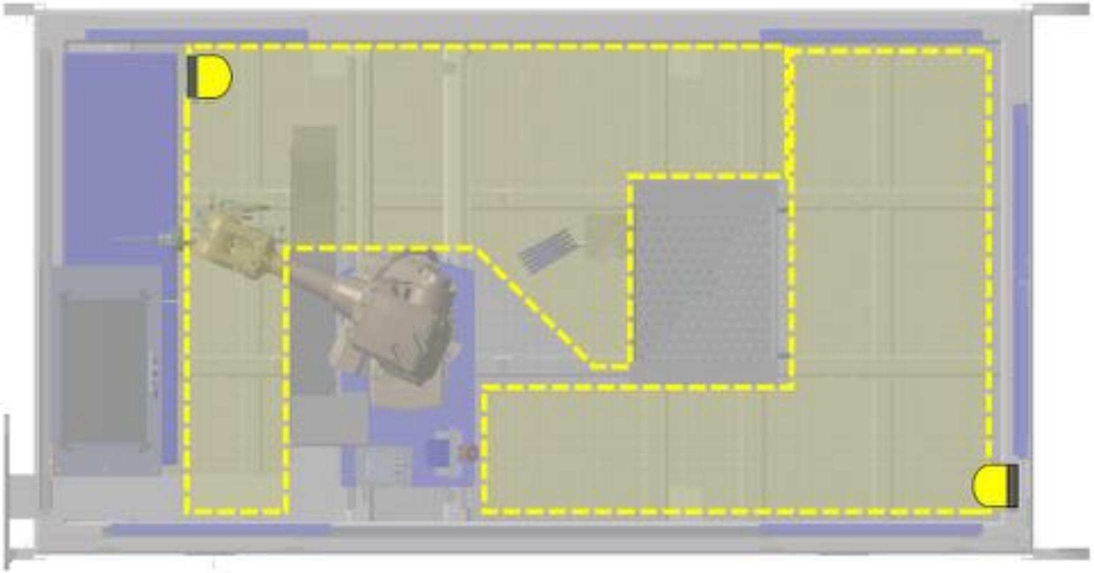
- reasons
  - Kinect hardware/driver fails, cable unplugged, ...
  - severe occlusion
  - bad lighting conditions
- detection
  - captured depth image is always the same
  - number of “black” pixels (associated to no valid depth values) in the depth image is larger than a critical threshold
  - frame rate is too slow
- mitigating actions
  - activate an alarm (acoustic and/or visual) to warn the operator
  - use optional laser scanner or barriers to understand where the human is and possibly slow down or stop the robot

# Risk assessment and mitigation – distance computation algorithm failure

- reasons
  - bad communication between robot and host PC (Ethernet unplugged?)
  - bad filtering of CAD robot model from the image
  - excessive noise in Kinect
- detection
  - discontinuity over short times of the (minimum) distance value
  - monitoring and averaging the last few distance samples
- mitigating actions
  - noise filtering of depth image to avoid isolated black pixels
  - activate an alarm (acoustic and/or visual) to warn the operator
  - define “macro areas” of robot operation using laser scanner or barriers
  - if the algorithm fails, robot slows down or stops depending on which macro area the human is in

# Additional safety hardware – Laser scanners

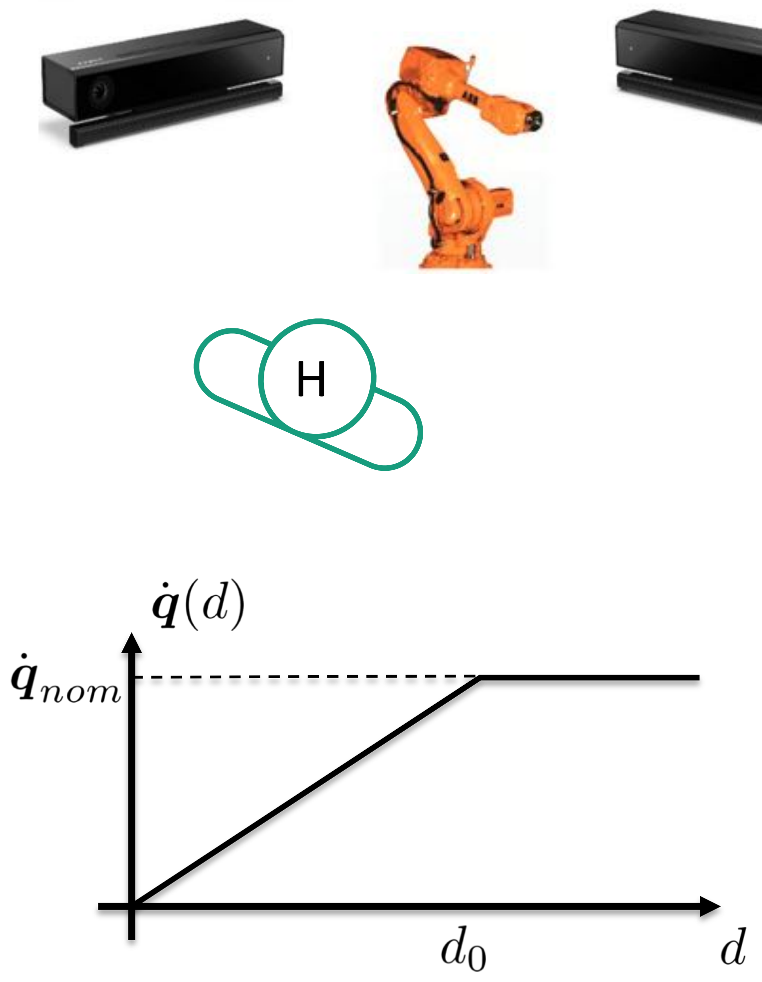




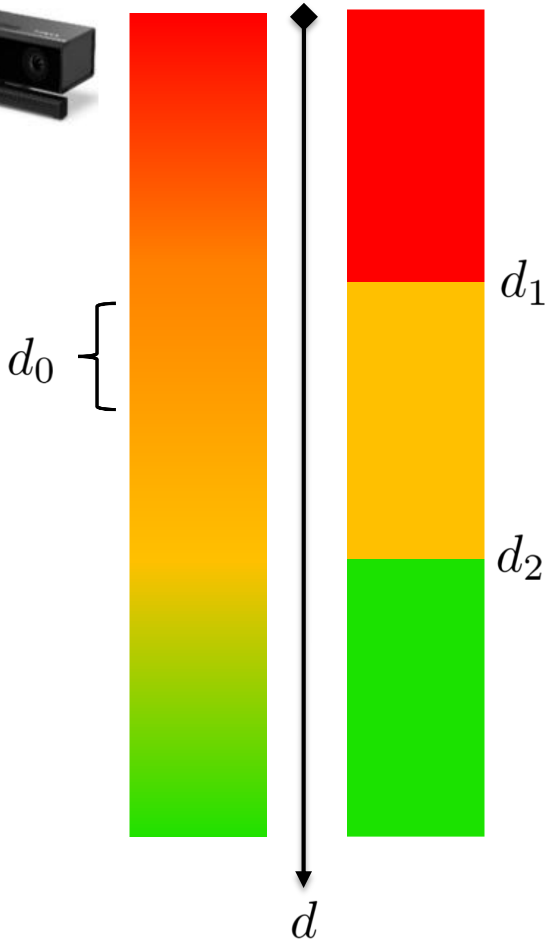
- add **two laser scanners** (KEYENCE SZ-V 32n), placed at calf height (∼50 cm)
- maximize **coverage** of the free area in the cell
- each sensor localizes the (radial) position of the operator in the cell, estimating an **approximate/conservative distance** to the robot
- **no missed situations**: robot slows down or stops according to sensed distance/area
- mixed Kinect/laser scanner solution is a **compromise** between certified safety and a more flexible sharing of the 3D workspace by human and robot

# Safety issues – solution with scaling of speed and **extra hardware**

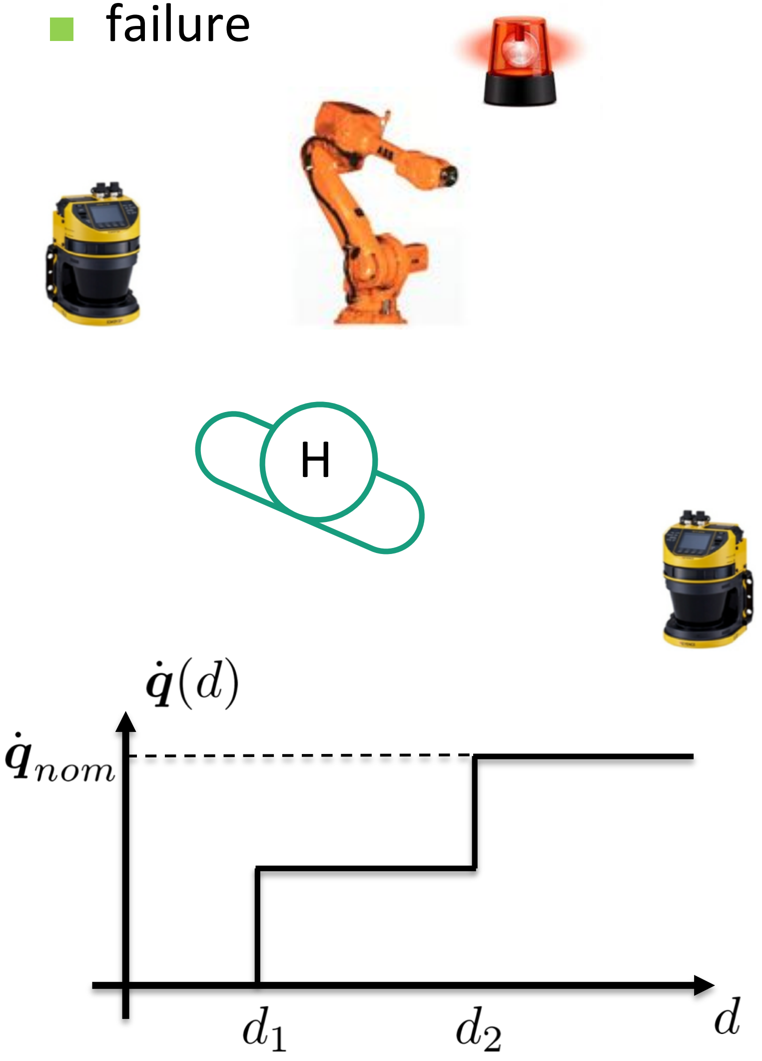
- working algorithms



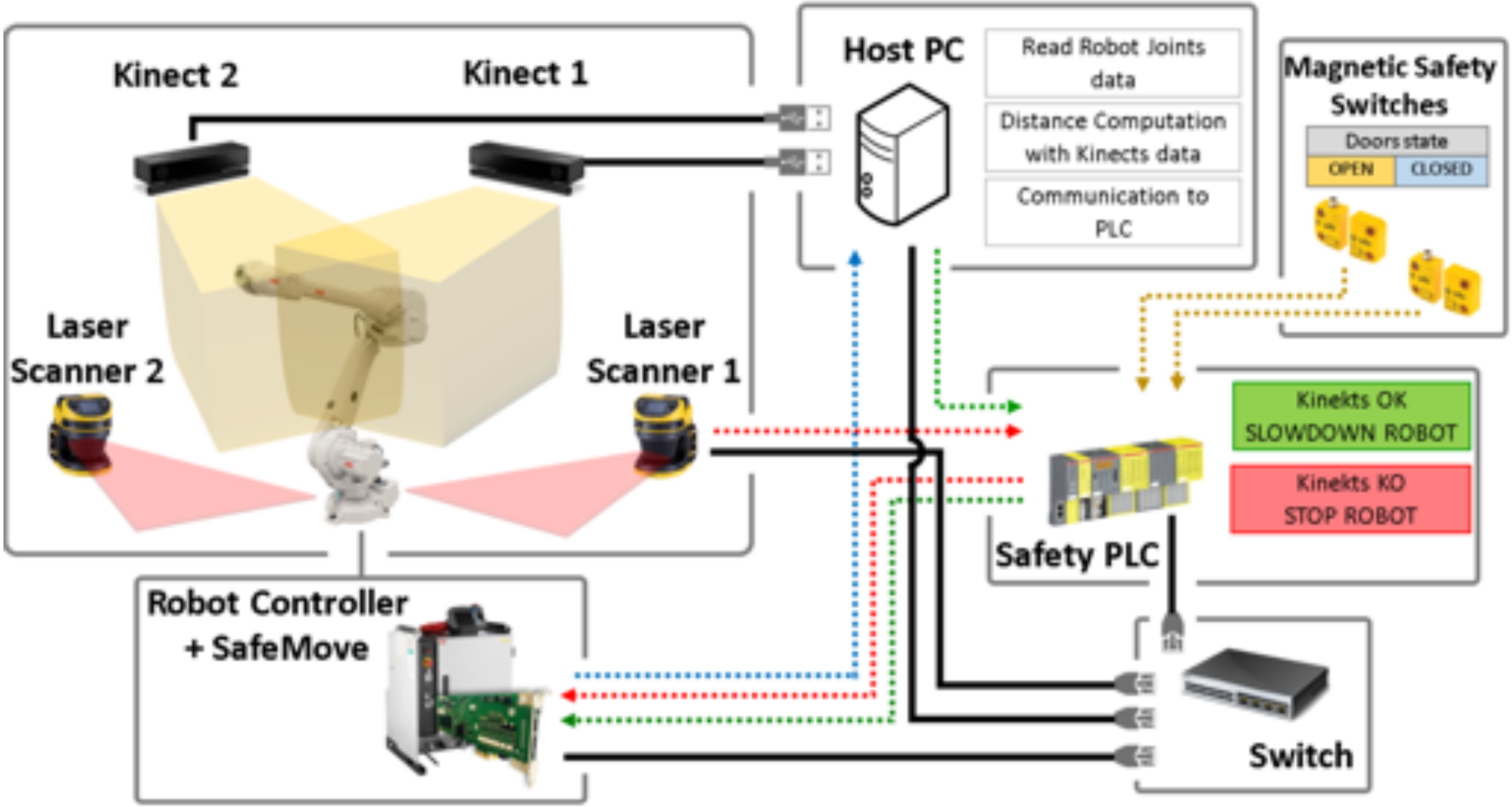
risk level
(distance to robot)



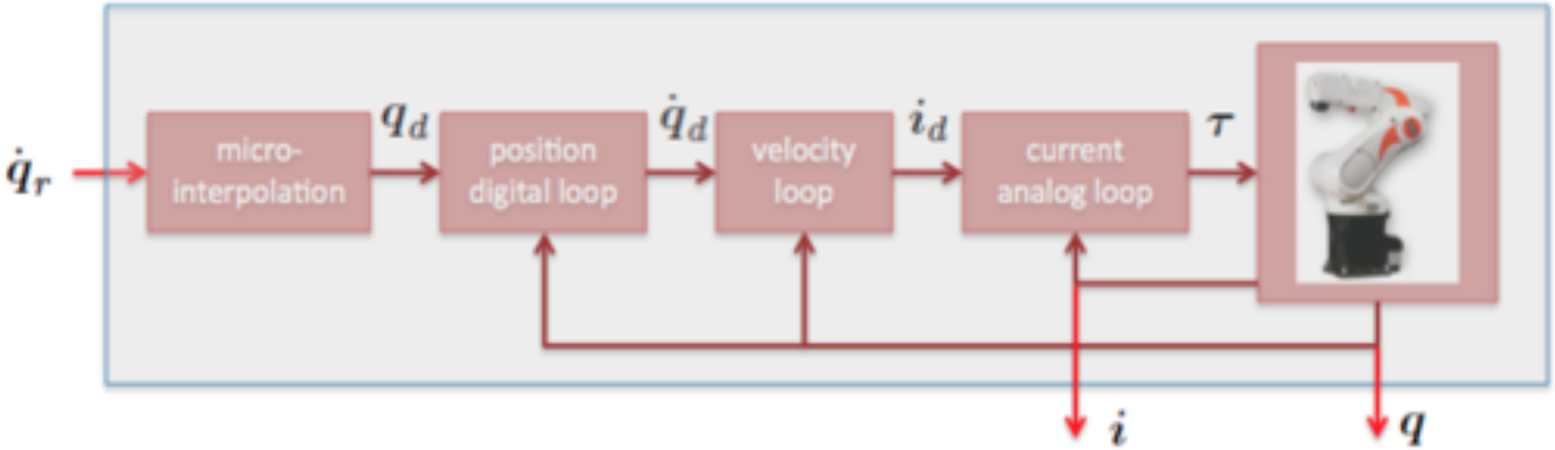
- failure



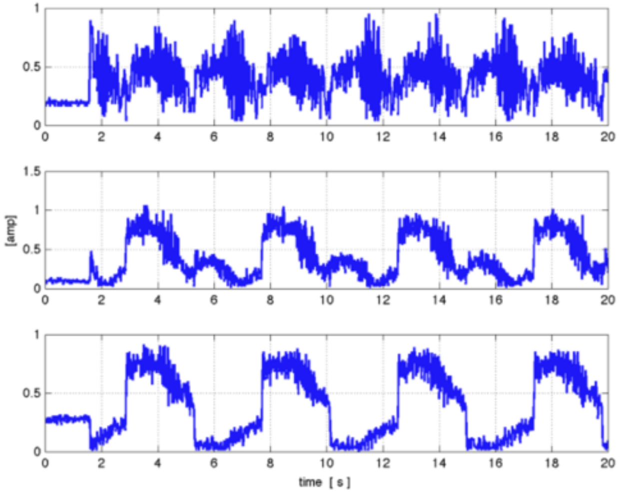
# Final control and communication architecture



# HRC under a closed control architecture – KUKA KR5 Sixx R650

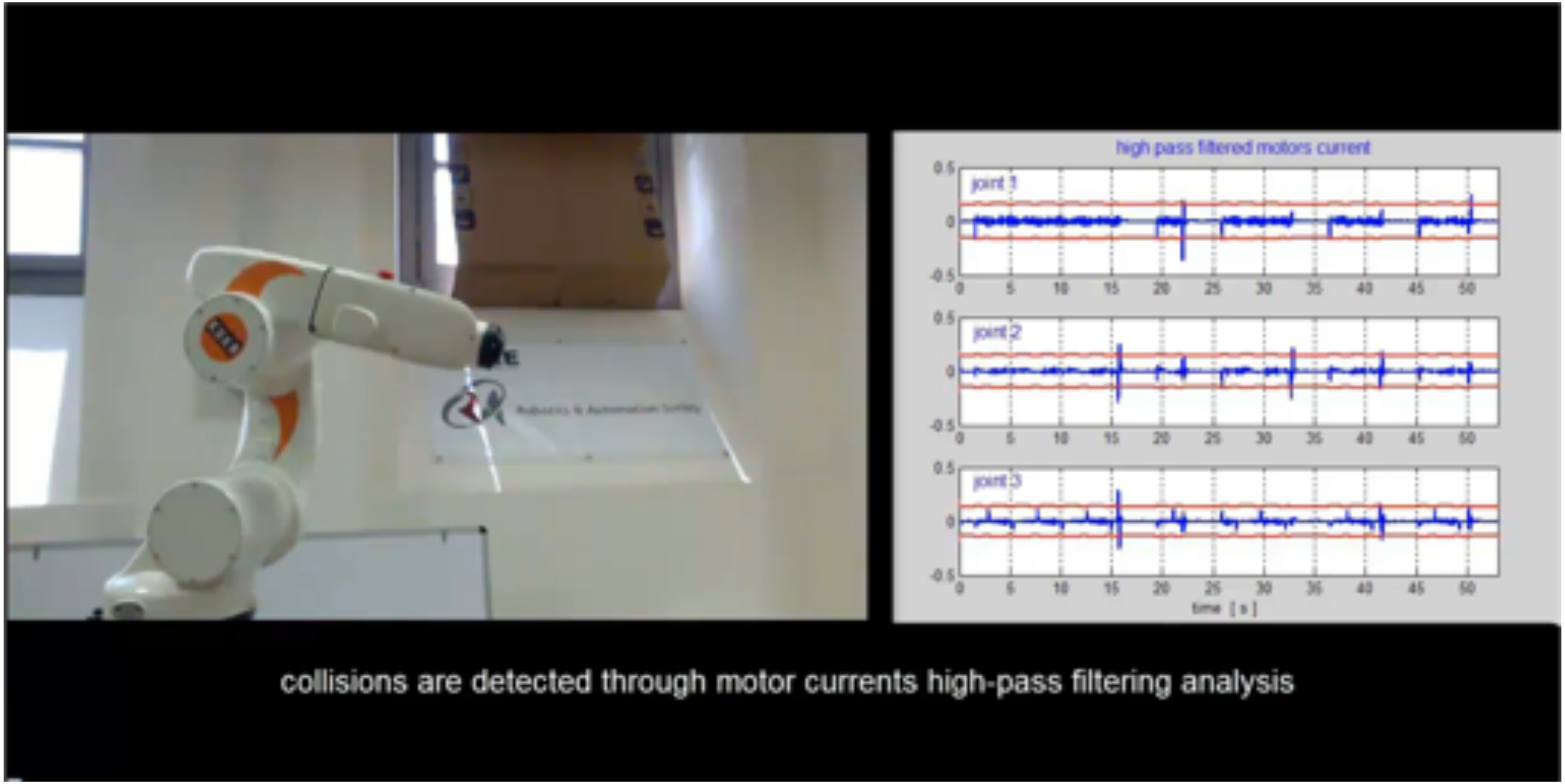


- low-level motor control laws not known nor accessible to the user
- controller reference is given as a velocity or a position in joint space (also Cartesian commands are accepted)
- user programs, based e.g. on other exteroceptive sensors (Kinect, F/T sensor, vision) implemented on external PC via the RSI (RobotSensorInterface), communicating with KUKA controller every 12 ms
- available measures: joint positions (by encoders) and (absolute value of) applied motor currents



typical motor currents
on the first three joints

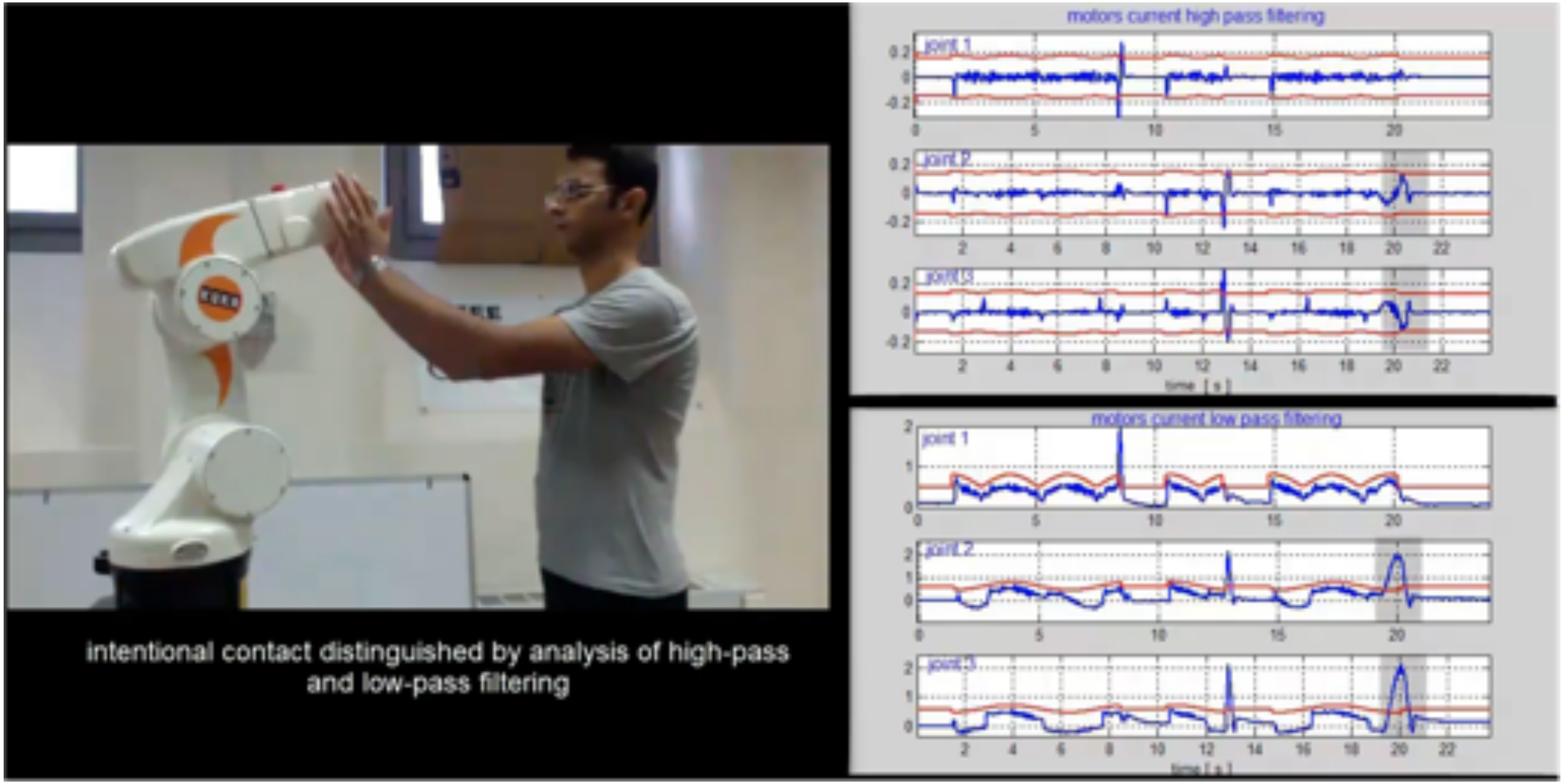
# Collision detection and then stop - KUKA KR5 Sixx



collisions are detected through motor currents high-pass filtering analysis

high-pass filtering of motor currents (a signal-based detection...)

# Distinguish accidental collisions from intentional contact and then collaborate - KUKA KR5 Sixx


intentional contact distinguished by analysis of high-pass and low-pass filtering

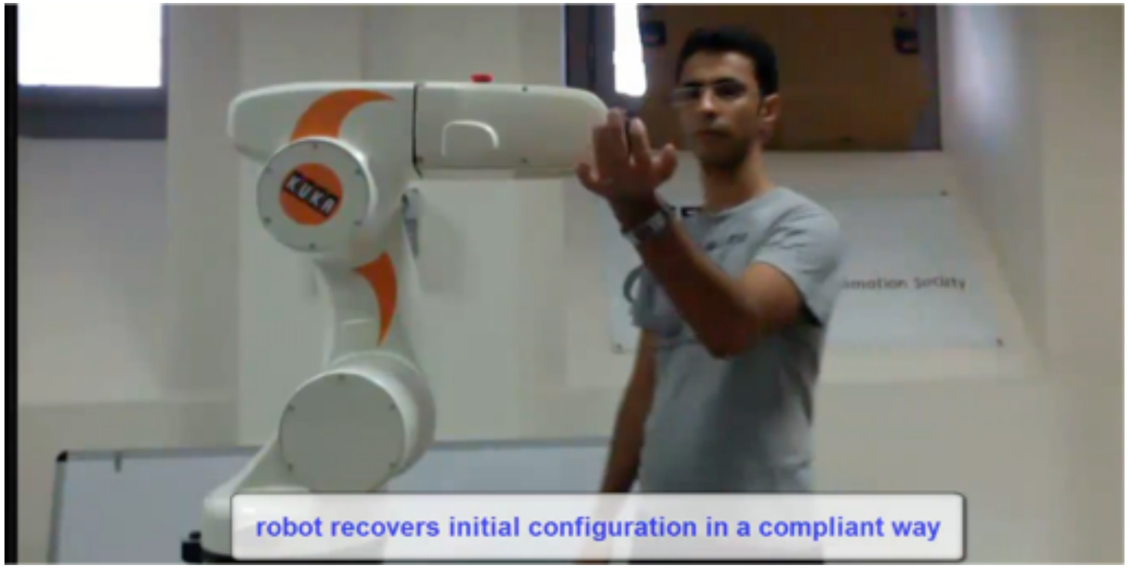
both high-pass and low-pass filtering of motor currents (with time-varying thresholds)
— here the collaboration mode is manual guidance of the robot

# Other possible robot reactions after collaboration mode is established

collaboration mode:
pushing/pulling
the robot

KUKA KR5 Sixx
*ICRA 2013*

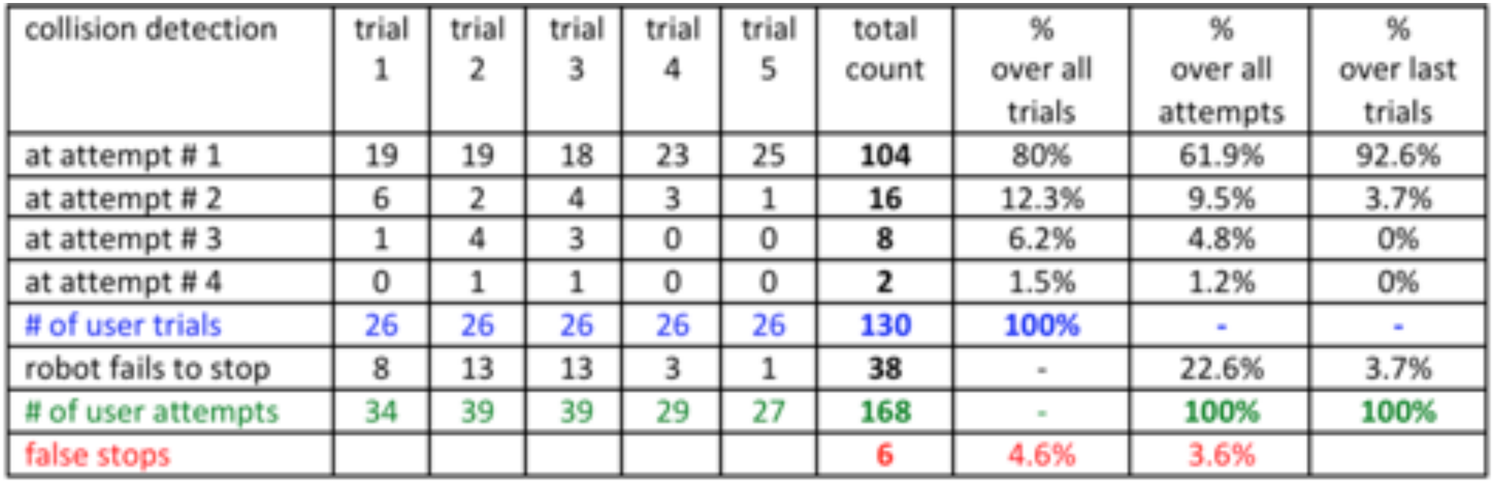
collaboration mode:
compliant-like
robot behavior



# Trials on collision detection and hard/soft contact with human subjects

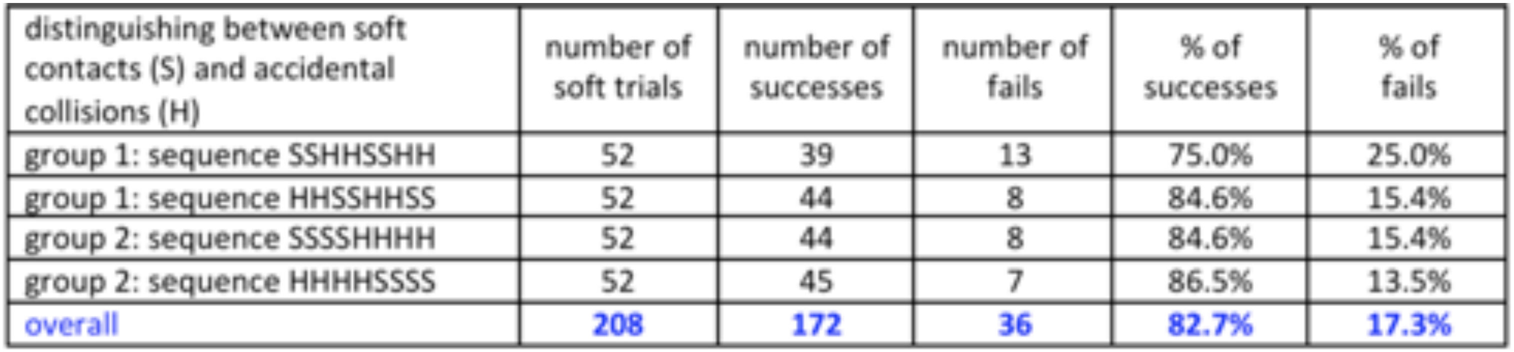
**26 volunteers** (informed students, in the age range 20-24, about 20% female)

a total of
**168 collisions**,
in series of 5
for each user
(with repeated
attempts)



| collision detection | trial 1 | trial 2 | trial 3 | trial 4 | trial 5 | total count | % over all trials | % over all attempts | % over last trials |
|---|---|---|---|---|---|---|---|---|---|
| at attempt # 1 | 19 | 19 | 18 | 23 | 25 | **104** | 80% | 61.9% | 92.6% |
| at attempt # 2 | 6 | 2 | 4 | 3 | 1 | **16** | 12.3% | 9.5% | 3.7% |
| at attempt # 3 | 1 | 4 | 3 | 0 | 0 | **8** | 6.2% | 4.8% | 0% |
| at attempt # 4 | 0 | 1 | 1 | 0 | 0 | **2** | 1.5% | 1.2% | 0% |
| # of user trials | 26 | 26 | 26 | 26 | 26 | **130** | **100%** | - | - |
| robot fails to stop | 8 | 13 | 13 | 3 | 1 | **38** | - | 22.6% | 3.7% |
| # of user attempts | 34 | 39 | 39 | 29 | 27 | **168** | - | **100%** | **100%** |
| false stops | | | | | | **6** | 4.6% | 3.6% | |

416 contacts,
**half** of which
were intended
to be **soft**



| distinguishing between soft contacts (S) and accidental collisions (H) | number of soft trials | number of successes | number of fails | % of successes | % of fails |
|---|---|---|---|---|---|
| group 1: sequence SSHHSSHH | 52 | 39 | 13 | 75.0% | 25.0% |
| group 1: sequence HHSSHHSS | 52 | 44 | 8 | 84.6% | 15.4% |
| group 2: sequence SSSSHHHH | 52 | 44 | 8 | 84.6% | 15.4% |
| group 2: sequence HHHHSSSS | 52 | 45 | 7 | 86.5% | 13.5% |
| overall | **208** | **172** | **36** | **82.7%** | **17.3%** |

end-users experience a “learning” process → adapt thresholds!

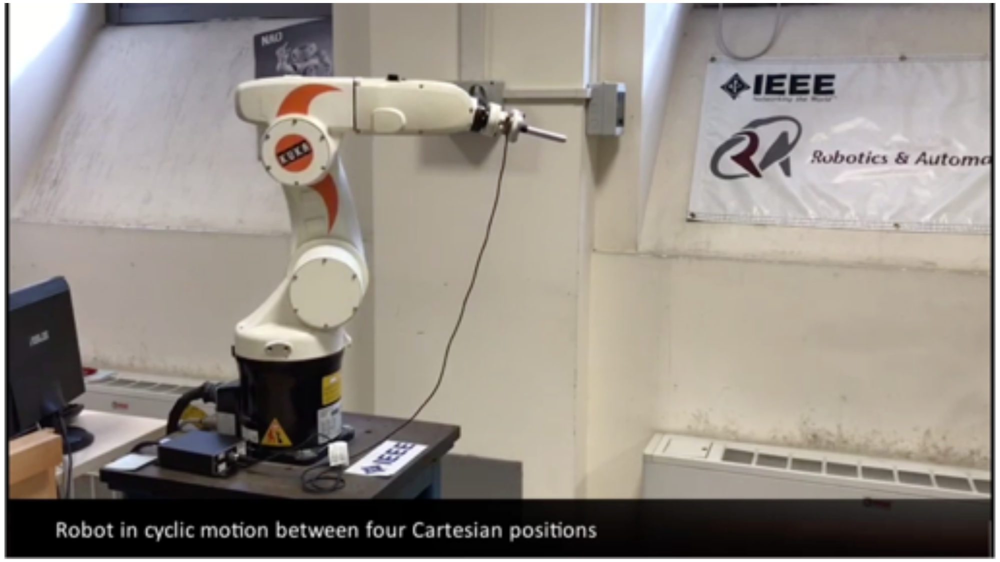
# Including the use of a F/T sensor to isolate whole-body collisions

collaboration
and collision
at end-effector

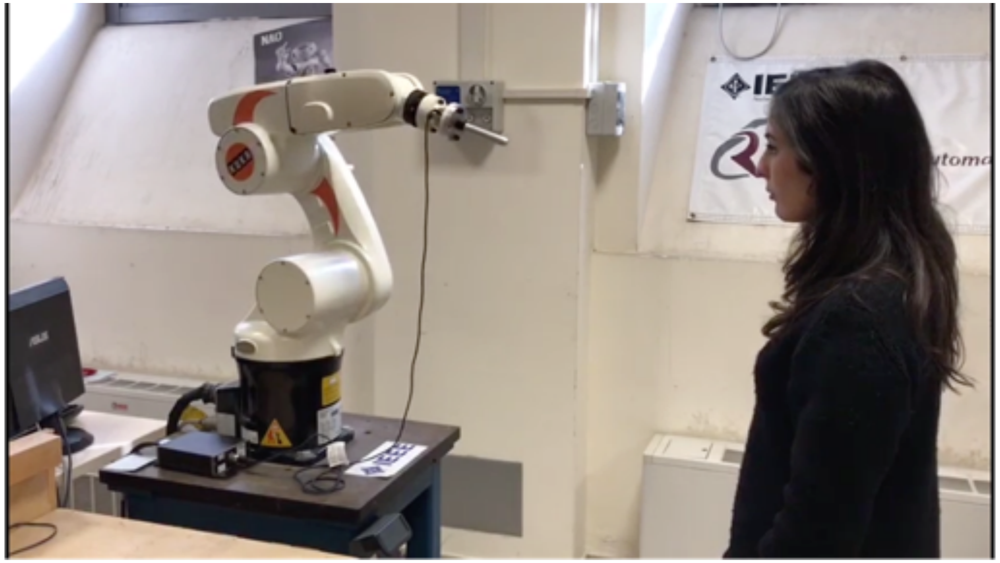
KUKA KR5 Sixx

*submitted to ICRA 2019*

collaboration
at end-effector
and collision
on robot body
(also simultaneously)



Robot in cyclic motion between four Cartesian positions



# Conclusions

- lightweight research manipulators
  - dynamic model more easily available, torque control mode, up to 1 KHz loops
  - safe collision detection, monitored coexistence, physical collaboration: **feasible**
- lightweight commercial manipulators
  - dynamic model to be identified, no access to current/torque control mode
  - certified control software for safety, **otherwise as above**
- full-size industrial robots in a cell
  - **coexistence** can still be achieved (using just kinematic motion commands)
  - safety requires low-level hardware in place and certified sensors for monitoring
  - **no** true physical collaboration
- medium-size robot with closed control architecture
  - “poor man’s” access/knowledge, user-defined control loops at low frequency
  - **moderate** physical collaborative features could be reached

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