Elective in Robotics/Control Problems in Robotics

Physical Human-Robot Interaction
Coexistence and Collaboration

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Human-friendly robotics

The goal

- Co-workers on factory floor
- Personal robots in service

Traditional robotics

Replacing humans

Human-friendly robotics

Collaborating with humans

pHRI
SAPHARI concept
Place the human at the center of the entire robot development

FP7 ICT EU project (2011-15)

address all essential aspects of safe and intuitive physical interaction between humans and complex human-like robots in a strongly integrated way
Handling of collisions and intentional contacts

Basic safety-related control problems in physical Human-Robot Interaction (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 (with or without a F/T sensor) for human-robot collaboration
Safe physical Human-Robot Interaction (pHRI)

Control architecture of consistent robot behaviors (De Luca, Flacco: IEEE BioRob 2012)

- integrated design & use of soft mechanics, actuation, (proprio- and exteroceptive) sensing, communication, and control algorithms
Safety is the most important feature of a robot that has to work close to human beings.

Classical solutions for preserving safety in industrial environments, i.e., using cages or stopping the robot in the presence of humans [ISO 10218], are inappropriate for pHRI.
**Physical HRI**

Hierarchy of consistent behaviors

**Safety**

**Coexistence** is the robot capability of sharing the workspace with other entities, most relevant with humans.

Human (and robot!) safety requirements must be always guaranteed (i.e., **safe coexistence**)

Original robot task

Sharing the workspace without the need of physical contacts

Safe HR coexistence
Physical HRI
Hierarchy of consistent behaviors

Collaboration occurs when the robot performs complex tasks with direct human interaction and coordination.

Two modalities which are not mutually exclusive: contactless and physical.

- Gestures or voice commands with visual coordination
- Intentional contact and exchange of forces
Types of collaborative operations
Qualification of our control architecture for pHRI

Relation with ISO Standard 10218 and Technical Specification 15066

<table>
<thead>
<tr>
<th>Speed</th>
<th>Separation distance</th>
<th>Torques</th>
<th>Operator controls</th>
<th>Main risk reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Safety-rated monitored stop</td>
<td>Zero while operator in CWS</td>
<td>Small or zero</td>
<td>Gravity + load compensation only</td>
<td>None while operator in CWS</td>
</tr>
<tr>
<td>Hand guiding</td>
<td>Safety-rated monitored speed</td>
<td>Small or zero</td>
<td>As by direct operator input</td>
<td>E-stop; Enabling device; Motion input</td>
</tr>
<tr>
<td>Speed and separation monitoring</td>
<td>Safety-rated monitored speed</td>
<td>Safety-rated monitored distance</td>
<td>As required to execute application and maintain min separation distance</td>
<td>None while operator in CWS</td>
</tr>
<tr>
<td>Power and force limiting</td>
<td>Max determined by RA to limit impact forces</td>
<td>Small or zero</td>
<td>Max determined by RA to limit static forces</td>
<td>As required by application</td>
</tr>
</tbody>
</table>

- collision detection and reaction
- workspace sharing – with collision avoidance
- coordinated motions & actions – with/without contact
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 decisions
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

3 videos (as in Block #3)

<table>
<thead>
<tr>
<th></th>
<th>Admittance mode</th>
<th>Reflex torque</th>
<th>Reflex torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>First impact</td>
<td>60°/s</td>
<td>90°/s</td>
<td></td>
</tr>
<tr>
<td>$\dot{q}_r = K_Q r$</td>
<td>$\tau = K_R r$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$pHRI$
Coexistence
Early days and yesterday ...

video
https://youtu.be/7IMfLzihCRE

informational video by National Institute for Occupational Safety and Health (USA)

1989

commercial video by ABB Robotics on EPS (Electronic Position Switch) and early SafeMove software

video (see also Block #1)
https://youtu.be/Fo_RvSmqZF8
Coexistence
Today and ... tomorrow?

SafeMove2
Safety certified monitoring of robot motion, tool and standstill supervision

Nov 2016, Singapore

IROS 2013
Best Video Award Finalist

Safe Physical Human-Robot Collaboration
Fabrizio Flacco  Alessandro De Luca
Robotics Lab, DIAG
Sapienza Università di Roma
March 2013

https://youtu.be/pIIhY8E3HFg
commercial video by ABB Robotics of SafeMove2 software (using 2 laser scanners)

https://youtu.be/2ad_ol_4eJ8

2016 video

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https://youtu.be/2ad_ol_4eJ8

2016 video
Coexistence

Industrial/conventional solutions waste free space or work only for occasional proximity...

https://youtu.be/_MVruSKhpHA

video
SafetyEye in EU project **X-act**

3-part video (see also Block #1)

https://youtu.be/dVVvoxDDkT8

evaluating in real-time the severity of a possible collision (**MeRLIn**@**PoliMI**)

- protective stop
- evasive motion
- speed reduction
- no special action
Collision avoidance
Using exteroceptive sensors to monitor robot workspace (ICRA 2010)

- **external sensing**: stereo-camera, TOF, structured light, depth, laser, presence, ...
  placed optimally to minimize occlusions (robot can be removed from images)
Depth image

How to use it?

Configuration Space

Cartesian Space

Depth Space

pHRI
Fusing multiple Kinects to survey human-robot workspaces

C. Lenz, M. Grimm, T. Röder, A. Knoll

Robotics and Embedded Systems
Technische Universität München

https://youtu.be/igp3UdIdDGA
Configuration space
Possible, but typically only for few dofs (here with a McKibben VSA-based arm)

Real time control for safe human-robot coexistence using stereo vision

The manipulator performs the assigned task until an unknown obstacle is detected.

video
Univ Pisa
Depth space
A 2.5-dimensional space

- non-homogeneous 2.5 dimensional space
  - $x, y$ position of the point in the image plane [pixel]
  - $d$ depth of the point with respect to the image plane [m]
- depth space is modeled as a pin-hole sensor
- point in Cartesian reference frame $P_R = (x_R, y_R, z_R)$
- point in sensor frame $P_C = RP_R + t = (x_C, y_C, z_C)$
- point in depth space

\[
\begin{align*}
p_x &= \frac{x_C f s_x}{z_C} + c_x \\
p_y &= \frac{y_C f s_y}{z_C} + c_y \\
d_p &= z_C
\end{align*}
\]
Depth space
Distance evaluation

- distance between a point of interest $P_D = (p_x, p_y, d_p)$ and an obstacle point $O_D = (o_x, o_y, d_o)$

$$
\begin{align*}
    v_x &= \frac{(o_x - c_x)d_o - (p_x - c_x)d_p}{f \cdot s_x} \\
    v_y &= \frac{(o_y - c_y)d_o - (p_y - c_y)d_p}{f \cdot s_y} \\
    v_z &= d_o - d_p
\end{align*}
$$

(if obstacle point is closer than point of interest, set $d_o = d_p$)

$$
\text{dist}(P, O) = \sqrt{v_x^2 + v_y^2 + v_z^2}
$$
Repulsive vector
A version of artificial potentials

- **repulsive vector** generated from the distance vector \( \mathbf{D}(P, O) = (v_x, v_y, v_z) \)

\[
V_C(p, O) = v(P, O) \frac{\mathbf{D}(P, O)}{||\mathbf{D}(P, O)||}
\]

\[
v(P, O) = \frac{V_{max}}{1 + e^{\frac{-D(P, O)}{2(\rho)\alpha}}}
\]

- repulsive vectors due to all obstacles near to point of interest are considered
  - **orientation** ⇒ sum of all repulsive vectors, **magnitude** ⇒ nearest obstacle only
  - inclusion of a **pivoting** strategy to avoid local minima or “too fast” obstacles
Obstacle velocity
The pivot method (similar to a vortex field)

- for moving obstacles that are faster than the control point (on the robot)
Motion control
Different handling of end-effector and other control points on the robot

- **end-effector** repulsive vector → repulsive velocity added to the original task velocity
- collision avoidance for the whole **robot body** (e.g., 8 control points)
  - repulsive vector
  - Cartesian constraints
  - joint velocity limits modification (using SNS)
- fluid, **jerk-limited** motion → human feeling of safety

www.reflexxes.com

Reflexxes GmbH
Safe coexistence
Collision avoidance in depth space (BioRob 2012)

video
https://youtu.be/ZQ_nRkAiv8g
video

https://youtu.be/iapfbAfklw4

resuming a cyclic Cartesian task as soon as possible ...
Monitoring the workspace with two Kinetics

... without giving away the depth space computational approach (RA-L 2016)

When a single camera is used the robot avoids occluded points even when generated by a far obstacle; the second camera will avoid this.

- eliminates collision with false, far away “shadow” obstacles
- reduces to a minimum gray areas, thus detects what is “behind” the robot
- relative calibration of the two Kinects is done off-line

video
https://youtu.be/WIw_Uj_ooYI

real-time efficiency
algorithm extremely fast also with 2 devices: 300 Hz rate (RGB-D camera has 30 fps)
SYMPLEXITY cell for robotized work on metallic surfaces
For abrasive finishing/fluid jet polishing tasks & for human-robot quality assessment

ABB IRB 4600-60 robot, with integrated SafeMove option

certified communication with cell PLC, using ProfiSAFE protocol

due to the intrinsic risks in the technological process, only for HR coexistence during visual check and measuring phase or for contactless collaboration

2 external Kinects to recognize human gestures (e.g., automatic door opening, ...)

initially ... 2 internal Kinects (placed at the top corners of the cabin) for monitoring human-robot distances

SYMPLEXITY  H2020 FoF EU project (2015-18)

two external  two internal
Additional safety hardware
Certified laser scanners to be used in parallel with the Kinects

- **two laser scanners** KEYENCE SZ-V 32n placed at calf height (~50 cm)
- maximize **coverage** of the free area inside 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
- a **cascaded solution** of Kinects/laser scanners is a viable compromise between certified safety and more flexible sharing of the 3D workspace by human and robot
CAD robot model and equipment in depth images

Considering **CWS laser measuring device, cables** or other equipment in distance computation

for each robotic set up, the suitable CAD model for depth space subtraction is loaded at start
Implemented control and communication architecture

Two *Kinects* for accurate HR distance monitoring, two *laser scanners* for backup safety
Safe coexistence in an industrial robotic cell

**ABB IRB 4600** operation in an abrasive finishing cell with human access

- robot is moving at max 100 mm/s
- no safety zones were defined in ABB SafeMove
- Kinects **OK** (except when the view of one of the cameras is obstructed on purpose)
**Collaboration**

Contactless or physical

- In **contactless** collaboration, robot (or human!) actions are guided or follow from an exchange of information without physical interaction:
  - this can be achieved via **direct communication**, e.g., with gestures and/or voice commands,
  - or via **indirect communication**, by recognizing human intention or attention, e.g., through eye gaze,
  - another form is **visual coordination** in which vision is used to coordinate human-robot relative motion.

- In **physical** collaboration, there is an explicit and intentional contact with exchange of forces between human and robot:
  - by measuring or **estimating contact forces**, the robot can predict human motion intention and react accordingly to it,
  - collaborative tasks (e.g., human and robot carrying a heavy object) require **control of exchanged forces (and motion)** at the contact.
Contactless collaboration
Using gesture and voice commands

- human body parts and gesture recognition

- speech recognition

voice command

collaboration starts
Human-robot communication
Using Kinect and SDK library

- the robot end-effector **position** is commanded by voice/gestures to **follow** (or **go to**) the human **left**, **right**, or **nearest** hand

[Video]

**pHRI**

35
Gesture communication in SYMPLEXITY cell

Using Kinect 2.0 RGB-D sensor, with built-in skeleton tracking

- initial 5 sec gesture to activate
- both hands open = start motion
- both hands closed = stop robot
- left closed + right open = limit speed
- left open + right closed = recover speed
- final gesture to deactivate
Visual coordination task
Dual formulations of human-robot relative tracking (IROS 2017)

- camera **on robot**, pointing to moving human head/face kept at a certain relative position
- camera **on human head**, with robot pointing to it and kept at a certain relative position

- different Cartesian motion tasks of varying dimension $m \leq n$
- cone represents a relaxation of the pointing task by some relative angle $\alpha_d$
Simulation
Motion control using Task Augmentation method

- Camera tracing a circle in a vertical plane, while pointing direction is kept constant
- ROS environment, integrated with robot simulator V-REP

Position errors < 1.5 mm
Pointing error < 0.006

Video
**Experiment of visual coordination**

KUKA LWR robot in ROS environment with FRI

https://youtu.be/SRfpNrZD7k0

**Visual Coordination Task for Human-Robot Collaboration**

Maram Khatib, Khaled Al Khudir, Alessandro De Luca

Robotics Lab, DIAG
Sapienza Università di Roma
March 2017

position error $\leq 5\, \text{cm}$
pointing error $< 0.03\, \text{rad}$

also in **multi-sensory** operation

**Video**
Visual coordination with Augmented Reality
Multi-sensory operation with collision avoidance

https://youtu.be/qa8lOu9ymLg
Safe human-robot interaction
From coexistence to physical collaboration

coexistence through collision avoidance

physical collaboration through contact identification (here, end-effector only)

https://youtu.be/pIIhY8E3HFg
distance and contact point localization

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

- **depth image** is acquired by a Kinect
- robot is removed from image (URDF filter by TUM), starting from its 3D CAD model
- human hand tracking on filtered image
- **3D CAD model of robot** and hand position are used to localize contact point on robot surface
- surfaces of robot links are modeled using polygonal patches
- 3D robot model is projected in workspace with a calibration matrix
- **distances are computed** between vertices of patches and the human hand
- ranges vary from about 20 cm (area of interest) down to 0 (contact)
- **residuals** are always zero when robot moves in free space
Distance and contact point localization

Use residuals to detect the contact event, also for multiple locations

- 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)

video
the algorithm, based on distance computation in depth space, takes advantage of a CUDA framework for massively parallel GPU programming; three 2.5D images are processed:

- real depth image $I_r$, captured by a RGB-D sensor (a Kinect)
- virtual depth image $I_v$, containing only a projection of the robot CAD model
- filtered depth image $I_f = f(I_r, I_v)$, containing only the obstacles

parallel distance computations between all robot points in virtual image and all obstacle points in filtered image (same time needed to localize one or multiple contact points!)
Contact force estimation
Combining internal and external sensing

▪ task
  ▪ localize (in the least invasive way) points on robot surface where contacts occur
  ▪ estimate exchanged \textbf{Cartesian} forces
  ▪ control the robot to react to these forces according to a desired behavior

▪ solution idea
  ▪ use residual method to \textbf{detect} physical contact, \textbf{isolate} the colliding link, and \textbf{identify} the joint torques associated to the external contact force
  ▪ use a depth sensor to \textbf{classify} the human parts in contact with the robot and \textbf{localize} the contact points on the robot structure (and the \textbf{contact Jacobian})
  ▪ \textbf{solve} a linear set of equations with the residuals, i.e., estimates of joint torques resulting from \textbf{contact wrenches (forces/moments)} applied anywhere to the robot

\[
\mathbf{r} \simeq \mathbf{\tau}_{ext} = \mathbf{J}_c^T(q)\mathbf{\Gamma}_c = \begin{pmatrix} \mathbf{J}_{L,c}^T(q) & \mathbf{J}_{A,c}^T(q) \end{pmatrix} \begin{pmatrix} \mathbf{F}_c \\ \mathbf{M}_c \end{pmatrix}
\]
Contact force estimation
Some simplifying assumptions

- dealing with contact forces
  - most **intentional** contacts with a single human part (hand, arm, fingers) are **not** able to transfer relevant **moments**
  - to estimate reliably $\Gamma_c$ we should have rank $J_c = 6$, which is true only if the robot has $n \geq 6$ joints and the contact occurs at a link with index $\geq 6$
    
    $$M_c = 0$$

    only a **pure Cartesian force** is considered

- dimension of the task related to the contact force is now $m = 3$ and its **estimation** is
  
  $$r \simeq \tau_{ext} = J^T_{Lc}(q)F_c \quad \Rightarrow \quad \hat{F}_c = \left( J^T_{Lc}(q) \right)^\# r$$

  the contact Jacobian can be evaluated once the contact point is detected by the external depth sensor that closely monitors the robot workspace

  this procedure represents a so-called **virtual force sensor**
evaluation of estimated contact force

\[ \hat{F}_c = \left( J_c^T(q) \right)^\# r \]

- estimation accuracy was initially tested using known masses in known positions
- a single mass hung either on link 4 or on link 7, to emulate a single (point-wise) contact
- a mass hung on link 7, and then a second on link 4 to emulate a double contact

<table>
<thead>
<tr>
<th>Link #</th>
<th>Mass</th>
<th>( F_z )</th>
<th>( \hat{F}_z )</th>
<th>Deviation</th>
<th>( \hat{F}_z )</th>
<th>Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1.93</td>
<td>-18.93</td>
<td>-18.75</td>
<td>0.95%</td>
<td>-4.46</td>
<td>76.43%</td>
</tr>
<tr>
<td>7</td>
<td>1.93</td>
<td>-18.93</td>
<td>-18.91</td>
<td>0.1%</td>
<td>-18.82</td>
<td>0.58%</td>
</tr>
</tbody>
</table>

case of two masses
On-line estimation of contact force

Used within an admittance control scheme (IROS 2014)

https://youtu.be/Yc5FoRGJsrc

Estimation of Contact Forces using a Virtual Force Sensor

Emanuele Magrini, Fabrizio Flacco, Alessandro De Luca

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

February 2014
On-line estimation of contact force
Evolution of residuals, estimated forces, and compliant displacements

- control gains are chosen so as to assign a stiff behavior at a reference configuration
- at a given time, human pushes on robot link 3
- due to the stiff robot behavior, a large force needs to be applied to move the robot
- when the hand is removed, the contact point returns smoothly to its initial position (zero error)

see slide #60 for the chosen admittance control scheme
Further validation of 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)

Estimation of contact force

Some limitations of the residual method

- **multiple** simultaneous contacts can be considered (e.g., with both human hands)

\[
\begin{pmatrix}
\hat{F}_1 \\
\hat{F}_2 \\
\end{pmatrix} = \left( J_{L1}^T(q) \quad J_{L2}^T(q) \right) \# r
\]

but with much **less confidence** in the resulting force estimates (detection is still ok)

- **estimates** will be limited only to those components of \( F_c \) which can be detected by the residual (i.e., that produce work on robot motion)

- **forces** \( F_c \in \mathcal{N}(J_c^T(q)) \) will never be recovered \( \Leftrightarrow \) they are ‘absorbed’ by the robot structure
A closer analysis

Which force components are being estimated? Do we really need external sensing?

- a simple 3R planar case, with contact on different links

\[
\text{rank } \{ J_{c1} \} = 1
\]

- only normal force to link, if contact point is known (1 informative residual signal)

\[
\text{rank } \{ J_{c2} \} = 2
\]

- full force on link, if contact point is known (2 informative residuals)

\[
\text{rank } \{ J_{c3} \} = 2
\]

- full force on link, even without knowing contact (3 informative residuals)

\[ \hat{F}_i \]

\[ \text{forces } F_k \in \mathcal{N}(J_k^T(q)) \] will never be recovered (even with known contact)

see also: Note1_Estimation of contact forces in 3R planar arm [Ex_Rob2_15Jul2013]
if contact is sufficiently “down” along the kinematic chain (≥ 6 residuals available), the estimation of pure contact forces does not need any external information ...

see also: Note2_Estimation of contact force & location from link frame info [Zurlo_etal_ICRA23]
A sensitive flexible skin

Conformable force/tactile skin for pHRI (detection, reaction, and collaboration)

- an array of optoelectronic sensor modules (each with 4 taxels) capable of measuring the position of the contact point and the 3 components of the applied force with high repeatability and accuracy

video https://youtu.be/ycJZYZLqDi0

PrismaLab @UniNapoli
Additional F/T sensor at the base

Combining real & virtual sensors for estimating interaction forces/moments (IROS 2016)

- Recursive Newton-Euler Algorithm (fed by the residuals) for ground force/moment prediction
- comparison with base F/T sensor readings

KUKA 6-dof Agilus robot (@Augsburg)

- an external wrench acting on link $l$ will only affect the first $l$ components of $\tau_{ext}$
- effect of $F_{ext}$ on $\tau_{ext}$ depends on point $p_l$ while that of $M_{ext}$ does not, since only the contact link is relevant (isolated by residual)

Table of possible options/improvements for a contact wrench $W_{ext,l} = (F_{ext,l}, M_{ext,l})$

<table>
<thead>
<tr>
<th>$l$</th>
<th>Known $p_l$</th>
<th>Unknown $p_l$ with pure contact force</th>
</tr>
</thead>
<tbody>
<tr>
<td>any</td>
<td>Estimate $W_{ext,l}$</td>
<td>Estimate $F_{ext,l}$ and $p_l$</td>
</tr>
<tr>
<td>any</td>
<td>Estimate $F_{ext,l}$</td>
<td>Estimate $F_{ext,l}$</td>
</tr>
<tr>
<td>$\geq 3$</td>
<td>Estimate $W_{ext,l}$</td>
<td>Estimate $F_{ext,l}$ and $p_l$</td>
</tr>
<tr>
<td>$\geq 6$</td>
<td>Estimate $W_{ext,l}$</td>
<td>Estimate $F_{ext,l}$ and $p_l$</td>
</tr>
</tbody>
</table>
Sensing redundancy in DLR SARA robot

Introducing more sensors: F/T at the wrist, Joint Torque sensors, F/T at the base (ICRA 2021)

- new 7R design with enlarged workspace and fully integrated sensors
- sensor data and control loop at 8 KHz
- 1250 mm outreach, up to 400°/s joint speed, 22.6 kg weight, 12 kg payload, 0.1 N force resolution

- add extra passive coordinates $q_{TCP}$, $q_{UI}$, $q_{b}$ at the force/torque sensing locations
- set associated constraints in the dynamics
Sensing redundancy in DLR SARA robot

Extended dynamic description and momentum-based residual (ICRA 2021)

\[
\begin{align*}
\bar{q} &= \begin{pmatrix} q_b \\ q \\ q_{ui} \\ q_{ee} \end{pmatrix}, \\
\bar{\tau}^{ext} &= \begin{pmatrix} \tau_b^{ext} \\ \tau_{ui}^{ext} \\ \tau_{ee}^{ext} \end{pmatrix}
\end{align*}
\]

\[
\begin{align*}
M(\bar{q})\ddot{\bar{q}} + \bar{C}(\bar{q}, \dot{\bar{q}})\dot{\bar{q}} + \bar{g}(\bar{q}) &= \bar{\tau} + \bar{\tau}^{ext} + A^T(\bar{q})\lambda \\
A(\bar{q})\dot{\bar{q}} &= 0
\end{align*}
\]

Constraints on extra DOFs in the dynamic model

\[
\begin{align*}
\bar{r}(t) &= K \left( \bar{p}(t) - \int_{0}^{t} \left( \bar{\tau}^s + \bar{C}^T(\bar{q}, \dot{\bar{q}})\dot{\bar{q}} - \bar{g}(\bar{q}) + \bar{r} \right) ds - \bar{p}(0) \right) \\
\bar{p} &= \begin{pmatrix} p_b \\ p \\ p_{ui} \\ p_{ee} \end{pmatrix} = \bar{M}(\bar{q})\dot{\bar{q}}, \\
\bar{\tau}^s &= \begin{pmatrix} \tau_b^s \\ \tau_{ui}^s \\ \tau_{ee}^s \end{pmatrix}
\end{align*}
\]

\[
\dot{\bar{r}} = K(\bar{\tau}^{ext} - \bar{r}) \quad \bar{r} \rightarrow F^{ext}
\]

Including transposed Jacobians and logical processing
Sensing redundancy in DLR SARA robot
Contact localization & force estimation, handling singularities, multiple contacts (ICRA 2021)

video @ICRA21
Collision or collaboration?

Distinguishing **hard/accidental** collisions and **soft/intentional** contacts

- using suitable **low** and **high** bandwidths for the residuals (first-order stable filters)
  \[ \dot{r} = -K_I r + K_I \tau_K \]
- a **threshold** is added to prevent false collision detection during robot motion

```latex
\text{for generic } j\text{-th joint}
```

**pHRI**
Collaboration control

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

- shaping the robot dynamic behavior in specific **collaborative tasks** with human
  - 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 (needs **torque** FRI mode)
    - all implemented at contact level
- e.g., admittance control law using estimated contact force (as in video/plots of slides #48-49)
  - 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 (anywhere/anytime)

![Contact force regulation](image)

**see ICRA 2015 trailer (at 3’26’’):**
- [https://youtu.be/glNHq7MpCG8](https://youtu.be/glNHq7MpCG8) (Italian)
- [https://youtu.be/OM_1F33fcWk](https://youtu.be/OM_1F33fcWk) (English)
Impedance-based control of interaction

Reaction to contact forces by generalized impedance — at different levels

Consider a fully rigid robot

**Joint** impedance
needs joint torque sensors

**Cartesian** impedance
needs F/T sensor

**Contact** point impedance
without force/torque sensing, with estimation of contact force

$pHRI$ 62
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 apparent masses along \( X, Y, Z \)

4-part video (+ next 2 slides)

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])

https://youtu.be/NHn2cwSyCCo
Control of generalized contact force

Direct force scheme

- explicit regulation of the contact force to a desired value, by imposing

\[ M_d \ddot{x}_c + K_d \dot{x}_c = K_f (F_d - \hat{F}_c) = K_f e_f \]

- a force control law needs always a measure (here, an estimate) of contact force

- task-compatibility: human-robot contact direction vs. desired contact force vector

\[ F_{d,x} = 0, \quad F_{d,y} = 15N, \quad F_{d,z} = 0 \]

however, drift effects due to poor control design

https://youtu.be/2X1e2PxwUKo
Control of generalized contact force
Task-compatible force control scheme (ICRA 2015)

- only the **norm** of the desired contact force is controlled 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**

---

... video

[task-compatible control of contact force](https://youtu.be/2X1e2PxwUKo)
Collaboration control
Hybrid force/velocity control scheme (ICRA 2016)

- it allows to control both contact force and motion in two mutually independent sub-spaces
- extends at the contact level a hybrid force/velocity control law, with the orientation of contact task frame being determined instantaneously
- task frame obtained by a rotation matrix $R_t$ such that $z_t$ is aligned with the estimated contact force
  \[
  R_t = \begin{bmatrix}
  u & v & w \\
  u & v & \frac{\hat{F}_c}{\|\hat{F}_c\|}
  \end{bmatrix}
  \]
- after feedback linearization with $\tau = Ma + n - J_c^T \hat{F}_c$, the acceleration command is
  \[
  a = J_c^# M_d^{-1} (R_t a_c + M_d (\dot{R}_t^T \dot{x}_c - J_c \dot{q})) + P_c \ddot{q}_0
  \]
- complete decoupling between force control and velocity control can be achieved by choosing the new auxiliary control $a_c$ input as
  \[
  a_c = S_f^c \dddot{f} + S_v^c \dot{v}
  \]
Collaboration control

Hybrid force/velocity control scheme

- the force regulation task should be along the instantaneous direction of the applied external force while the motion control task lives in the orthogonal plane
- the selection matrices are chosen as

\[
S_f^c = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \quad S_\nu^c = \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}
\]

- regulation of the contact force to desired constant value \( F_d > 0 \) is obtained choosing

\[
\ddot{y}_f = k_f \left( F_d - \| \hat{F}_c \| \right) - k_{df} y_f
\]

- control of the desired velocity can be achieved using

\[
\dot{\nu} = \dot{\nu}_d + K_d (\nu_d - \nu) + K_i \int_0^t (\nu_d - \nu) \, ds,
\]

- the final control acceleration input becomes

\[
a = J_c^\# M_d^{-1} \left[ R_t S_f^c (k_f e_f - k_{df} y_f) + R_t S_\nu^c (\dot{\nu}_d + K_d \dot{\nu} + K_i \nu) \\
+ M_d \dot{R}_t^c \dot{x} - M_d J_c \dot{q} \right] + P_c \ddot{q}_0,
\]
Collaboration control

Hybrid force/velocity control at contact level (IROS 2016)

- desired contact force along $Y$ direction regulated to $F_d = 15[N]$
- constant desired velocity to perform a line in the vertical $XZ$ plane

$$\nu_d = \begin{bmatrix} 0.015 \\ 0.03 \end{bmatrix} \quad \dot{\nu}_d = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

https://youtu.be/tlhEK5f00QU

2-part video
Collaboration control
Hybrid force/velocity control at contact level (IROS 2016)

- desired contact force along the $X$ direction regulated to $F_d = 15[N]$
- desired velocity/acceleration to perform a circle in the vertical $YZ$ plane

$$
\nu_d = \begin{bmatrix}
\omega \rho \sin \omega t \\
\omega \rho \cos \omega t
\end{bmatrix}
$$

$$
\dot{\nu}_d = \begin{bmatrix}
\omega^2 \rho \cos \omega t \\
-\omega^2 \rho \sin \omega t
\end{bmatrix}
$$

...video

https://youtu.be/tIhEK5f00QU

$\approx 7$ cm of motion in the force-controlled direction
- 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
SYMPEXITY cell for laser polishing

Including a manual polishing station with human-robot physical collaboration

Contact detection (model-based) for safety

3D workspace monitoring with 2 Kinects for HR coexistence

Use of F/T sensor and of residuals for HR physical collaboration

Universal Robots UR10
- lightweight design
- CE safety certified

speed scaling/stop from sensing HR distance (= 0 in physical collaboration)

Scenario for HRC in manual polishing
Preparation a metallic part for the final polishing by the laser machine

**UR10 robot operation with HR coexistence/collaboration**

- Measuring Berlin Heart part with the CWS
- Physical collaboration in contact
- Coexistence
- Coordination with LP machine

*CWS = Coherent Wave Scattering (laser measurement of surface quality)*
Scenario for HRC in manual polishing

Distinguishing different contact forces

6D Force/Torque (F/T) sensor at wrist
- manual polishing force is measured
- end-effector Jacobian $J_e$ 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 $J_c$ is not known
Handling multiple contacts
Dynamic model and residual computation using also the F/T sensor

- **robot dynamic model** takes the form

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

- joint torques resulting from different contacts
  (measured) at the end-effector level \( \tau_e = J_e^T(q)F_e \) 
  at a generic point along the structure \( \tau_c = J_c^T(q)F_c \)

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

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

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

\[ K_i \to \infty \text{ (sufficiently large)} \implies r \simeq \tau_c \]
Admittance control strategy during manual polishing

Human and robot are physically collaborating

- 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:

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

- in this way, the control law 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:

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

- human can reconfigure the arm, thus reorient the work piece held by the robot.
HRC phase with **UR10** robot

Experimental verification in the lab (Mechatronics 2018)

[HRC phase activated by hand waving](https://youtu.be/slwUiRT_lJQ)

no F/T sensor, switch to **UR FreeDrive** mode

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

for a similar behavior with the KUKA LWR

see [https://youtu.be/TZ6nPqLpDxI](https://youtu.be/TZ6nPqLpDxI)
HRC phase with **UR10 robot**

Experimental results (separating F/T measures from residuals)

- **both forces at the same time...**
- **polishing force only...**
- **in all cases, no linear motion of EE position!**
- **extra force detected...**
- **...joints move accordingly**
- **...no joint motion**
- **...joints move due to extra force only**
Combining motor currents and F/T sensor data
Enhanced flexible interaction by filtering, thresholding, merging signals (ICRA 2019)

intentional contacts and/or collisions may occur anywhere

6-dof **KUKA KR5 Sixx** with **closed control** architecture and RSI interface at $T_c = 12$ ms

2-part video

**ATI Mini45** F/T sensor

https://youtu.be/SfZcG1Y713w
Our former team at DIAG
Robotics Lab of the Sapienza University of Rome

back in 2014

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• E. Magrini, F. Flacco, and A. De Luca, “Control of generalized contact motion and force in physical human-robot interaction,” IEEE Int. Conf. on Robotics and Automation, pp. 2298-2304, 2015 (ICRA 2015 Best Conference Paper Award Finalist)


Safety Configuration - Kinects OK

- Robot speed 50 mm/s
- Activation of a *SafeMove* area with max speed 50 mm/s

STOP
- Robot speed drops to 0 mm/s
- Activation of a *SafeMove* area with max speed 0 mm/s

- Robot speed decreases to 20 mm/s

2 extra slides linked from slide #31
Safety Configuration - Kinects KO

- Robot speed 100 mm/s
- Activation of a restricted SafeMove area with max speed 100 mm/s

STOP

- Protective stop in a monitor area
- Robot speed drops to 0 mm/s

- Robot speed already 0 mm/s
- Activation of a SafeMove function Safe Stand Still (SST), certified safety function

- In case of fast approaches to the red zone or Kinect failure the SST will cause an immediate Emergency stop if the robot is moving

HR coexistence still present

go back to slide #31
SYMPLEXITY industrial cell on display at one of the largest fairs in Europe (in Munich)

@SIR in Modena