Experiences with a control architecture enabling safe human-robot collaboration

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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
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

<table>
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<tr>
<th>Safety-rated monitored stop</th>
<th>Speed</th>
<th>Separation Distance</th>
<th>Torques</th>
<th>Operator controls</th>
<th>Main risk reduction</th>
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<td>Zero while operator in Collaborative WS</td>
<td>Small or zero</td>
<td>Gravity + load compensation only</td>
<td>None while operator in Collaborative WS</td>
<td>No motion in presence of operator</td>
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<th>Hand guiding monitored speed</th>
<th>Safety-rated monitored speed</th>
<th>Small or zero</th>
<th>As by direct operator input</th>
<th>E-stop; Enabling device; Motion input</th>
<th>Motion only by direct operator input</th>
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<th>Speed and separation monitoring</th>
<th>Safety-rated monitored speed</th>
<th>Safety-rated monitored distance</th>
<th>As required to execute application and maintain min separation distance</th>
<th>None while operator in Collaborative WS</th>
<th>Contact between robot and operator prevented</th>
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<tr>
<th>Power and force limiting</th>
<th>Max determined by RA to limit impact forces</th>
<th>Small or zero</th>
<th>Max determined by RA to limit static forces</th>
<th>As required by application</th>
<th>By design or control, robot cannot impart excessive force</th>
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Implementation of Safety, Coexistence, and Collaboration layers - 1

1. Sensorless collision detection (use this if everything else fails!): robot stops and is gravity compensated

2. 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
Digital implementation of Safety, Coexistence, and Collaboration layers - 2

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

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

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KUKA LBR 4+

ICRA 2012, IROS 2013, J Intell Rob Syst 2015
Implementation of Safety, Coexistence, and Collaboration layers - 3

1. **Physical collaboration**: contact force estimation combining internal signals and external depth sensing (virtual force sensor)

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

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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)


RGB & D views from the right Kinect
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

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**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...

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*from the manual* | *in use: a screenshot..*
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

\[
M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau + J_e^T(q)F_e + J_c^T(q)F_c
\]

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

\[
\tau_e = J_e^T(q)F_e \quad \tau_c = J_c^T(q)F_c
\]

- monitor the robot generalized momentum

\[
p = M(q)\dot{q}
\]

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

\[
r(t) = K_i \left( p - \int_0^t \left( C^T(q, \dot{q})\dot{q} - g(q) + \tau + J_e^T(q)F_e - r \right) ds \right)
\]

\[
K_i \rightarrow \infty \text{ (sufficiently large)} \quad \Rightarrow \quad r \simeq \tau_c
\]
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

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

as large as possible

- 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

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

3×6 for UR10

residual-based reaction to extra contacts

\[ \dot{q} = J^\# K_p (p_d - p) + (I - J^\# J_p) K_r r \]

- 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
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

Recognition of human gesture commands by an external Kinect

Kinect views of the real-time distance computation
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

- **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

\[ \dot{q}(d) \]

\[ \dot{q}_{\text{nom}} \]

\[ d_0 \]

\[ d_1 \]

\[ d_2 \]

\[ d \]
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
Collision detection and then stop - **KUKA KR5 Sixx**

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

**collisions are detected through motor currents high-pass filtering analysis**
Distinguish accidental collisions from intentional contact and then collaborate - **KUKA KR5 Sixx**

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)

416 contacts, half of which were intended to be soft

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)
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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