Elective in Robotics/Control Problems in Robotics

Physical Human-Robot Interaction
Collision Detection and Reaction

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Handling of robot collisions

- safety in physical Human-Robot Interaction (pHRI)
- robot dependability
  - mechanics: lightweight construction and inclusion of compliance
  - next generation with variable stiffness actuation devices
  - typically, more/additional exteroceptive sensing needed
  - human-oriented motion planning (“legible” robot trajectories)
  - control strategies with safety objectives/constraints
- prevent, avoid, detect and react to collisions
  - possibly, using only robot proprioceptive sensors
- different phases in the collision event pipeline

European projects that have funded our research developments

- PHRIENDS FP6 STREP (2006-09)
- SAPHARI FP7 IP (2011-15)
- SYMPLEXITY H2020 IP (2015-18)
Collision event pipeline

Collision detection in industrial robots

- advanced option available for some robots (ABB, KUKA, UR ...)
- mainly intended for detection only, not for isolation
  - based on large variations of control torques (or motor currents)
    \[ \|\tau(t_k) - \tau(t_{k-1})\| \geq \varepsilon \Leftrightarrow |\tau_i(t_k) - \tau_i(t_{k-1})| \geq \varepsilon_i, \text{ for at least one joint } i \]
  - based on comparison with nominal torque on the desired trajectory
    \[ \tau_d = M(q_d)\ddot{q}_d + S(q_d, \dot{q}_d)\dot{q}_d + g(q_d) + f(q_d, \dot{q}_d) \Rightarrow \|\tau - \tau_d\| \geq \varepsilon \]
  - based on robot state and numerical estimate of its acceleration
    \[ \ddot{q}_N = \frac{d\dot{q}}{dt} \Rightarrow \tau_N = M(q)\ddot{q}_N + S(q, \dot{q})\dot{q} + g(q) + f(q, \dot{q}) \Rightarrow \|\tau - \tau_N\| \geq \varepsilon \]
  - based on the parallel simulation of robot dynamics
    \[ \ddot{q}_C = M^{-1}(q)[\tau - S(q, \dot{q})\dot{q} - g(q) - f(q, \dot{q})] \Rightarrow \|\dot{q} - \dot{q}_C\| \geq \varepsilon_\dot{q}, \|q - q_C\| \geq \varepsilon_q \]
- sensitive to the actual control law and reference trajectory
- require noisy acceleration estimates or on-line inversion of the robot inertia matrix
ABB collision detection

- ABB IRB 7600 (heavy!)

  video

- the only feasible robot reaction is to stop!
Collisions as system faults

- robot model with (possible) collisions
  \[ M(q)\ddot{q} + S(q, \dot{q})\dot{q} + g(q) = \tau + \tau_K = \tau_{\text{tot}} \]
  - inertia matrix
  - Coriolis/centrifugal (with “good” factorization): \( M - 2S \) is skew-symmetric
  - control torque
  - joint torque caused by link collision
  - with transpose of the Jacobian associated to the contact point/area

- collisions may occur at any (unknown) location along the whole robot body, and with any (unknown) force

- simplifying assumptions (some may be relaxed)
  - manipulator is an open kinematic chain
  - single contact/collision
  - negligible friction (else, to be identified and used in the model)
Analysis of a collision

\[ V_K = \begin{bmatrix} v_K \\ \omega_K \end{bmatrix} = \begin{bmatrix} J_{K,\text{lin}}(q) \\ J_{K,\text{ang}}(q) \end{bmatrix} \quad \dot{q} = J_K(q)\dot{q} \in \mathbb{R}^6 \]

\[ F_K = \begin{bmatrix} f_K \\ m_K \dot{q} \end{bmatrix} \in \mathbb{R}^6 \]

In static conditions, a contact force/torque on \( i \)th link is balanced ONLY by torques at preceding joints \( j \leq i \).

In dynamic conditions, a contact force/torque on \( i \)th link produces accelerations at ALL joints.
Relevant dynamic properties

- total energy and its variation

\[ E = T + U = \frac{1}{2} \dot{q}^T M(q) \dot{q} + U_g(q) \]
\[ \dot{E} = \dot{\dot{q}}^T \tau_{tot} \]

- generalized momentum and its decoupled dynamics

\[ p = M(q) \dot{q} \]
\[ \dot{p} = \tau_{tot} + S^T(q, \dot{q}) \dot{q} - g(q) \]

using the skew-symmetric property

\[ \dot{M}(q) = S(q, \dot{q}) + S^T(q, \dot{q}) \]

prove this expression!
Monitoring collisions

Normal Mode of Operation

Collision Monitor

Detection

Isolation

Collision recognized

Reaction Strategy

$\sigma$ | $\sigma \geq \sigma_{\text{coll}}$ \quad $\|r\| \geq r_{\text{coll}}$

$\tau$

$q, \dot{q}$

without external or contact sensors

deactivate/activate

continue

use

pHRI
Energy-based detection of collisions

- **scalar residual** (computable)

\[ \sigma(t) = k_D \left[ E(t) - \int_0^t (\dot{q}^T \tau + \sigma) \, ds - E(0) \right] \]

\[ \sigma(0) = 0 \quad k_D > 0 \]

- ... and its dynamics (needed only for analysis)

\[ \dot{\sigma} = -k_D \sigma + k_D (\dot{q}^T \tau_K) \]

a stable first-order linear filter, excited by a collision!
Block diagram of residual generator
energy-based scalar signal

\[
\sigma(t) = k_D \left[ E(t) - \int_0^t (\dot{\mathbf{q}}^T \tau + \sigma) \, ds - E(0) \right]
\]

rigid robot with possible extra torque due to collision

initialization of integrator
\( \hat{\sigma}(0) = E(0) \) (zero if robot starts at rest)
Analysis of the energy-based method

- a very simple scheme (scalar signal)
- rewritten as a monitor of the kinetic energy $T$, by replacing total energy $E$ with $T$ and adding $-\dot{q}^T g(q)$ in the integral
- it can only detect the presence of collision forces/torques (wrenches) that produce work on the linear/angular velocities (twists) at the contact
- moreover, it does not succeed when the robot stands still...

\[
\begin{align*}
\dot{q}^T \tau_K &= \dot{q}^T J_K^T(q) F_K = V_K^T F_K = 0 & \iff & V_K \perp F_K \\
V_K &= \begin{bmatrix} v_K \\ \omega_K \end{bmatrix} = \begin{bmatrix} J_{K,\text{lin}}(q) \\ J_{K,\text{ang}}(q) \end{bmatrix} \dot{q} = J_K(q) \dot{q} \in \mathbb{R}^6 & F_K &= \begin{bmatrix} f_K \\ m_K \end{bmatrix} \in \mathbb{R}^6
\end{align*}
\]
Collision detection simulation with a 7R robot

detection of a collision with a fixed obstacle in the work space during the execution of a Cartesian trajectory (redundant robot)
Collision detection
experiment with a 6R robot

robot at rest or moving under Cartesian impedance control on a straight horizontal line (with a F/T sensor at wrist for analysis)

6 phases

A: contact force applied is acting against motion direction ⇒ detection
B: no force applied, with robot at rest
C: force increases gradually, but robot is at rest ⇒ no detection
D: robot starts moving again, with force being applied ⇒ detection
E: robot stands still and a strong force is applied in $z$-direction ⇒ no detection
F: robot moves, with a $z$-force applied $\approx$ orthogonal to motion direction ⇒ poor detection
Momentum-based isolation of collisions

- residual vector (computable)

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

\[
r(0) = 0 \quad K_I > 0 \quad \text{(diagonal)}
\]

- ... and its decoupled dynamics

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

\[
\frac{r_j(s)}{\tau_{K,j}(s)} = \frac{K_{I,j}}{s + K_{I,j}}
\]

\[
j = 1, \ldots, N
\]

\[N\] first-order, linear filters with unitary gains, excited by a collision!
(all residuals go back to zero if there is no longer contact = post-impact phase)
Block diagram of residual generator
momentum-based vector signal

rigid robot with possible extra torque due to collision

initialization of integrators
\( \hat{p}(0) = p(0) \)
(zero if robot starts at rest)

\[
r(t) = K_I \left[ p(t) - \int_0^t (\tau + S^T(q, \dot{q}) \dot{q} - g(q) + r) \, ds - p(0) \right]
\]
Analysis of the momentum method

- **ideal situation** (no noise/uncertainties)
  
  \[ K_I \rightarrow \infty \Rightarrow r \approx \tau_K \]

- **isolation property**: collision has generically occurred in an area located up to the \( i \)th link if

  \[ r = \begin{bmatrix} * & \ldots & * & * \\ \end{bmatrix} ^T \begin{bmatrix} 0 & \ldots & 0 \end{bmatrix} \]

  \[ \uparrow \quad \uparrow \quad \quad i + 1 \quad \ldots \quad N \]

- residual vector contains **directional** information on the torque at the robot joints resulting from link collision (useful for robot reaction in post-impact phase)
Momentum-based method
experiment on 3 moving links of a position controlled DLR LWR-III

collision at link 4

\begin{align*}
    \text{cd}_1 &= \text{off} \\
    \text{cd}_2 &= \text{ON} \\
    \text{cd}_3 &= \text{off} \\
    \text{cd}_4 &= \text{ON} \\
    \text{cd}_5 &= \text{off} \\
    \text{cd}_6 &= \text{off} \\
    \text{cd}_7 &= \text{off}
\end{align*}

\text{pHRI}
Safe reaction to collisions

Normal Mode of Operation

Collision Monitor

Collision recognized

Reaction Strategy

internal robot state and control command

without external or contact sensors

\( \sigma \)

\( r \)

\( \tau \)

\( \tau_R \)

\( F_K \)

\( \tau \)

\( \sigma \)

NO

YES

continue

use

deactivate

reactivate
Robot reaction strategy

- "zero-gravity" control in any operative mode

\[ \tau = \tau' + g(q) \]

- upon detection of a collision (\( \tau \) is over some threshold)
  - no reaction (strategy 0): robot continues its planned motion...
  - stop robot motion (strategy 1): either by braking or by stopping the motion reference generator and switching to a high-gain position control law
  - reflex* strategy: switch to a residual-based control law

\[ \tau' = K_R \tau \quad K_R > 0 \quad \text{(diagonal)} \]

"joint torque command in same direction of collision torque"

* = in robots with transmission/joint elasticity, the reflex strategy can be implemented in different ways (strategies 2, 3, 4)
Zero gravity operation

WAM Barrett

\[ \tau = \tau' + g(q) \]

KUKA LWR4

here, only as result of human pushes ...

http://handbookofrobotics.org/view-chapter/69/videodetails/611
Analysis of the reflex strategy

- in ideal conditions, this control strategy is equivalent to a reduction of the effective robot inertia as seen by the collision force/torque

\[(I + K_R)^{-1} (M(\dot{q})\ddot{q} + S(q, \dot{q})\dot{q}) = \tau_K\]

"a lighter robot that can be easily pushed way"

from a cow ... ... to a frog!
**DLR LWR-III robot dynamics**

- lightweight (14 kg) 7R anthropomorphic robot with harmonic drives (elastic joints) and joint torque sensors

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

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

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

- proprioceptive sensing: motor positions and joint elastic torques

\[
\theta \quad \tau_J \quad \rightarrow \quad q = \theta - K^{-1} \tau_J
\]

friction at motor side can be compensated!

joint torques due to link collision

friction at link side is negligible!

elastic torques at the joints
Exploded joint of LWR-III robot
Collision isolation for LWR-III robot
elastic joint case

- few alternatives for extending the rigid case results
- for collision isolation, the simplest one takes advantage of the presence of joint torque sensors
  
  \[
  \tau \rightarrow \tau_J
  \]
  
  “replace the commanded torque to the motors with the elastic torque measured at the joints”

\[
r_{EJ}(t) = K_I \left[ p(t) - \int_0^t (\tau_J + S^T(q, \dot{q}) \dot{q} - g(q) + r_{EJ}) \, ds - p(0) \right]
\]

\[
\dot{r}_{EJ} = -K_I \, r_{EJ} + K_I \, \tau_K
\]

- other alternatives use
  - link+motor position measures ⇒ needs knowledge also of joint stiffness \( K \)
  - link+motor momentum + commanded torque ⇒ affected by motor friction
- motion control is more complex in the presence of joint elasticity
- different active strategies of reaction to collisions are possible
Control of DLR LWR-III robot
elastic joint case

- general control law using **full state feedback**
  (motor position and velocity, joint elastic torque and its derivative)

\[
\tau = K_P (\theta_d - \theta) - K_D \dot{\theta} + K_{Pr} (\tau_{J,d} - \tau_J) - K_{Dr} \dot{\tau}_J + \tau_{J,d}
\]

- DLR “zero-gravity” condition is realized in a **(quasi-static) approximate** way, using just motor position measures

\[
\bar{g}(\theta) = g(q), \quad \forall (\theta, q) \in \Omega := \{(\theta, q) | K(\theta - q) = g(q)\}
\]
Exact gravity cancellation
in robots with elastic joints

\[
M(q) \ddot{q} + c(q, \dot{q}) + g(q) + D_q \dot{q} + K(q - \theta) = 0
\]

\[
B \ddot{\theta} + D_\theta \dot{\theta} + K(\theta - q) = \tau
\]

\[
q(t) \equiv q_0(t) \quad \forall t \geq 0 \quad \tau = \tau_g + \tau_0
\]

\[
\tau_g = g(q) + D_\theta K^{-1} \dot{g}(q) + BK^{-1} \ddot{g}(q)
\]

\[
\dot{g}(q) = \frac{\partial g(q)}{\partial q} \dot{q}
\]

\[
\ddot{g}(q) = \frac{\partial g(q)}{\partial q} M^{-1}(q) \left( K(\theta - q) - c(q, \dot{q}) - g(q) - D_q \dot{q} \right) + \sum_{i=1}^{n} \frac{\partial^2 g(q)}{\partial q \partial q_i} \dot{q} \dot{q}_i
\]

it requires **full state** feedback

A. De Luca, F. Flacco, *IEEE CDC 2010*
Reaction strategies
specific for elastic joint robots

- **strategy 2** floating reaction (robot \(\approx\) in “zero-gravity”)
  \[
  \tau_{J,d} = \ddot{g}(\theta) \quad K_P = 0
  \]

- **strategy 3** reflex torque reaction (closest to the rigid case)
  \[
  \tau_{J,d} = K_R r_{EJ} + \ddot{g}(\theta) \quad K_P = 0
  \]

- **strategy 4** admittance mode reaction (residual \(r_{EJ}\) is used as the new reference for the motor velocity)
  \[
  \tau_{J,d} = \ddot{g}(\theta) \quad \dot{\theta}_d = K_{R,\theta} r_{EJ}
  \]

- **further** possible reaction strategies (rigid or elastic case)
  - based on impedance control
  - sequence of strategies (e.g., 4 + 2)
  - **time scaling**: stop/reprise of reference trajectory, keeping the path
  - **Cartesian task preservation**: exploits robot redundancy by projecting reaction torque in a task-related dynamic null space

pHRI
Experiments with LWR-III robot “dummy” head

dummy head equipped with an accelerometer
robot straighten horizontally, mostly motion of joint 1 @30°/sec
Dummy head impact

strategy 0: **no reaction**
planned trajectory ends just after the position of the dummy head

strategy 2: **floating reaction**
impact velocity is rather low here and the robot stops switching to float mode
Delay in collision detection

impact with the dummy head

- measured (elastic) joint torque
- residual $r_1$
- 0/1 index for detection
- dummy head acceleration

gain $K_I = \text{diag}\{25\}$

threshold = 5-10% of max rated torque

---

joint 1

2-4 msec!
Delay in collision detection

Impact with the dummy head + F/T sensing

- Measured (elastic) joint torque
- Residual $r_4$
- Sensed external force
- 0/1 index for detection
- Dummy head acceleration

Detection delay

5 msec
Experiments with LWR-III robot balloon impact

possibility of repeatable comparison of different reaction strategies at high speed conditions
Balloon impact

strategy 4: admittance mode reaction

video

coordinated joint motion @90°/sec
Experimental comparison of strategies balloon impact

- residual and velocity at joint 4 with various reaction strategies

Impact at 90°/sec with coordinated joint motion
Human-Robot Interaction

- first impact @60°/sec

strategy 4: admittance mode

strategy 3: reflex torque
Human-Robot Interaction

- first impact \( @90^\circ/\text{sec} \)

**strategy 3**: reflex torque
Need for a good dynamic model ...

- performance of model-based detection/isolation methods is limited by uncertainties and unmodeled dynamics (e.g., when adding an unknown payload)
- there is a need for accurate (and fast) online schemes for identification
- here, ~10 small motions are sufficient to capture the mass and CoM of a payload (becoming part of dynamic parameters of the last link)

video @IROS17
https://youtu.be/fNP6smdp7aE
Simultaneous use of two residuals

- use of the two types of introduced residuals, with different thresholds
  - momentum-based vector $\mathbf{r}$ + energy-based scalar $\sigma$ (less sensitive at slow speed)
  - more robust to dynamic uncertainties (in particular, to unmodeled friction)

LARA 5 6R cobot by Neura Robotics

video @ICRA23
Other uses of residuals

- the design concept of a residual can be used also to estimate online any “missing” dynamic term in the model of a (mechanical) system
  - it has in fact the structure of a “disturbance” or “input” observer
- we have used it to estimate (and control) at run time the time-varying nonlinear stiffness of a VSA device (which cannot be directly measured ...)
- being a (first-order) filtered version of the unknown/missing term, it may be used as a compensation signal within any control law, without having “algebraic loops” or attempting a (difficult) model-based identification
- consider a (relevant) motor-side friction $\tau_F$ in a robot with elastic joints

\[
B \ddot{\theta} + K (\theta - q) = B \ddot{\theta} + \tau_J = \tau + \tau_F
\]

\[
r_F = K_F \left[ B \dot{\theta} - \int_0^t (\tau - \tau_j + r_F) \, ds \right]
\]

\[
\Rightarrow \dot{r}_F = K_F \left[ \tau_F - r_F \right]
\]

\[
\Rightarrow r_{F,i}(s) = \frac{\tau_{F,i}(s)}{1 + \left(1/k_{F,i}\right)s}
\]

\[
\Rightarrow \text{model-less friction compensation: } \tau = \tau_{\text{any control}} - r_F
\]
Experiments on friction compensation

- Results on the DLR 7R MIRO medical robot
  
  Friction estimate via residuals used then on-line in a control law...

  HD at the joints ⇒ elastic joint dynamic model
“Portfolio” of reaction strategies

residual amplitude $\propto$ severity level of collision

Stop  Reflex  Preserve

Reaction

Reprise

Cartesian path (time scaling)

Cartesian trajectory (use of redundancy)

Task relaxation

All transitions are controlled by suitable thresholds on the residuals
Experiments with LWR-III robot

time scaling

- robot is position-controlled (on a given geometric path)
- timing law slows down, stops, possibly reverses (and then reprises)
Reaction with time scaling

video

Trajectory scaling
Use of kinematic redundancy

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

$pHRI$
Task kinematics

- task coordinates \( \mathbf{x} \in \mathbb{R}^m \) with \( m < n \) (redundancy)

\[
\dot{\mathbf{x}} = J(q)\dot{q} \quad \ddot{\mathbf{x}} = \dot{J}(q)\dot{q} + J(q)\ddot{q}
\]

- (all) generalized inverses of the task Jacobian

\[
J(q)G(q)J(q) = J(q), \quad \forall q
\]

- all joint accelerations realizing a desired task acceleration (at a given robot state)

\[
\ddot{q} = G(q)(\dddot{x} - \dot{J}(q)\dot{q}) + (I - G(q)J(q))\ddot{q}_0
\]
Dynamic redundancy resolution

set for compactness

$n(q, \dot{q}) = S(q, \dot{q})\dot{q} + g(q)$

- all joint torques realizing a precise control of the desired (Cartesian) task

\[
\ddot{\mathbf{x}}_d + K_P e + K_D \dot{e}
\]

\[
\tau = M(q)G(q) \left[ \dddot{\mathbf{x}} - \dot{\mathbf{J}}(q)\dot{q} + \mathbf{J}(q)M^{-1}(q)n(q, \dot{q}) \right] \\
+ M(q)(I - G(q)\mathbf{J}(q))M^{-1}(q)\mathbf{\tau}_0
\]

projection matrix in the dynamic null space of $\mathbf{J}$

arbitrary joint torque available for reaction to collisions

for any generalized inverse $\mathbf{G}$, the joint torque has two contributions:
one imposes the task acceleration control, the other does not affect it
Dynamically consistent solution

inertia-weighted pseudoinverse

- the most natural choice for matrix $G$ is to use the dynamically consistent generalized inverse of $J$
- in a dual way, denoting by $H$ a generalized inverse of $J^T$, the joint torques can always be decomposed as

$$\tau = J^T(q)F + (I - J^T(q)H(q))\tau_0$$

- the inertia-weighted choices for $H$ and $G$ are then

$$H_M(q) = \left( J(q)M^{-1}(q)J^T(q) \right)^{-1} J(q)M^{-1}(q)$$

$$=: \Lambda(q)J(q)M^{-1}(q),$$

$$G = H_M^T = M^{-1}J^T\Lambda$$

- thus, the dynamically consistent solution is given by

$$\tau = J^T(q)\Lambda(q)(\ddot{x} - \dot{J}(q)\dot{q} + J(q)M^{-1}(q)n(q, \dot{q}))$$

$$+ (I - J^T(q)H_M(q))\tau_0$$

$\Lambda(q)$ is the effective Cartesian inertia!
Cartesian task preservation

- wish to preserve the whole Cartesian task (end-effector position & orientation) reacting to collisions by using only self-motions in the joint space
- if the residual ($\propto$ contact force) grows too large, orientation is relaxed first and then, if necessary, the full task is abandoned (priority is given to safety)
Cartesian task preservation experiments with LWR4+ robot

Human-Robot Coexistence and Contact Handling with Redundant Robots

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February 2017

idle ⇔ relax ⇔ abort

https://youtu.be/q4PZKE-kgc0
Combined use
6D F/T sensor at the robot wrist + residuals

- include the F/T measures in the expression of the residual: $J_{EE}(q)F_m$
- may be used to distinguish intentional contacts vs. unexpected collisions
- ... but only at the end-effector level!
- in case of intentional contacts, what should a robot do other than react to contacts/collisions by stopping or escaping? ⇒ physical collaboration (pHRC)
pHRI in low-cost (humanoid) robots forearm of the ROMEO personal robot

- the momentum-based residual method has been implemented worldwide in a large number of robotic systems (industrial robots, prototypes, VSA-based manipulators, ...)
- a different computation of residuals is needed for “floating base” humanoids and UAVs
Collision detection and reaction with full VSA-based DLR HASY robot

- with a momentum-based residual method

video
Collision detection and isolation using a joint velocity observer in the residual

- numerical differentiation of encoders vs. dynamic reduced-order observer
- 6 link collisions in sequence (over 30 s):
  L4 (twice, ±) ⇒ L5 (twice, ±) ⇒ L2 (twice, ±)
- both methods detect collisions correctly
- ND has two false isolations (#5 and #6)
- OBS isolates the colliding link correctly

video only first 5 residuals are shown (out of 7)
pHRI in closed control architectures
KUKA KR5 Sixx R650 robot

- Low-level control laws are not known nor accessible by the user: no current or torque commands can be used.
- User programs, based also on other exteroceptive sensors (vision, Kinect, F/T sensor) can be implemented on an external PC via the RSI (RobotSensorInterface), communicating with the KUKA controller every 12 ms.
- Robot measures available to the user: joint positions (by encoders) and [absolute value of] motor currents.
- Controller reference is given as a velocity or a position in joint space (also Cartesian commands are accepted).
Collision detection and stop

[Video Link]

Collisions are detected through motor currents high-pass filtering analysis.

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

pHRI
Collisions vs intentional contact
distinguish and then collaborate ...

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

with both high-pass and low-pass filtering of motor currents — here collaboration mode is manual guidance of the robot
Other possible robot reactions after collaboration mode is established

Collaboration mode: pushing/pulling the robot

Collaboration mode: compliant-like robot behavior

Here, time-varying thresholds based on the desired trajectory... we are “control-cheating” a bit: no torque command is ever issued!

Video @ICRA 2013

Video @ICRA 2013
Dynamic modeling
KUKA KR5 Sixx R650 robot (in 2021)

- identify signs of motor currents by means of a Tree Penalty-Based Parameter Retrieval algorithm
- use the method in experimental identification of robot dynamic model, followed by validation tests

Simulation test
39/39 segments of motor currents correctly handled (assign right +/-)
Collision detection and isolation
KUKA KR5 Sixx R650 robot

\[ \sigma_{mod}(t) = k_\sigma \int_0^t [\hat{\pi}^T Y^T(s)Y(s)\hat{\pi} - \tau^T(s)\tau(s) - \sigma_{mod}(s)] \, ds \]

use of extra residuals for motor currents of a priori unknown signs
Further pHRI results obtained within/beyond the SAPHARI project

- **integrated** control approach with
  - collision **avoidance** (using exteroceptive sensors)
  - collision **detection** (with residual methods, whenever safe coexistence fails)
  - collision **reaction** (not limited to retracting the robot from contact areas)
- **distinguish** intentional contact from unexpected collision without F/T sensor
  - more general types of contacts (at any location, not just at the end-effector)
- understanding **human intentions of motion**
  - gesture recognition and classification
  - incremental learning of motion/interaction primitives (kinesthetic teaching)
- **Human-Robot Collaboration (HRC)**
  - search/detect an intentional contact
  - keep the contact while **regulating exchanged forces** (without force sensing) or
  - impose a **generalized human-robot impedance behavior** at the contact
- **portfolio of complex reactive actions** to perform HRC in a robust way
  - sequencing of tasks, monitoring progress, switching control laws in real time
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- D. Zurlo, T. Heitmann, M. Morlock, A. De Luca “Collision detection and contact point estimation using virtual joint torque sensing applied to a cobot”, IEEE ICRA, May 2023
Reduced-order velocity observer for rigid robots

- for use in position-only feedback control laws and for collision detection/isolation
- nice to have the same first-order structure of a momentum-based residual
- should work in closed-loop or open-loop mode (with possibly unbounded velocity)

\[
M(q) \ddot{z} = \tau - S(q, \hat{q}) \dot{\hat{q}} - g(q) - f(q, \hat{q}) - k_0 M(q) \dot{\hat{q}}
\]

\[
\hat{q} = z + k_0 q
\]

**Theorem 1.** Assume that \( \|\dot{q}\| \leq v_{\text{max}} \) is known. Then, for any fixed \( \eta > 0 \), by choosing

\[
k_0 \geq (c_0 v_{\text{max}} + \eta)/\lambda_{\text{min}}(M(q))
\]

we obtain **local exponential stability** of the observation error \( \varepsilon = \dot{q} - \dot{\hat{q}} \)

with a region of attraction \( \mathcal{E}(\eta) \)

**Theorem 2.** Assume that \( \lim_{n \to \infty} \sup_n \|\dot{q}\| \leq v \) exists but is yet unknown. Then, using a switching logic to adjust the gain with a hybrid dynamics scheme,

we obtain **local exponential stability** of the observation error \( \varepsilon = \dot{q} - \dot{\hat{q}} \)