Recent Advances in physical Human-Robot Interaction

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Motivation
Human-friendly robotics

traditional robotics
replacing humans
human-friendly robotics
collaborating with humans
co-workers on factory floor
personal robots in service
Human-Robot Interaction
Need of revisiting robot control architectures

- **cognitive HRI**: bi-directional multi-modal communication and understanding
- **physical HRI**: exchange of contact forces, coordinated operation

![Diagram showing today and tomorrow scenarios.](image)
Safe physical Human-Robot Interaction

Hierarchy of consistent robot behaviors

- integrated design and use of mechanics, actuation, (proprio- and exteroceptive) sensing, communication, and control components
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.
Coexistence is the robot capability of sharing the workspace with other entities, most relevant with humans

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

original robot task

safe HR coexistence
Collaboration occurs when the robot performs complex tasks with direct human interaction and coordination, in two modalities that are not mutually exclusive (contactless and physical).
“soft” robots or “soft” robot behavior is expected to reduce potential injuries due to unforeseen collisions with humans sharing the same workspace. Can we quantify this intuition?

\[ M_{\text{rob}} = M_{\text{rotor}} + M_{\text{link}} \]

HIC = Head Injury Criterion (used in automotive industry)

\[ \text{HIC} = \frac{2^{\frac{5}{2}} M_{\text{rob}}^4 K_{\text{cov}}^{\frac{3}{4}}}{\pi^\frac{3}{2} M_{\text{ope}}^\frac{3}{4} (M_{\text{rob}} + M_{\text{ope}})^\frac{7}{4}} |v|^{\frac{5}{2}} \]

\[ |v|_{\text{max}} = \beta(M_{\text{ope}}, M_{\text{rob}}, K_{\text{cov}}) \text{HIC}^{\frac{2}{5}} \]
active force feedback from contact sensor is not enough to increase operating speed with rigid joint and safety constraint (limited control/sampling bandwidth)

- **basic idea**: decouple rotor from link inertia via passive compliant transmission (elastic joint) and reduce link inertia (lightweight manipulator)
Mechanics and Safety

Variable Stiffness Actuation (VSA)

- Low joint stiffness ⇒ slow response; high stiffness ⇒ high reflected inertia
  limited safe speed under safety constraint (limited control/sampling bandwidth)
- Idea: a second motor to modify online the nonlinear stiffness of transmissions

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not only safety, but also efficient use of energy
co-design techniques of mechanics and control for safe, yet fast, strong, and accurate robot arms

use of constant or variable stiffness joints are viable solutions, complemented by lightweight materials for the robot links

new paradigm: “design for safety, control for performance”

Q: can all robots with nonlinear flexible transmissions and multi-body dynamics be controlled so as to behave as “rigid” & “independent single-dofs systems”? (at least, during free motion)

YES! Using feedback linearization (nonlinear feedback law, based on measures of the robot state)

what happens when (intended) contacts or (unexpected) collisions occur?

can a control design help in keeping a safe behavior? if so, how?
Safe collision handling
Detection of undesired collisions and robot reaction

- **phases**: pre-impact (avoidance), impact (detection), and post-impact (reaction)
- Collision detection using only on-board robot proprioceptive sensors (encoders)
- Safe reaction (apart from stopping the robot) requires not only “detection” but also “isolation” (which link has collided)
- Monitoring of possible collisions should be **always active**
- Collisions may occur at **any (unknown) place** along the whole robotic structure
- Working assumptions:
  - One single collision at a time
  - Manipulator as an open kinematic chain
  - First, rigid joints case ⇒ then, extension to flexible joints

\[
M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau + \tau_K
\]

- Inertia matrix
- Coriolis/centrifugal terms
- Any control torque
- Transpose of the Jacobian associated to the contact point
- Joint torque due to link collision

\[
\tau_K = J_K^T(q)F_K
\]
Collision detection and isolation

Method based on residual vector for robots with rigid joints

**Analysis:** In dynamic conditions, a contact force/torque acting on the i-th link produces accelerations at ALL joints.

The residual vector monitors the robot's generalized momentum: \( p = M(q)\dot{q} \)

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

(diagonal)

Each component of \( \mathbf{r} \) is a decoupled, first-order, unity-gain filtered version of the unknown external torque.

\[
\dot{\mathbf{r}} = -K_I \mathbf{r} + K_I \mathbf{\tau}_K
\]

\( K_I \rightarrow \infty \quad \mathbf{r} \approx \mathbf{\tau}_K \) (over a threshold)

Detection

Isolation

**Collision at link i**

\[
\mathbf{r} = \begin{bmatrix} * & \cdots & * & * & 0 & \cdots & 0 \\ i+1 & \cdots & N \end{bmatrix}^T
\]
Collision detection and isolation

Extension to robots with elastic joints

- dynamic model of robots with elastic joints

\[ M(q)\ddot{q} + C(q, \dot{q})\dot{q} + g(q) = \tau_J + \tau_K \]

\[ B\ddot{\theta} + \tau_J = \tau \]

\[ \tau_J = K(\theta - q) \]

- joint torque due to link collision
- motor torques commands
- elastic torques at the joints

- the DLR LWR-III robot has multiple joint sensors
  - encoders for motor (\(\theta\)) and link (\(q\)) positions
  - joint torque sensor for \(\tau_J\)

\[ \tau \rightarrow \tau_J \]

“replace the commanded torque to the motors with the elastic torque measured at the joints”

\[ r_{EJ}(t) = K_I \left[ p(t) - \int_0^t (\tau_J + C^T(q, \dot{q})\dot{q} - g(q) - r_{EJ}) \, ds \right] \]
Collision reaction
Method based on residuals

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Collision detection and reaction
Residual-based experiments on DLR LWR-III

- collision detection followed by different reaction strategies
- detection time: 1-2 ms, reaction time: + 1 ms

\[
\dot{q}_r = K_Q r \\
\tau = M(q) (K_R r - D_R \dot{q}) + C(q, \dot{q}) \dot{q} + g(q) - r
\]
Collision reaction
Portfolio of possible robot reactions

residual amplitude $\propto$ severity level of collision

- Reaction
  - 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

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Collision reaction
Further examples

- without external sensing & no strict need of joint torque measurements
- any place, any time ...

results from PHRIENDS project
(and thanks to DLR volunteer Sami Haddadin!)
Collision avoidance
Using exteroceptive sensors to monitor robot workspace

- 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
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 w.r.t. 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

\[p_x = \frac{x_C f s_x}{z_C} + c_x\]
\[p_y = \frac{y_C f s_y}{z_C} + c_y\]
\[d_p = z_C\]
- distance between a point of interest $P_D = (p_x, p_y, d_p)$ and an obstacle point $O_D = (o_x, o_y, d_o)$

$$v_x = \frac{(o_x - c_x)d_o - (p_x - c_x)d_p}{fs_x} \quad v_y = \frac{(o_y - c_y)d_o - (p_y - c_y)d_p}{fs_y} \quad v_z = d_o - d_p$$

(if obstacle point is closer than point of interest, set $d_o = d_p$)
Repulsive vector
A version of artificial potentials

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

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

- repulsive vectors due to all obstacles near to point of interest are considered
  - orientation \( \Rightarrow \) sum of all repulsive vectors, magnitude \( \Rightarrow \) nearest obstacle
  - inclusion of a pivoting strategy to avoid local minima or “too fast” obstacles
Safe coexistence
Collision avoidance in depth space

Human and Robot share the same workspace...
What about using industrial robots?
From DLR LWR-III and KUKA LWR 4 to commercial manipulators

- 7-dof human-arm size, weight = 14 kg = payload
- dynamic model available
- joint torque sensor available
- torque controlled
- Fast Research Interface (FRI) @1 ms, with access to motor current commands

- 6-dof arm, weight = 28 kg, payload = 3 kg
- closed control architecture
- no information on dynamic model and on the industrial low-level controllers
- Robot Sensor Interface (RSI) @12 ms, for reading encoder positions and motor currents

- common aspects
  - can interface with MS Kinect and integrate Reflexxes Motion Libraries
  - user may develop middleware in ROS (operational nodes)
Closed control architecture

What can (or could) be done with the RSI

- the external reference velocity can be updated (every 12 ms), based on encoder and motor current readings + external sensor information
  - no torque or current command can be imposed
  - relies on the “good” properties of the low-level (P/PD/PID) KUKA controllers
- a reference velocity could be computed so as to apply a desired torque to the robot (“torque transformer” method by O. Khatib)
  - based on inverting the closed-loop plant
  - needs knowledge of robot dynamics and of low-level control laws & parameters
Contactless collaboration
Using gesture and voice commands

- human body parts and gesture recognition
- speech recognition

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Human-robot communication
Using MS 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
Human stopping the robot

Signal-based collision detection processing motor currents

- detection of collisions and temporary stop
  - no force sensing, no dynamic model, closed architecture (here: work with 3 joints only)
  - low-pass (LPF) and high-pass (HPF) filtering of measured motor currents used in parallel

- time-varying thresholds depend only on commanded velocity and acceleration
Designing robot reaction strategies

Detect collision & stop / Detect interaction intent, stop, float away upon contacts / Imposing a compliant-like behaviour

- distinguish undesired collisions (*hard*) from human intention to interact (*soft*), by looking at motor current HPF and LPF alarms (HPF off, LPF on in latter case)
similarly to what done for the currents, by processing the residual (external forces) in the frequency domain, it is possible to distinguish

\[ r \simeq \tau_{ext} \]

for intentional contacts, Kinect data are used to locate contact points

using the Jacobians \( J^k(q) \) associated to the contact points, external forces can be estimated (without the need of force/torque sensors!) as

\[
\begin{pmatrix}
\hat{F}_1 \\
\hat{F}_2 
\end{pmatrix} = \left( J^T_1(q) \quad J^T_2(q) \right)^\# r 
\]

\( (k = 2) \)

estimates of the external forces can be used for controlling the robot (e.g., by an impedance scheme) at the Cartesian level
Safe physical collaboration

Robot searching for contact with designated human part (one of the hands)

Collaboration phase activated by the human
Safe collaboration
Merging all together

Robot Co-worker

- Contactless Collaboration
- Multiple contact points
- Gesture Recognition
- Speech Recognition
- Collision Avoidance
- External Forces
- Collaboration
Robot co-worker

Physical HRI during task execution, with friendly user interface (@DLR)
A further use of pHRI
Learning by human imitation and incremental kinesthetic refinement (@TUM)
Conclusions
Toward human-robot safe physical collaboration

- a **unified framework** for safe human-robot collaboration, based on a hierarchy of consistent behaviours that the robot must accomplish
  - residual-based collision **detection**
  - portfolio of collision **reaction** algorithms
  - collision **avoidance** based on depth space data
  - **gesture** and **speech** for contactless collaboration
  - **contact** force estimator

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Selected references
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www.dis.uniroma1.it/deluca