From human-robot interaction to collaborative control: A human centered perspective
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Control of Physical Human-Robot Interaction for Safe Collaborative Tasks

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Summary
A survey of pHRI/HRC research at DIAG Sapienza in the last decade

- **Control architecture for physical Human-Robot Interaction/Collaboration**
- **Safety**
  - detecting/isolating contacts and unexpected collisions in the presence of humans
  - reacting promptly in a safe mode
- **Coexistence**
  - human and robot actively sharing the same workspace
  - coordinated actions without contacts
- **Collaboration**
  - localization of physical interaction
  - estimation of exchanged forces between human and robot
  - robot control (admittance, force, impedance, hybrid motion-force, ...) for collaboration
- **Implementation**
  - on lightweight/research robots
  - on standard industrial robots
Handling of collisions and intentional contacts

Basic safety-related control problems in pHRI

collision detection/isolation and reaction
(without the use of external sensing)

workspace monitoring
for continuous collision avoidance
(while the task is running)

estimation and control
of intentional forces
exchanged at the contact
(without or with a F/T sensor)
for human-robot collaboration
A control architecture for physical HRI
Hierarchy of consistent robot behaviors (BioRob 2012)

Safety is the most important feature of a robot that has to work close to humans (requires collision detection and reaction)

Coexistence is the robot capability of sharing the workspace with humans (collision avoidance)

Collaboration occurs when the robot performs complex tasks with direct human coordination (mostly, with physical interaction)
Safe coexistence and collaboration in pHRI
Excerpt from the finalist video at IROS 2013

■ collaboration through contact force identification (here, at end-effector only)
A control architecture for physical HRI
Relation with ISO Standard 10218 and Technical Specification 15066

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- **Safety**:
  - Zero while operator in CWS
  - Small or zero
  - Gravity + load compensation only
  - None while operator in CWS
  - No motion in presence of operator

- **Coexistence**:
  - Safety-rated monitored speed
  - Small or zero
  - As by direct operator input
  - E-stop; Enabling device; Motion input
  - Motion only by direct operator input

- **Collaboration**:
  - Speed and separation monitoring
  - Safety-rated monitored speed
  - Safety-rated monitored distance
  - As required to execute application and maintain min separation distance
  - None while operator in CWS
  - Contact between robot and operator prevented
  - 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

- **ISO 10218-1/2:2011**
  - ISO 12100 IEC 61508
  - ISO 13849-1 IEC 62061
  - ISO 13850 ISO 13851

- **ISO/TS 15066:2016**
  - ANSI/R15.06
  - CAN/CSA-Z434
  - ISO TS 15066

- **Key Features**:
  - Collision detection and reaction
  - Workspace sharing – with collision avoidance
  - Coordinated motions & actions – with/without contact

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Collision event pipeline

Haddadin, De Luca, Albu-Schäffer (T-RO 2017)

Monitoring signals can be generated from sensors or models (signal- or model-based methods)

Context information is needed (or useful) to take the right or most suitable decision
Monitoring robot collisions

Applies to rigid and elastic joints, with and without joint torque sensing (IROS 2006)

\[ q, \dot{q} \]

normal mode of operation

\[ \tau \]

\[ F_K \]

without external or contact sensors

\[ \sigma = \text{energy-based scalar residual for detection} \]

\[ r = \text{momentum-based vector residual for detection and isolation} \]
Momentum-based residual

Block diagram for the generator of a vector residual signal (ICRA 2005, IROS 2006)

(rigid) robot with possible extra torque due to collision

\[
\hat{p}(0) = p(0)
\]

\[
r(t) = K_I \left[ p(t) - \int_0^t (\tau + C^T(q, \dot{q})\dot{q} - g(q) + r) ds - p(0) \right]
\]

\[
\dot{r} = -K_I r + K_I \tau_K
\]
Collision detection and reaction
Residual-based experiments on DLR LWR-III (IROS 2006, IROS 2008)

- collision detection followed by different reaction strategies
- zero-gravity behavior: gravity is always compensated first (by control)
- detection time: 2-3 ms, reaction time: + 1 ms

- admittance mode
- reflex torque
- reflex torque

\[
\dot{q}_r = K_Q r \\
\tau = K_R r
\]

first impact at 60°/s

first impact at 90°/s

3 videos
Sensitivity to payload changes/uncertainty

Collision detection and isolation after few moves for identification (IROS 2017)

an unknown payload (of 3 kg) is added

residuals with online estimated payload after 10 positioning

three collisions (link 6 \(\rightarrow\) 5 \(\rightarrow\) 5) detected & isolated by residuals when exceeding a threshold of 2 Nm

video
Collision reaction
Portfolio of possible robot reactions

residual amplitude $\propto$ severity level of collision

- Stop
- Reflex
- Preserve
- Reprise

Cartesian path (time scaling)
Cartesian trajectory (use of redundancy)
Task relaxation

all transitions are controlled by suitable thresholds on the residuals
Collision reaction
Further examples (IROS 2008)

- without external sensing
- implementation using joint torque sensing (not strictly needed)

- "volunteer" is Sami Haddadin
  (a master student at that time...)

- manipulator is position-controlled on a geometric path
- timing slows down, stops, possibly reverses

2 videos
Collision avoidance working in depth space

Efficient robot-obstacle distance computations in a 2½D space (ICRA 2012)

\[ p_x = \frac{xc \cdot f \cdot s_x}{z_c} + c_x \]
\[ p_y = \frac{yc \cdot f \cdot s_y}{z_c} + c_y \]
\[ d_p = z_c \]

**no** 3D-Cartesian reconstruction or models
**no** need to use Point Cloud Library (PCL)

Distances are used, e.g., with artificial potentials, for collision avoidance during motion or to slow down/stop the robot

One or two RGB-D sensors (Kinects) monitor the robot workspace @ 300 Hz with minimal gray areas

See also the video [https://youtu.be/iapfbAfklw4](https://youtu.be/iapfbAfklw4)
Safe human-robot coexistence

Excerpt from the finalist video at IROS 2013

- coexistence through collision avoidance using a single Kinect
- the robot is performing a cyclic positional task in the Cartesian space
Monitoring the workspace with two Kinects
...without giving away the depth space computational approach (RA-L 2016)

problems solved by the second camera
+ eliminates collision with false, far away “shadow” obstacles
+ reduces to a minimum gray areas, thus detects what is “behind” the robot
+ calibration is done off-line

real-time efficiency
extremely fast also with 2 devices: 300 Hz rate
(RGB-D camera has 30 fps, but the KUKA robot works at 0.5-1 KHz rate)
CAD model of the robot and equipments/tools/cables
Filtering out the right parts from the depth images
Safe coexistence in an industrial robotic cell

ABB IRB 4600 operation in an Abrasive Finishing cell with human access

- the robot is moving at max 100 mm/s
- no safety zones were defined in the ABB SafeMove software
- a risk analysis & a mitigation plan on the Kinect data and algorithm
  - e.g., when the view of one camera is obstructed, safety-certified laser sensors are used instead to estimate human distance (in a conservative way)
Coexistence with visual coordination

Robot motion coordinated with the human, avoiding proximity (IROS 2017, RCIM 2021)

- the robot tracks remotely & points to the head of the human (wearing Oculus Rift)
- it reacts so as to keep a safe distance to human and environment obstacles

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Distance and contact estimation

Using Kinect, CAD model, distance computation, and residual to localize contact (early 2014)

- When the residual indicates a contact/collision (and colliding link), the vertex in the robot CAD surface model with minimum distance is taken as the contact point.
- Algorithm applied here in parallel to both left and right hand (no other body parts).

- Parallel GPU computation on CUDA framework: distances between all robot points in virtual depth image and all obstacle points in filtered depth image (IROS 2017)
Force estimation for collaboration
Combining internal and external sensing

- **Task**
  - **localize** (in the least invasive way) points on robot surface where contacts occur
  - **estimate** exchanged *Cartesian forces*
  - **control** the robot to react to these forces according to a desired behavior

- **Solution idea**
  - model-based residuals to **detect** contact, **isolate** colliding link, and **identify** the joint torques associated to the external contact force
  - depth sensor to **classify** human part in contact with the robot and **localize** the contact point on the robot structure (and **contact Jacobian**)
  - **solve** a linear set of equations with the residuals, i.e., filtered estimates of joint torques resulting from contact **forces/moments** applied (anywhere) to the robot

\[ r \simeq \tau_{ext} = J_c^T(q)\Gamma_c = (J_{L,c}^T(q) \quad J_{A,c}^T(q)) \begin{pmatrix} F_c \\ M_c \end{pmatrix} \Rightarrow \begin{pmatrix} \hat{F}_c \\ \hat{M}_c \end{pmatrix} = (J_c^T(q))^\# \begin{pmatrix} r \end{pmatrix} \Rightarrow \hat{F}_c = (J_{Lc}^T(q))^\# r \]
Control based on contact force estimation

Used within an admittance control scheme (IROS 2014)
Additional validation of the virtual force sensor

In static and dynamic conditions, using a hand-held F/T sensor (February 2019)

- comparing the F/T ground truth contact force measure with its residual-based estimation
  - with robot at rest (pushing)
  - in robot motion (hitting)

2 videos
Estimation of the contact force

Sometimes, even **without** external sensing (T-RO 2017)

- if contact is sufficiently “down” the kinematic chain (≥ 6 residuals are available), the estimation of pure contact forces does not need any external information ...
Enhanced collision detection & identification

DLR SARA 7R robot with joint torque, base F/T and end-effector F/T sensors (ICRA 2021)

- generalized momentum-based residual exploiting the redundant sensing system
- handles multiple contacts, singularities, and external force/torque estimation

[Video]

Multiple contacts (dynamic)
Identification and localization of multiple contacts along the structure
Collision or collaboration?

Distinguishing hard/accidental collisions and soft/intentional contacts

- Using suitable low and high bandwidths for the residuals (first-order stable filters)

\[ \dot{r} = -K_I r + K_I \tau_K \]

- Thresholds prevent false collision detections

- Collision: stop & float ⇔ Contact: collaborate

![Graph showing residual vs time and frequency for collision or collaboration](image.png)
Collaboration control

Use of the estimate of external contact force for control (e.g., on a Kuka LWR)

- shaping the robot dynamic behavior in specific **collaborative tasks** with humans
  - joint carrying of a load, holding a part in place, whole arm **force** manipulation, ...
- robot motion controlled by
  - **admittance** control law (in **velocity** FRI mode)
  - **force**, **impedance** or **hybrid force-motion** control laws (in **torque** FRI mode)
    all implemented **at contact level**
- e.g., admittance control law using the estimated contact force
  - the scheme is realized at the single (or first) contact point
  - desired **velocity** of contact point taken proportional to (estimated) contact force

\[
\dot{p}_c = K_a F_a, \quad K_a = k_a I > 0
\]

\[
F_a = \hat{F}_c + K_p (p_d - p_c), \quad K_p = k_p I > 0
\]

initial contact point position when interaction begins
Contact force regulation with virtual force sensing
Human-robot collaboration in torque control mode (ICRA 2015)

- contact force estimation & control (any place/any time)

see ICRA 2015 trailer (at 3’26’’): https://youtu.be/glNHq7MpcG8 (Italian); https://youtu.be/OM_1F33fcWk (English)
Impedance-based control of interaction

Reaction to contact forces by generalized impedance — at different levels

- **Joint** impedance needs joint torque sensors
- **Cartesian** impedance needs F/T sensor
- **Contact point** impedance without force/torque sensing, by estimation of the contact force

consider a fully rigid robot
Control of generalized impedance

HR collaboration at the contact level (ICRA 2015)

natural (unchanged) robot inertia at the contact

\[ M_d = \left( J_c M^{-1} J_c^T \right)^{-1} \]

assigned robot inertia at the contact with different desired masses along \( X, Y, Z \)

contact force estimates are used here only to detect and localize contact in order to start a collaboration phase

contact force estimates used explicitly in control law to modify robot inertia at the contact

\( M_{d,X} = 20, M_{d,Y} = 3, M_{d,Z} = 10 \) [kg]

2 videos
Control of generalized contact force

Task-compatible force control scheme (ICRA 2015)

- regulation of the **norm** of the contact force along the **instantaneous direction** of the **estimated** contact force

\[
F_{d,x} = 15 \frac{\hat{F}_{c,x}}{\| \hat{F}_c \|}, \quad F_{d,y} = 15 \frac{\hat{F}_{c,y}}{\| \hat{F}_c \|}, \quad F_{d,z} = 15 \frac{\hat{F}_{c,z}}{\| \hat{F}_c \|} \quad \Leftrightarrow \quad \| F_d \| = 15 \ [N]
\]

- in static conditions, the force control law is able to regulate contact forces **exactly**

**task-compatible control of contact force**
Validation with an extra F/T sensor

**Force** and hybrid force/velocity control for collaboration at contact level (February 2019)

- desired contact force along the estimated contact direction regulated at 15 N
- ... and trajectory control with constant speed along a circle in the orthogonal plane

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Control experiment 4:
Hybrid force/velocity control scheme

Control experiment 3:
Force control scheme

2 videos
Scenario for HRC in manual polishing

H2020 SYMPLEXITY project: Preparing a metallic part for a laser polishing machine

- Calibration
- Ethernet receiver node (C++ code)
- Distance computation with Kinect (C++ code)
- Socket TCP/IP
- Host PC
- Robot controller (C++ code)
- Slow down / stop signal
- Digital I/O
- QISAB CWS
- LP machine
- Video

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Scenario for HRC in manual polishing
Distinguishing different contact forces (with F/T sensor)

- 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
HRC phase with **UR10 robot**

Experimental results (Mechatronics 2018)

**no F/T sensor, switching to FreeDrive mode**

**with F/T sensor, using our residual method**

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Collaboration phase activated by hand waving (using a Kinect)

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3 videos
both forces at the same time...

in all cases, no linear motion of EE position!

polishing force only...

extra body force detected ...
... joints move accordingly

... no joint motion ...
... joints move due to extra body force only
Use of kinematic redundancy in pHRI

Robot reaction to collisions, in parallel with execution of original task

- collision detection $\Rightarrow$ robot reacts so as to preserve as much as possible (if at all possible) the execution of a planned task trajectory, e.g., for the end-effector.

\[
\tau = M(q)G(q) \left[ \ddot{x} - \dot{J}(q)\dot{q} + J(q)M^{-1}(q)n(q,\dot{q}) \right]
+ M(q)(I - G(q)J(q))M^{-1}(q)\tau_0.
\]
Selective reaction to estimated contact force
Robot control strategy (IROS 2008, IROS 2017)

- execution of original end-effector task preserved while reacting to a detected contact, when the estimated contact force is above a threshold $F_{relax}$ but is not too large
- using null-space motion, the robot tries to eliminate, reduce or keep low the contact force
- if the contact force exceeds a threshold $F_{abort}$, the robot abandons the original task and reacts with admittance control at the contact
Use of kinematic redundancy
Robot reaction to collisions, in parallel with execution of original task (IROS 2017)

idle ⇔ relax ⇔ abort
HRC under a closed control architecture

KUKA KR5 Sixx R650 robot

- low-level motor control laws are not known and not accessible by the user
- user programs based on exteroceptive sensors (vision, Kinect, F/T sensor) implemented on external PC and communicate via RSI (RobotSensorInterface) with KUKA controller every 12 ms
- available robot measures are joint positions (by encoders) and (absolute value of) applied motor currents
- the only user commands for the controller, are velocity or position references in joint (or Cartesian) space

**typical motor currents on first three joints**
Distinguish accidental collisions from intentional contacts
... and then either stop or start to collaborate (ICRA 2013)

using high-pass and low-pass filtering of motor currents
— here collaboration mode is manual guidance of the robot
Combining motor currents and F/T sensor data
Enhanced flexible interaction by filtering, thresholding, merging signals (ICRA 2019)

interaction may occur at the **end-effector**, on **robot body**, or both

2 videos
Conclusions

Toward a safer and efficient control of human-robot physical collaboration

- framework for safe human-robot coexistence and collaboration, based on a hierarchy of consistent, **controlled** behaviors of the robot
  - collision detection (and isolation) with model-based residuals
  - portfolio of collision reaction algorithms (using also redundancy)
  - real-time collision avoidance based on data processed in depth space
  - coexistence with visual coordination
  - distinguishing intentional/soft contacts from accidental/hard collisions
  - estimation of contact force and location, by combining inner/outer sensing
  - “control bricks” for collaborative tasks
    - admittance/impedance/force/hybrid laws, generalized at the contact level
  - useful behaviors can be obtained also with limited model information
  - applications are coming from industrial and service stakeholders
  - many interesting research extensions ahead
    - human motion and intention prediction, merging models and data
    - integration with AI-based cognitive HRI modules
Our team at DIAG
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References


