Safe Control of Robotic manipulators in Dynamic Contexts

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PhD defence

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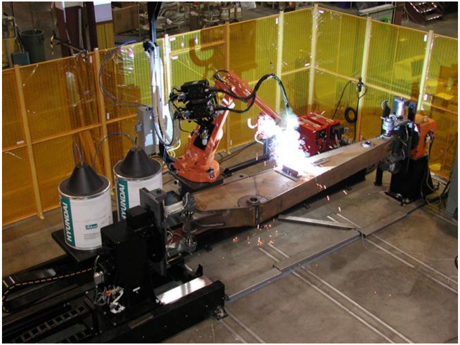
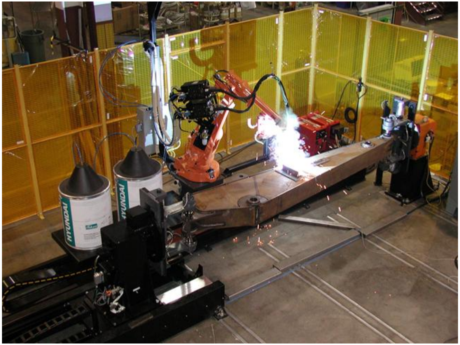
From a well-identified situation



- Static/Known environment
- Known and repetitive trajectories
- Not much considerations for safety

↪ No need for much reactivity: Offline planning

From a well-identified situation ... to a complex one



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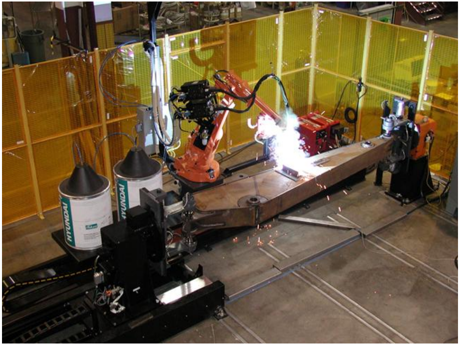

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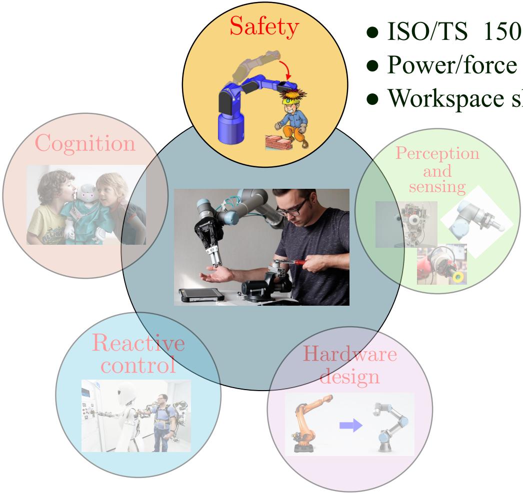
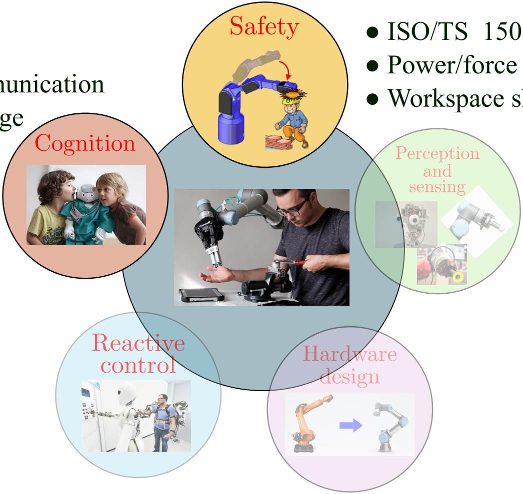
↪ ***"collaborative"*** **robotics, a problem with many dimensions.**


Safety
Cognition
Perception and sensing
Reactive control
Hardware design



- ISO/TS 15066
- Power/force limiting
- Workspace sharing

- Verbal communication
- Body language
- Emotion



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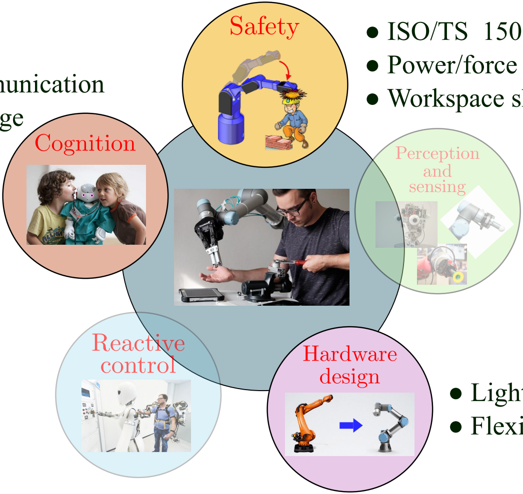

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- Lightweight structures
- Flexible actuators

Collaborative robotics – aspects

- Verbal communication
- Body language
- Emotion

- ISO/TS 15066
- Power/force limiting
- Workspace sharing

- Torque sensors
- Depth sensors
- Tactile skins

- Lightweight structures
- Flexible actuators

- Teleoperation
- Hand guiding
- Sensory based tracking

Dimensions addressed in our work:

↪ I. **Problems related to the use of reactive control loops.**

II. **Safety during Human-Robot physical Interaction.**

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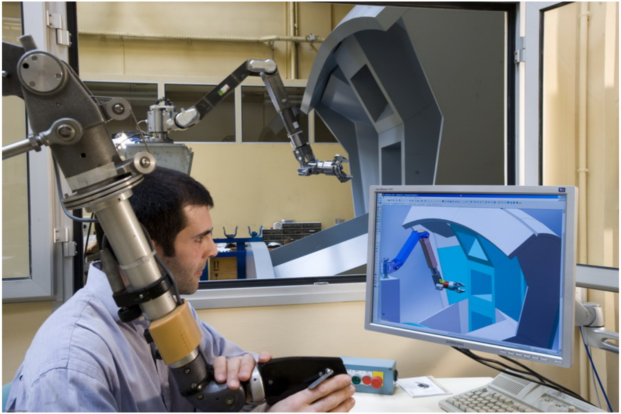
II. Safety during Human-Robot physical Interaction.

Outline

1. Part I: Reactive control and constraints incompatibility
   - Reactive control – the problem
   - Constraints incompatibility, problem illustration (car example)
   - Articular constraints and the incompatibility problem
   - Literature
   - Constraints on articular position/velocity, naive VS new formulations
   - Conclusion I
2. Part II: Safe Human-Robot Interaction
   - Safety as a constraint on energy
   - Safety indicator/limit during the pre-collision phase
   - Safety indicator/limit during the physical-contact phase
   - The controller
   - Simulation and experimental results
   - Conclusion II.
3. Conclusion

- Task and desired trajectory discovered online.
- Constraint handled reactively, not by planning [Katzschmann 2013].

- **Example scenario** [Rubrecht 2012]:



- Reactive control $\Rightarrow$ constraint handled reactively, not by planning [Katzschmann 2013].

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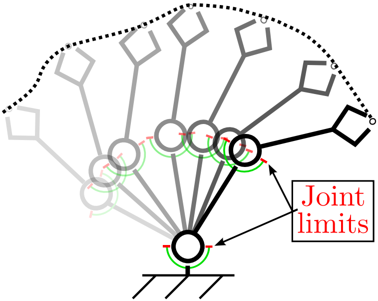

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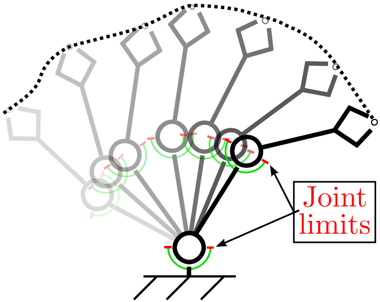

↪ **Problem I: How to compute at each time-step an optimal control solution that allows the system to cope with its articular constraints while performing at best its assigned task ?**

- **In an analytical scheme:** Operational space task projected in the nullspace of the constraints Jacobian [Flacco 2012].

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  - **Trajectory tracking task** in articular space (on a KUKA LWR4):

$$\boldsymbol{\tau}^{c^*}_{|k} = \arg\min_{\boldsymbol{\tau}^c_{|k}, \ddot{q}^c_{|k}} \left\| \ddot{q}^{des}_{|k} - \ddot{q}^c_{|k} \right\|^2_{Q_t} + \epsilon \|\boldsymbol{\tau}^c_{|k}\|^2_{Q_r}, \tag{1}$$

With:

$$\ddot{q}^{des}_{|k} = K_p(q^*_{|k} - q_{|k}) - K_d \dot{q}^*_{|k}. \tag{2}$$

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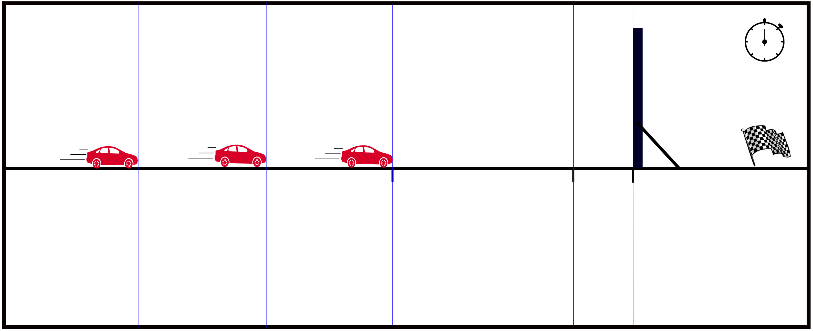
$$\begin{cases} q_m \leq q \leq q_M, & \text{(4a)} \\ \dot{q}_m \leq \dot{q} \leq \dot{q}_M, & \text{(4b)} \\ \ddot{q}_m \leq \ddot{q}^c_{|k} \leq \ddot{q}_M, \; (\tau_m \leq \tau^c_{|k} \leq \tau_M) & \text{(4c)} \\ \dddot{q}_m \leq \dddot{q} \leq \dddot{q}_M. & \text{(4d)} \end{cases}$$

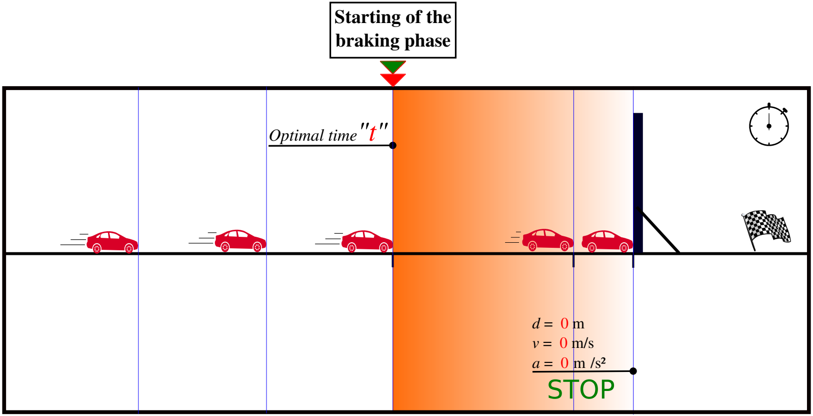
$\longleftarrow$ **Depending on how these are formulated, incompatibility cases may occur.**



- **Constraints on the car:**

$$\begin{cases} d \leq d_{safe}, & (5a) \\ v \leq v_{Max}, & (5b) \\ a \geq -a_{Max}. & (5c) \end{cases}$$

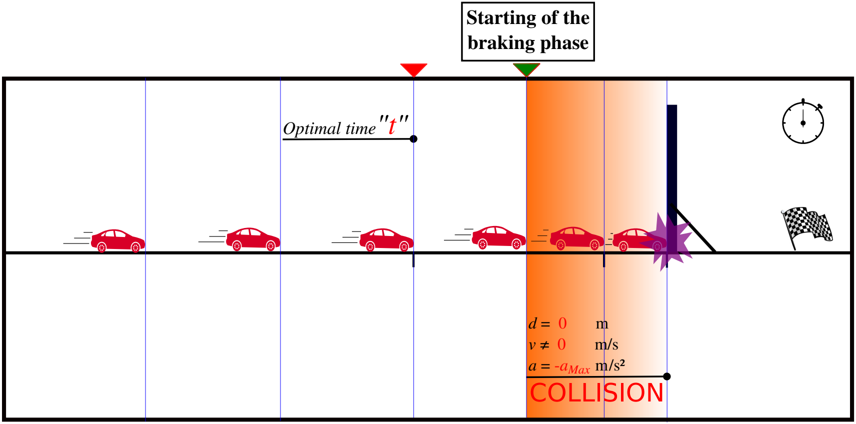
- Case 1: the car starts braking at the optimal time t.



- **t depends on:**
  - The car's position limit d_{safe}.
  - The car's deceleration limit $-a_{Max}$.

↪ **Optimal solution w.r.t to the objective and to the constraints.**

- Case 3: the car starts braking after the optimal time t → **inevitable Collision !**



↪ **Problem: constraints incompatibility (position *VS* deceleration)**

- **Naive formulation**, discretization over just one δt time-step:

$$\begin{cases} q_m \leq q_{|k+1} = q_{|k} + \delta t \dot{q}_{|k} + \frac{\delta t^2}{2} \ddot{q}^c_{|k} \leq q_M, & (6a) \\ \dot{q}_m \leq \dot{q}_{|k+1} = \dot{q}_{|k} + \delta t \ddot{q}^c_{|k} \leq \dot{q}_M, & (6b) \\ \ddot{q}_m \leq \ddot{q}^c_{|k} \leq \ddot{q}_M, & (6c) \\ \dddot{q}_m \leq \dddot{q}_{|k+1} = \frac{1}{\delta t}(\ddot{q}^c_{|k} - \ddot{q}_{|k}) \leq \dddot{q}_M. & (6d) \end{cases}$$

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$\hookrightarrow$ **Formulations of (6a) and (6b) should be modified to account for the system's dynamic capabilities.**

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  - [Lange 2015]: Jerk-Limited stopping motion generation.

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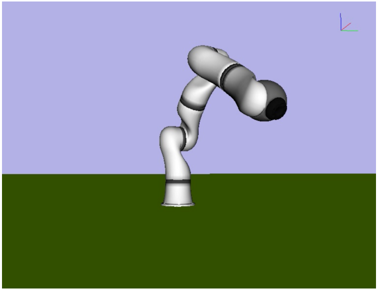
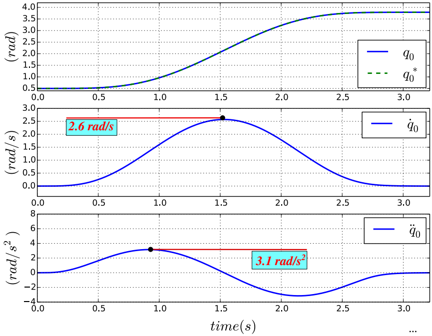
↪ **Contribution I:**
- **New formulations of the articular position & velocity constraints that account for the dynamic capabilities of the system are proposed.**
- **A dynamic optimal control solution for a reactively controlled robotic arm that preserves the viability of its state is guaranteed.**

- **The new formulations to be introduced are compared to the naive ones.**
- The dynamic optimization control scheme is used.
- Trajectory traking task in articular space.
- Control time-step $= 1\ ms$.
- Only the movement of joint 0 is constrained.





- **Naive formulation** [Park 1998]:

$$q_{|k+1} = q_{|k} + \delta t \dot{q}_{|k} + \frac{\delta t^2}{2} \ddot{q}^c_{|k} \leq q_M, \tag{7}$$

  - Discretization over only one δt time-step.
  - Accounts for the system's state $q_{|k}$, $\dot{q}_{|k}$ **and not** for its dynamic capabilities $\ddot{q}_m$, $\dddot{q}_m$ and $\dddot{q}_M$.

$\hookrightarrow$ $\boxed{\textbf{Often results in incompatibility issues !}}$

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- **New proposed formulation**:

$$f(q_{|k}, \dot{q}_{|k}, \ddot{q}_m, \dddot{q}_m, \dddot{q}_M, n_i \delta t) \leq q_M, \tag{8}$$

- Discretization over $n_i \delta t$ time-steps.
- Accounts for both the system's state $q_{|k}$, $\dot{q}_{|k}$ **and also** for its dynamic capabilities $\ddot{q}_m$, $\dddot{q}_m$ and $\dddot{q}_M$.

↪ **No incompatibility issues with the constraints on $\ddot{q}$ and $\dddot{q}$.**

- **Using the naive formulation of the articular position constraint:**
  - No available control solution to cope with the joint position constraint within one δt time-step considering the constraints on the articular deceleration and jerk.

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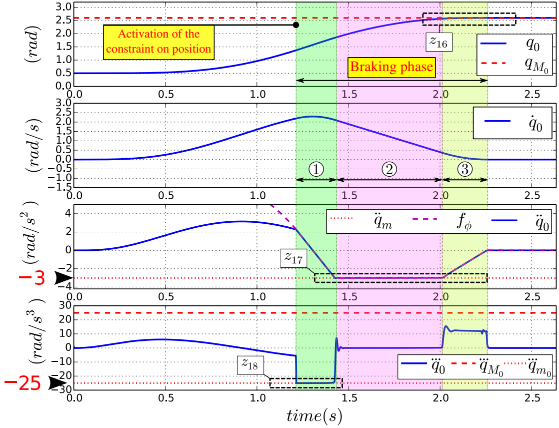
- **Using the new formulation of the articular position constraint:**

- **All constraints on:**
  - Articular position
  - Articular deceleration
  - Articular jerk

↪ **Are all simultaneously satisfied.**



- **Naive formulation**:

$$\dot{q}_{|k+1} = \dot{q}_{|k} + \delta t \ddot{q}^{c}_{|k} \leq \dot{q}_{M}, \tag{9}$$

  - Discretization over only one δt time-step.
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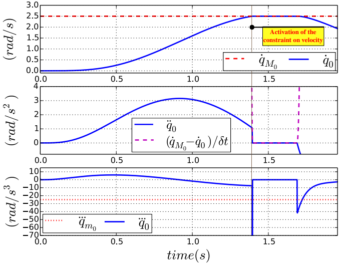
- **New proposed formulation**:

$$\dot{q}_{|k+n_1} = \dot{q}_{|k} + n_1 \ddot{q}^{c}_{|k} \delta t + \frac{({n_1}^2 - n_1)}{2} \dddot{q}_{m} \delta t^2 \leq \dot{q}_{M}, \tag{10}$$

  - Discretization over $n_1 \delta t$ time-steps.
  - Accounts for both the system's state $\dot{q}_{|k}$ **and** for its producible jerk $\dddot{q}_{m}$.

↪ $\boxed{\textbf{No incompatibility with the constraint on jerk !}}$

- **Naive formulation:**



↪ **•High peak of jerk !**
•If $\dddot{q}$ constrained, the control problem is un-solvable.

- **New formulation:**

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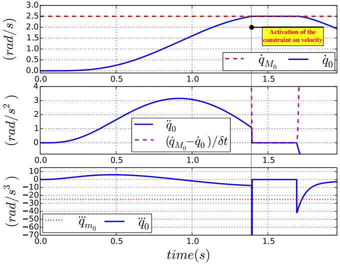

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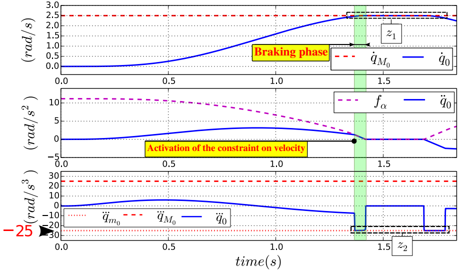


↪
- **Both jerk and velocity limits are satisfied.**

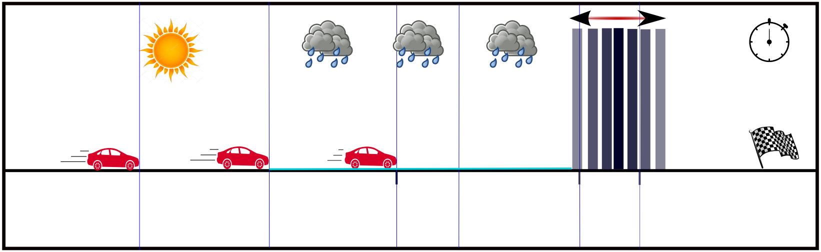
- With the **new introduced formulations**, the articular constraints:

$$\begin{cases} q_m \leq q \leq q_M, & (11a) \\ \dot{q}_m \leq \dot{q} \leq \dot{q}_M, & (11b) \\ \ddot{q}_m \leq \ddot{q}^c_{|k} \leq \ddot{q}_M, & (11c) \\ \dddot{q}_m \leq \dddot{q} \leq \dddot{q}_M. & (11d) \end{cases}$$

$\hookrightarrow$ **Are all simultaneously and reactively coped with.**

$\hookrightarrow$ **The viability of the state of the system is guaranteed over an infinite horizon of time.**

- **Even more complex**



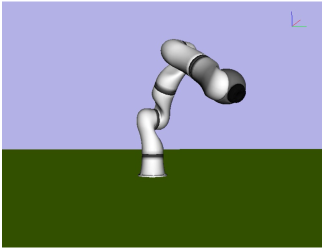
- **Solving the problem of constraints incompatibility is more complex if:**
  1. The position of the obstacle is dynamic $\widetilde{d}_{safe}$.
  2. The car's deceleration capability $-\widetilde{a}_{Max}$ is variable.

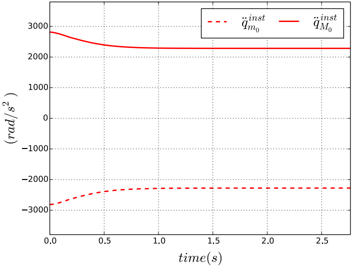
- **The robot system's articular deceleration capabilities are not constant:**

$$M(q_{|k})\ddot{q}^c_{|k} + b(q_{|k}, \dot{q}_{|k}) = \tau^c_{|k}, \tag{12}$$

$$\begin{cases} q_m \leq q \quad \leq q_M, & (13a) \\ \dot{q}_m \leq \dot{q} \quad \leq \dot{q}_M, & (13b) \\ \ddot{q}_m \leq \ddot{q}^c_{|k} \leq \ddot{q}_M, \; (\tau_m \leq \tau^c_{|k} \leq \tau_M) & (13c) \\ \dddot{q}_m \leq \dddot{q} \quad \leq \dddot{q}_M. & (13d) \end{cases}$$

- τ_M and τ_m are constant.
- $\ddot{q}_M$, $\ddot{q}_m$, $\dddot{q}_M$, and $\dddot{q}_m$ are configuration dependent.





- **Open problem:** constraints incompatibility for dynamic constraints, use MPC ?

Dimensions addressed in our work:

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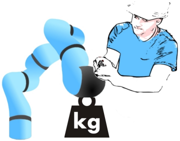
II. Safety during Human-Robot physical Interaction.

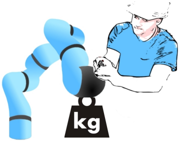


- **Motivations:**
  - Safely share the robot's workspace.
  - Enable safe Human-Robot physical Interaction.

- **State of the art: safety at the control level**

Velocity ■
Apparent inertia ■
Impact force ■
Contact force ■
Discontinuities at contact release ■

■ Force control [Raibert 1981]
■ Impedance force control [Hogan 1984, Ott 2010]
■ Hybrid force/impedance control [Schindlbeck 2015]
■ Impact force modulation [Heinzmann 2003]
■ Velocity saturation [Haddadin 2012a]
■ Inertia shaping of falling humanoids[Yun 2008]



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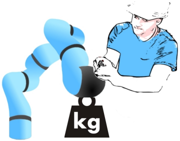
Safety during Human-Robot Interaction – state of the art



- **Motivations:**
  - Safely share the robot's workspace.
  - Enable safe Human-Robot physical Interaction.

- **State of the art: safety at the control level**

Velocity

Apparent inertia

Impact force

Contact force

Discontinuities at contact release

- Force control [Raibert 1981]
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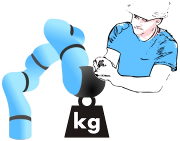

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Velocity, Apparent inertia, Impact force, Contact force, Discontinuities at contact release

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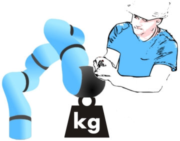

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Velocity
Apparent inertia
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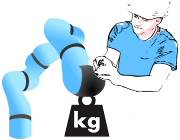
↪ $\boxed{\textbf{Available approaches not sufficiently generic.}}$



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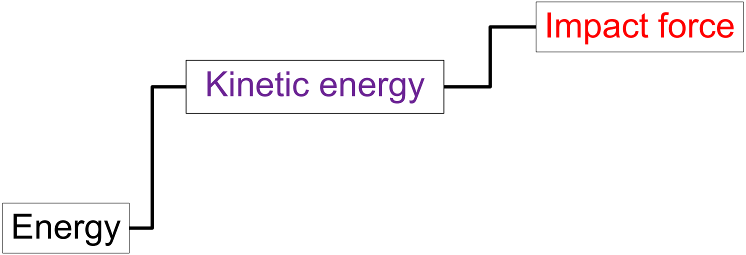
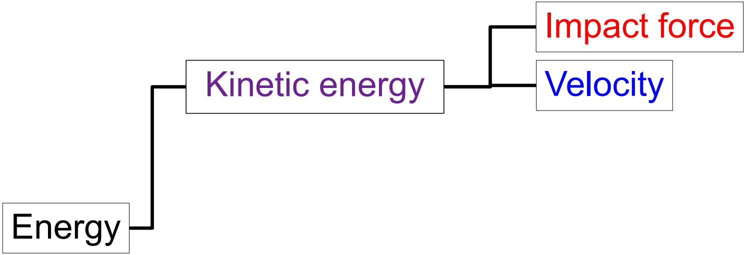
↪ **Available approaches not sufficiently generic.**

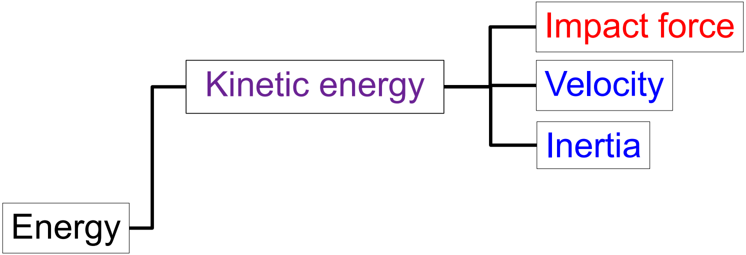
↪ **Contribution II: the use of energy as a safety indicator to modulate the system's dynamics.**

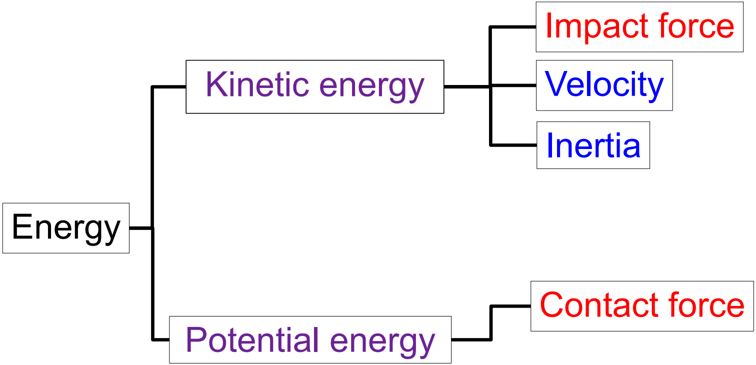
Energy as a safety indicator

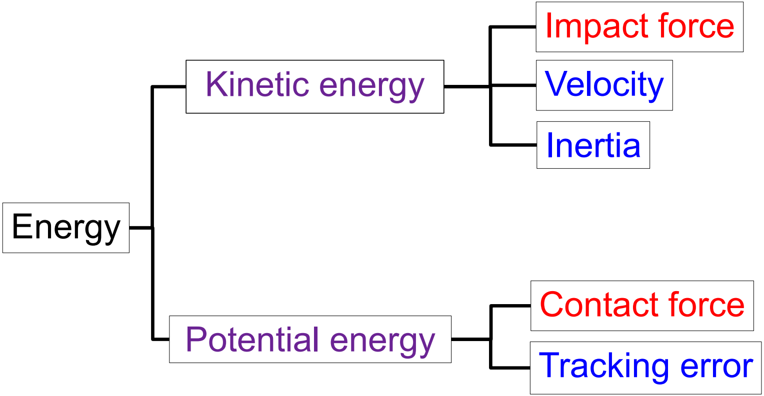


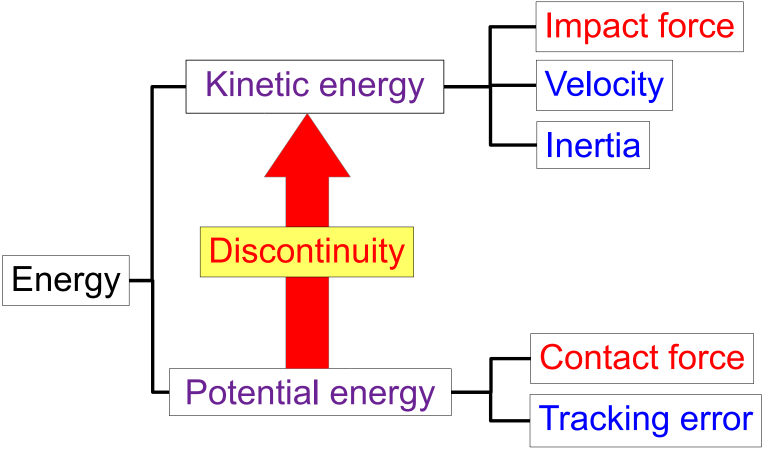

Energy
Kinetic energy
Impact force
Velocity

Energy as a safety indicator




Impact force
Kinetic energy
Velocity
Inertia
Energy
Contact force
Potential energy


Energy
Kinetic energy
Potential energy
Impact force
Velocity
Inertia
Contact force
Tracking error


Impact force
Kinetic energy
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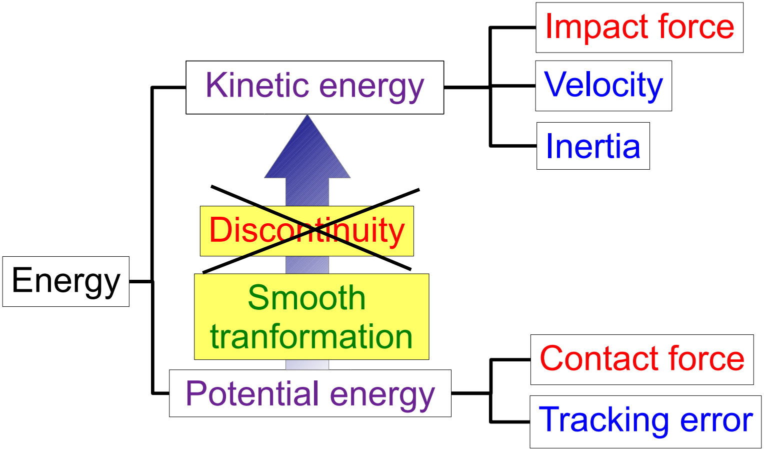
Impact force
Kinetic energy
Velocity
Inertia
~~Discontinuity~~
Energy
Smooth tranformation
Contact force
Potential energy
Tracking error

- **Two interaction phases**:
  - **Pre-collision phase.**
  - **Physical contact phase.**

- **For each phase is defined**:
  - **A safety indicator S.**
  - **A safety limit S_{limit}.**
  - **A safety constraint**:

Safety indicator $\leq$ Safety limit

Pre-collision phase

- **Dissipated kinetic energy in case of collision is source of danger:**

$$\begin{aligned} \int_u F_{impact}\, du &= E_{dissipated} \\ &= E_c^{hum} + E_c^{rob}, \end{aligned} \tag{14}$$

with u: the shock absorption distance.

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$$\begin{aligned}\int_u F_{impact}\, du &= E_{dissipated} \\ &= E_c^{hum} + E_c^{rob},\end{aligned} \tag{14}$$

with u: the shock absorption distance.

- **Proposed safety indicator 1 (Pre-collision phase):**

$$\begin{aligned}S_c &= E_c^{rob \to hum} \\ &= \frac{1}{2} m(q)^{eq}_{eff \to hum} v^2_{eff \to hum}\end{aligned} \tag{15}$$

- $E_{c_{limit}}$: **Amount of kinectic energy allowed to be dissipated at impact.** [ISO/TS 15066]

- $E_{C_{limit}}$: **Amount of kinectic energy allowed to be dissipated at impact.** [ISO/TS 15066]
- **Safety Constraint 1:** Decrease the robot's kinetic energy before collision

$$\underbrace{S_c \leq E_{C_{limit}} = E_{c_{safe}} + f(d)}_{\text{Constraint in the LQP}}. \tag{16}$$

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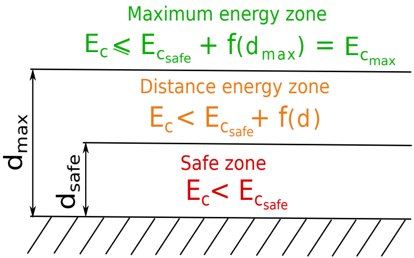
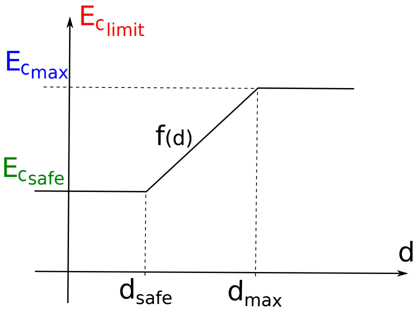




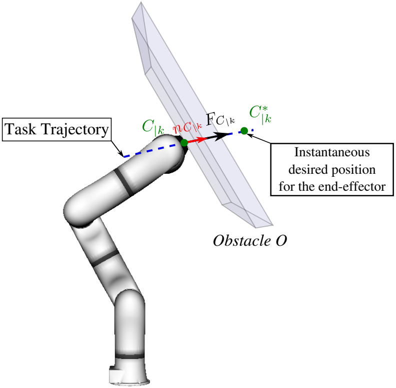
- d is the real-time distance between the human and the robot's end-effector.

Physical-contact phase

- **Accumulated energy** after the establishment of **physical-contact**:

$$F_{C_{|k}} = -\nabla E_{p_{|k}} \Rightarrow E_{p_{|k}} = -\int_{X^*_{C_{|k}}}^{X_{C_{|k}}} F_{C_{|k}} dx = F_{C_{|k}} \left(X^*_{C_{|k}} - X_{C_{|k}} \right) n_{C_{|k}}. \qquad (17)$$

  - $X_{C_{|k}}$, $X^*_{C_{|k}}$: Current real and desired position of the end-effector.
  - $F_{C_{|k}}$: Equivalent effort expressed at the end-effector.



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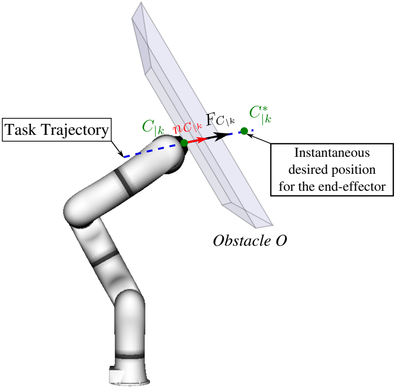

- **Proposed safety indicator 2 (physical-contact phase):**

$$S_{p_{contact}} = E_{p_{|k}}. \quad (18)$$

  - Accounts for the control effort $F_{C_{|k}}$.
  - Accounts for the tracking error δX.

- $E_{p_{limit}}$: **Energy allowed to be accumulated in the robot's controller during physical-contact.**

- **Safety Constraint 2:**

$$\underbrace{S_{p_{contact}} \leq E_{p_{limit}} = E_{p_{safe}} \leq E_{c_{safe}}}_{\text{Constraint in the LQP}}. \tag{19}$$

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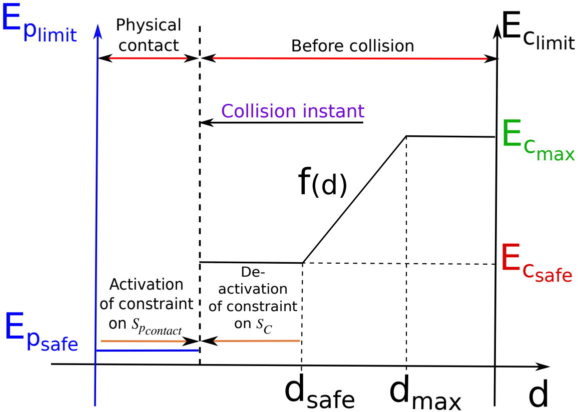

- **Trajectory tracking task** in operational space:

$$\boldsymbol{\tau}^{c\,*}_{|k} = \arg\min_{\ddot{q}^{c}_{|k},\boldsymbol{\tau}^{c}_{|k}} \left\| \ddot{X}^{des}_{|k} - \ddot{X}^{c}_{|k} \right\|^2_{Q_t} + \epsilon \|\boldsymbol{\tau}^{c}_{|k}\|^2_{Q_r}, \tag{20}$$

With:

$$\ddot{X}^{des}_{|k} = \ddot{X}^{*}_{|k} + K_p(X^{*}_{|k} - X_{|k}) + K_d(\dot{X}^{*}_{|k} - \dot{X}_{|k}). \tag{21}$$

- **Trajectory tracking task** in operational space:

$$\tau_{|k}^{c\,*} = \arg\min_{\ddot{q}_{|k}^{c},\tau_{|k}^{c}} \left\| \ddot{X}_{|k}^{des} - \ddot{X}_{|k}^{c} \right\|_{Q_t}^{2} + \epsilon \|\tau_{|k}^{c}\|_{Q_r}^{2}, \tag{20}$$

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- **Subject to:**

$$M(q_{|k})\ddot{q}_{|k}^{c} + b(q_{|k},\dot{q}_{|k}) = \tau_{|k}^{c}, \tag{22}$$

$$\begin{cases} q_m \leq q \leq q_M, & (23a) \\ \dot{q}_m \leq \dot{q} \leq \dot{q}_M, & (23b) \\ \tau_m \leq \tau_{|k}^{c} \leq \tau_M, & (23c) \end{cases}$$

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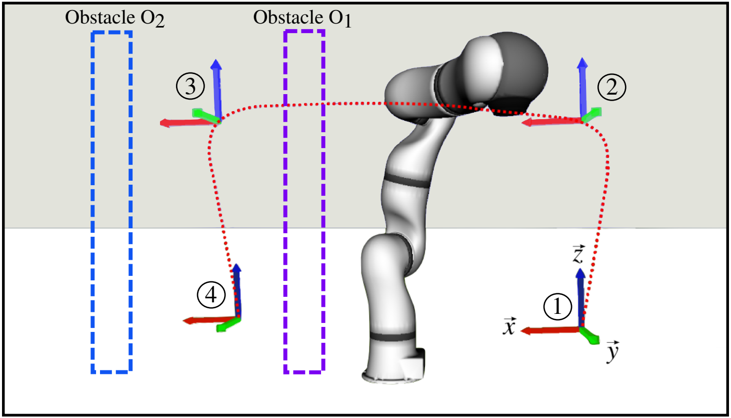
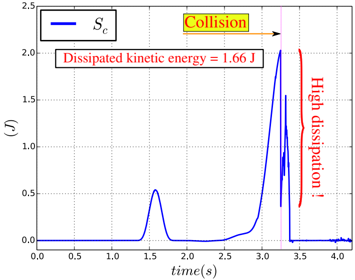
  - **And to the constraints on the robot's energy**:

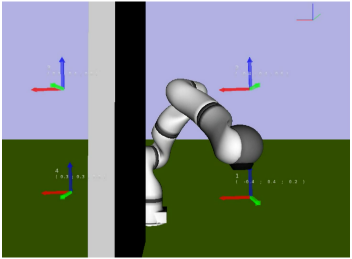
$$\begin{cases} S_c \leq E_{c_{safe}} + f(d), \\ S_{p_{contact}} \leq E_{p_{safe}}. \end{cases} \tag{24}$$

- **The robot performs a repetitive pick and place movement, tracking a desired position and orientation in operational space:**

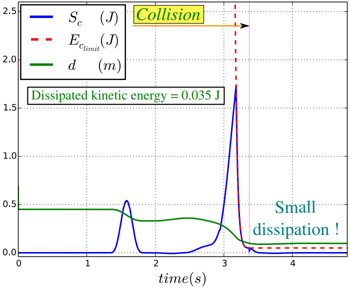


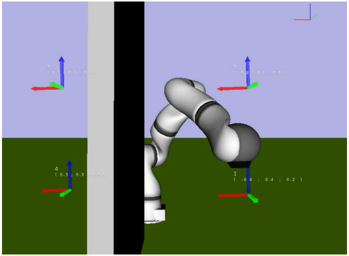
- **Robot/obstacle collision:**
  - **Without constraints on energy.**



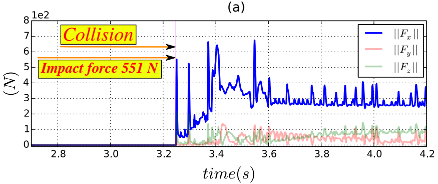


  - **With constraints on energy.**





- **Without constraining the robot's energy.**



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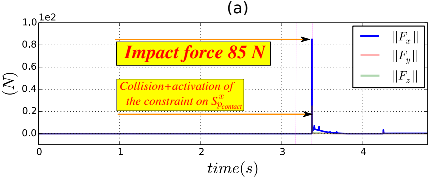

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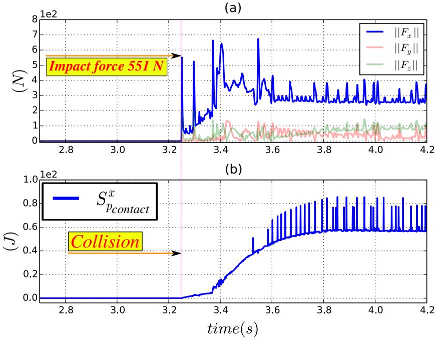

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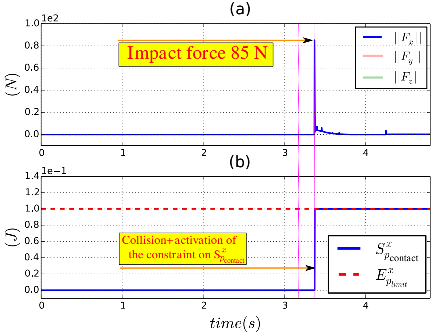
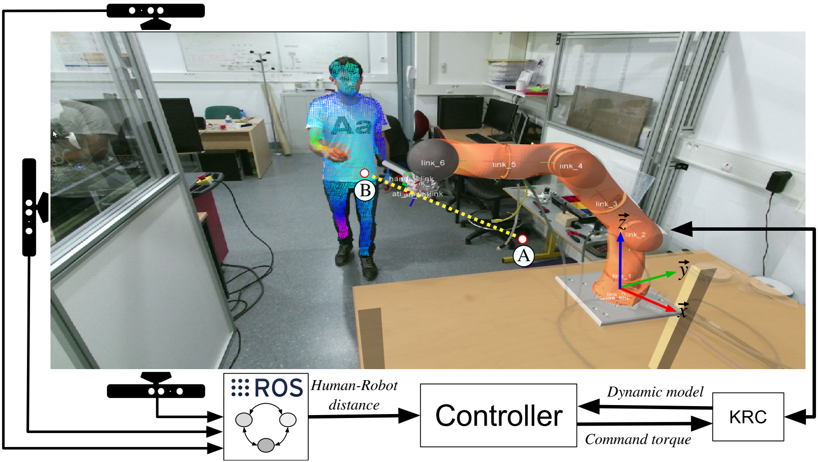
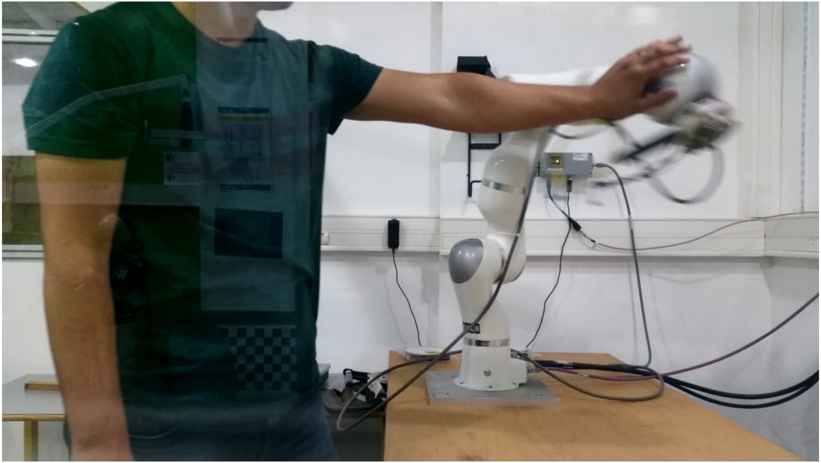
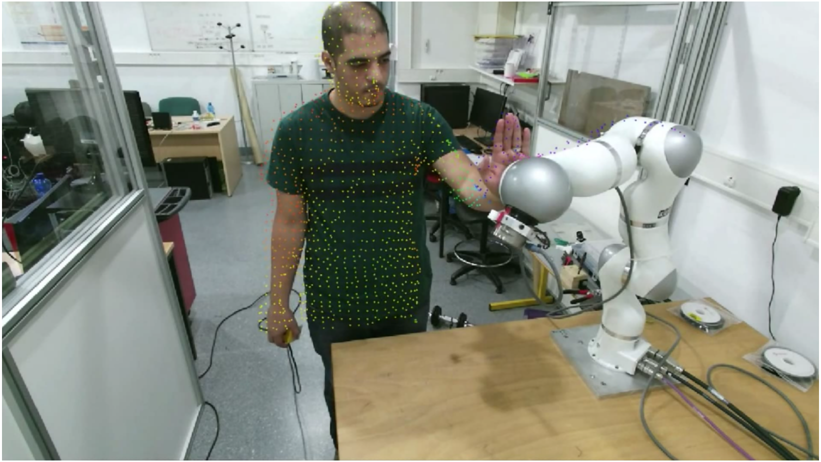


- The controller is implemented as an OROCOS node.
- Control time-step = energy constraints time-step = 15 *ms*.
- Real-time human-robot distance is acquired using a set of 3 Kinects.





Experiment 2 : With constraints on kinetic and potential energy



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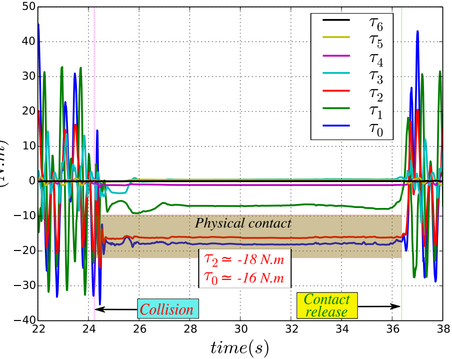

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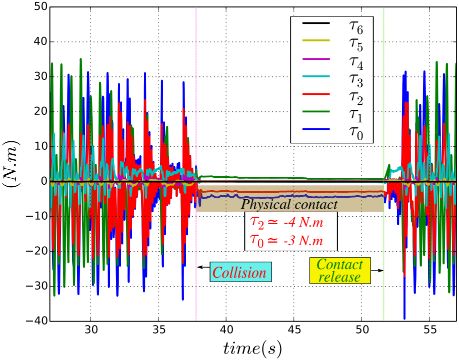

- **Using the introduced safety indicators and criteria, safety for the human is guaranteed during different interaction phases :**
  - Before/at collision.
  - During physical contact.
  - When physical-contact is released.

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- **Impact and contact forces are successfully reduced by the modulation of the energetic level of the robot.**

- **Addressed topics:**

I. **Constraints incompatibilities for reactively controlled robots.**

II. **Safety during Human-Robot physical Interaction.**

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  - An optimal solution to the problem of constraints incompatibility is proposed.

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  - An optimal solution to the problem of constraints incompatibility is proposed.
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- **Future work for topic I:**
  - Implementation on a real-world system [Del Prete 2016].

Conclusion – future work

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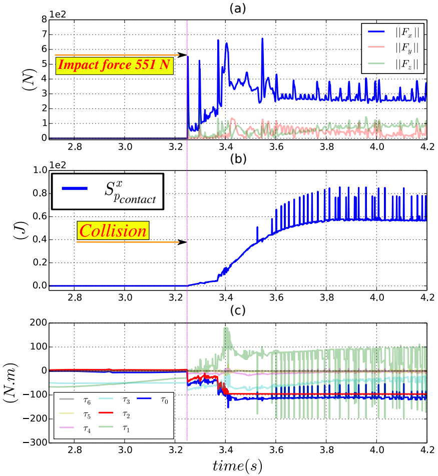
  - Biomechanical analysis.

- Meguenani, A., Padois, V., & Bidaud, P. (2015, September). Control of robots sharing their workspace with humans: an energetic approach to safety. In Intelligent Robots and Systems (IROS), 2015 IEEE/RSJ International Conference on (pp. 4678-4684). IEEE.
- Meguenani, A., Padois, V., Da Silva, J., Hoarau, A., & Bidaud, P. (2017). Energy based control for safe human-robot physical interaction. In 2016 International Symposium on Experimental Robotics (Vol. 1). Springer.
- Meguenani, A., Padois, & Bidaud, P. A unified formulation of energetic constraints for collaborative robots. (Submitted For ICRA 2018).

Thank you !

Simulation results 1

- **Without constraining the robot's energy.**



- **With constraints on energy.**