Robot Control

A Personal View on Some Limits and Perspectives

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Interactive robots do not exist for real

Real-world ...

Basic locomotion and manipulation skills

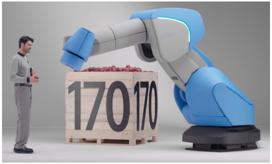
Advanced locomotion skills

Cognitive and physical interactions

Interactive robots do not exist for real

... vs Laboratory science and technology

Advanced control but no living bodies around



How many (trully) collaborative robots have you seen in the industry ?

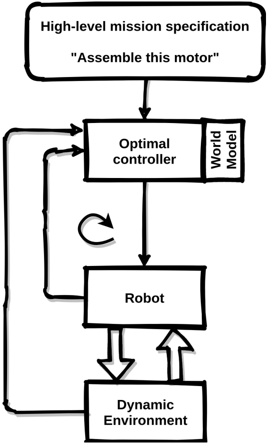
Why is it so ?

The world is dynamic, complex and hard to predict (impact in 6s)

Outline of the presentation

(Reactive) Optimal control

Ideally, solve reactively ...



$$\min_{t_0, t_f, \boldsymbol{x}(t), \boldsymbol{u}(t)} \underbrace{J_b(t_0, t_f, x(t_0), x(t_f))}_{boundary\ \ objective\ \ function} + \underbrace{\int_{t_0}^{t_f} J_i(s, x(s), u(s))ds}_{integral\ \ objective\ \ function}$$

subject to :

- Dynamics : $\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(t, \boldsymbol{x}(t), \boldsymbol{u}(t))$
- Path constraints : $\boldsymbol{h}(t, \boldsymbol{x}(t), \boldsymbol{u}(t)) \leq \boldsymbol{0}$
- State constraints : $\boldsymbol{x}_l(t) \leq \boldsymbol{x}(t) \leq \boldsymbol{x}_u(t)$
- Control bounds : $\boldsymbol{u}_l(t) \leq \boldsymbol{u}(t) \leq \boldsymbol{u}_u(t)$

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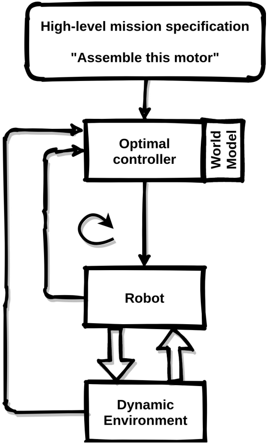

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... but in practice

- infinite dimensional problem
- can generally not be solved, even once

↪ transformed in a finite dimensional problem : non linear program / constrained parameter optimization

↪ hard to solve, cannot be solved reactively

Looking closer

In dynamic environments, $\boldsymbol{x}(t) = \{\boldsymbol{x}_{rob}(t), \boldsymbol{x}_{env}(t)\}$
$\hookrightarrow$ requires **perception** for the state of the environment $\boldsymbol{x}_{env}(t)$
$\hookrightarrow$ no control over $\boldsymbol{x}_{env}(t) \rightarrow$ reactive planning needed

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  - $\boldsymbol{M}(\boldsymbol{q})\dot{\boldsymbol{\nu}} + \boldsymbol{b}(\boldsymbol{q}, \boldsymbol{\nu}) = \boldsymbol{S}^T(\boldsymbol{q})\boldsymbol{\tau}\ (+\sum_i^{n_c} \boldsymbol{J}_{c_i}^T(\boldsymbol{q})\boldsymbol{f}_{c_i})$
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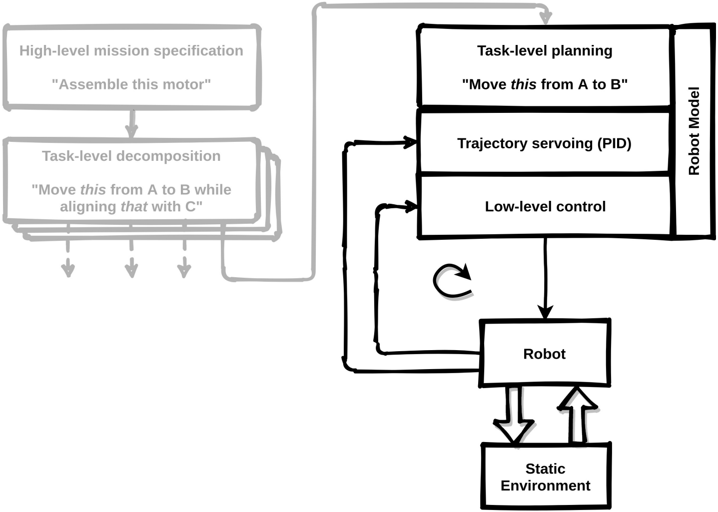
  - $\boldsymbol{v}_i = \boldsymbol{J}(\boldsymbol{q})\dot{\boldsymbol{\nu}} \ \ \forall i \in [1, n_o]$ and $\boldsymbol{v}_i := \dot{\boldsymbol{H}}_i$
- Constraints :
  - $\boldsymbol{\tau}_l \leq \boldsymbol{\tau} \leq \boldsymbol{\tau}_u$
  - $\dot{\boldsymbol{\tau}}_l \leq \dot{\boldsymbol{\tau}} \leq \dot{\boldsymbol{\tau}}_u$
  - $\boldsymbol{q}_l \leq \boldsymbol{q} \leq \boldsymbol{q}_u$
  - $\dot{\boldsymbol{\nu}}_l \leq \dot{\boldsymbol{\nu}} \leq \dot{\boldsymbol{\nu}}_u$
  - $\boldsymbol{h}(\boldsymbol{x}_{env}, \boldsymbol{q}) \leq \boldsymbol{0}$
  - ...

$\hookrightarrow$ **very complex and computationnally demanding control / optimization problem**

Outline of the presentation

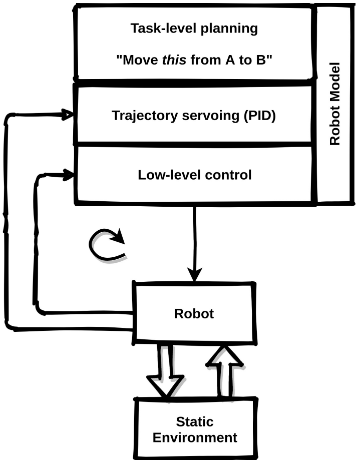
Optimal control vs real-life

Historically in the industry, the problem left to robots is simplified



Optimal control vs real-life

Static environment → reactivity not required at the task planning level ...



... as constraints are met

- offline, through planning
- a posteriori through emergency stops or stereotypical safety zones definition

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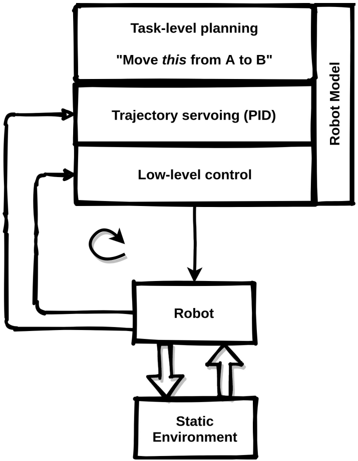

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Yet finding a control trajectory is complex

↪ Decouple planning and control

- Plan for $\boldsymbol{q}(t)$ or $\boldsymbol{H}(t)$
- Perform trajectory servoing and low level-control

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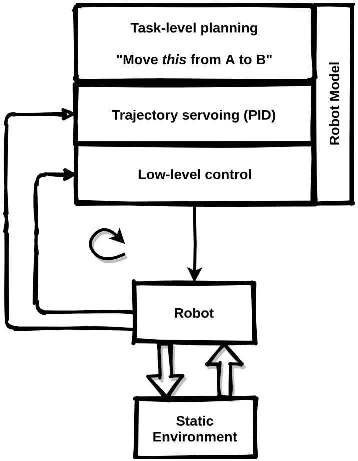

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Still too complex !

- Simplification based on an underestimation of the true robot capacities

↪ the industry is full of oversized and dangerous robots

- Highly expert manual tuning required

↪ robots are not the promised versatile tools

Illustration with the Franka Emika Panda Robot

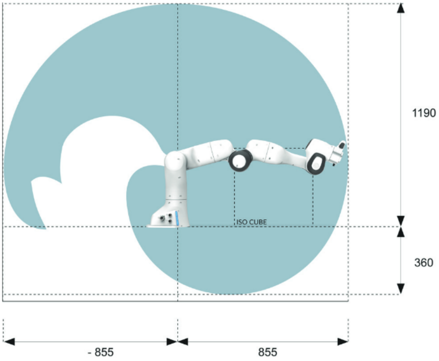
Constants

Limits in the Cartesian space are as follows:

Name	Translation	Rotation	Elbow
$\dot{p}_{max}$	1.7000 $\frac{m}{s}$	2.5000 $\frac{rad}{s}$	2.1750 $\frac{rad}{s}$
$\ddot{p}_{max}$	13.0000 $\frac{m}{s^2}$	25.0000 $\frac{rad}{s^2}$	10.0000 $\frac{rad}{s^2}$
$\dddot{p}_{max}$	6500.0000 $\frac{m}{s^3}$	12500.0000 $\frac{rad}{s^3}$	5000.0000 $\frac{rad}{s^3}$

Joint space limits are:

Name	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6	Joint 7	Unit
q_{max}	2.8973	1.7628	2.8973	-0.0698	2.8973	3.7525	2.8973	rad
q_{min}	-2.8973	-1.7628	-2.8973	-3.0718	-2.8973	-0.0175	-2.8973	rad
$\dot{q}_{max}$	2.1750	2.1750	2.1750	2.1750	2.6100	2.6100	2.6100	$\frac{rad}{s}$
$\ddot{q}_{max}$	15	7.5	10	12.5	15	20	20	$\frac{rad}{s^2}$
$\dddot{q}_{max}$	7500	3750	5000	6250	7500	10000	10000	$\frac{rad}{s^3}$
$\tau_{j\,max}$	87	87	87	87	12	12	12	Nm
$\dot{\tau}_{j\,max}$	1000	1000	1000	1000	1000	1000	1000	$\frac{Nm}{s}$



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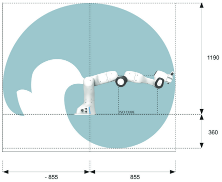
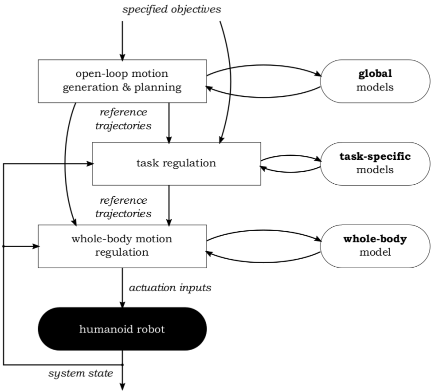


$\hookrightarrow$ **Curse of "collaborative" robotics**

- Safety in the collaboration requires small robots and controlled stops
- Small robots capabilities are small
- Underestimating the capabilities of small robots leads to "not much" capabilities
- Potentially safe robots are mostly useless

Optimal control vs complex robots (e.g. humanoids)

For systems making intermittent contacts with the environment (e.g. humanoids walking)...



[Ibanez 2017]

... mostly two solutions

- Sequential simplified planning problem solving from contact sequence to center of mass trajectory under balance constraints and in purely static environment (plan once)
- Stereotypical walking gaits (planned once) on flat grounds and online planar trajectory adaptation

\+ Trajectory servoing and multi-task whole-body control

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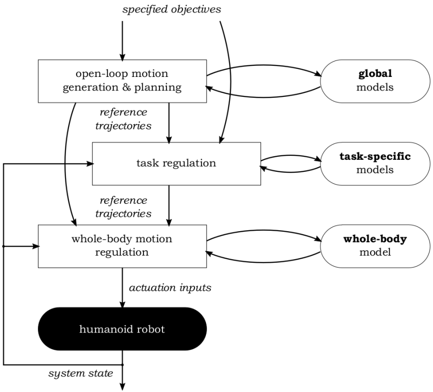

[Ibanez 2017]

Difficulties

- Planning performed with advanced models is costly → no reactivity
- Simplified models do not account for the true capabilities of the system
- ↪ underestimation / overstimation → manual tuning
- Humanoids can't do much in real life

Outline of the presentation

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Robot low-level control as an optimisation problem

In a dynamic environment, performance and safety requires to embed constraints in the low-level control problem : at each control instant, find the actuation torque $\boldsymbol{\tau}^*$ optimizing under constraints some objective related task $\boldsymbol{v}^* = \boldsymbol{J}(\boldsymbol{q})\boldsymbol{\nu}$

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. * see the work of [Liégeois 1977], [Khatib 1987], [Siciliano 1991], [Chiaverini 1997], [Mansard 2009], [Flacco 2012],...

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$$\boldsymbol{D}(\boldsymbol{q},\boldsymbol{\nu})\mathbb{X} \leq \boldsymbol{h}(\boldsymbol{q},\boldsymbol{\nu})$$

- These constraints are linear wrt control variables : **convex solution space**
  ↪ convex optimization (LQP) is a powerful tool to solve optimally the reactive control problem.

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Robot low-level control as an optimisation problem

3 reasons why Quadratic Programs are better than explicit Jacobian inversions

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3 reasons why Quadratic Programs are better than explicit Jacobian inversions

1. Leave your robot alone
   - Methods based on $\boldsymbol{J}^+$ forces constraints to be treated as tasks $\rightarrow$ active avoidance
   - QP allows to consider constraints as such $\rightarrow$ passive avoidance

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2. More constraints than DoFs : choose which one to consider at each time
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   - QP comes with an optimal active constraints determination algorithm

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2. More constraints than DoFs : choose which one to consider at each time
   - Methods based on $\boldsymbol{J}^{+}$ use context specific heuristics to do so
   - QP comes with an optimal active constraints determination algorithm
3. Infeasibilty can't be ignored
   - Methods based on $\boldsymbol{J}^{+}$ can solve infeasible problems $\rightarrow$ constraints violation
   - QP can't be solved if infeasible $\rightarrow$ deal with this problem first
     [Rubrecht 2012a, Meguenani 2017b, Del Prete 2018a]

Constraints compliance as a control feature

For example :

$$\boldsymbol{\tau}_{k+1}{}^{*} = \underset{\boldsymbol{\tau}_{k+1},\ddot{\boldsymbol{q}}_{k+1}}{\arg\min} \left\| \boldsymbol{obj}\left(\ddot{\boldsymbol{q}}_{k+1}, \ddot{\boldsymbol{x}}^{*}_{k+1}\right) \right\|^{2}_{\boldsymbol{Q}_t} + \epsilon \left\| \begin{bmatrix} \boldsymbol{\tau}_{k+1} \\ \ddot{\boldsymbol{q}}_{k+1} \end{bmatrix} \right\|^{2}_{\boldsymbol{Q}_r}$$

$$\text{such that} \quad \boldsymbol{M}(\boldsymbol{q}_k)\ddot{\boldsymbol{q}}_{k+1} + \boldsymbol{b}(\boldsymbol{q}_k, \dot{\boldsymbol{q}}_k) = \boldsymbol{S}^{T}(\boldsymbol{q}_k)\boldsymbol{\tau}_{k+1}$$

$$\boldsymbol{\tau}_{min} \leq \boldsymbol{\tau}_{k+1} \leq \boldsymbol{\tau}_{max}$$

$$\boldsymbol{q}_{min} \leq \boldsymbol{q}_{k+1} \leq \boldsymbol{q}_{max}$$

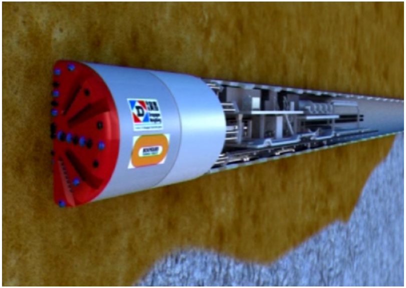
$$\dot{\boldsymbol{q}}_{min} \leq \dot{\boldsymbol{q}}_{k+1} \leq \dot{\boldsymbol{q}}_{max}$$

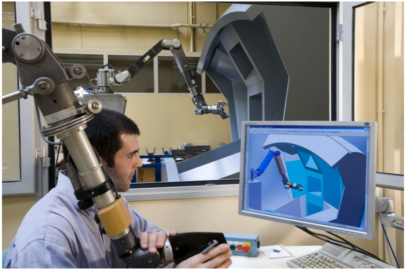
$$0 \leq d^{rob,obj_j}_{k+1} \qquad \forall j \in \{1, \ldots, n_{obj}\}$$

$$\boldsymbol{obj}\left(\ddot{\boldsymbol{q}}_{k+1}, \ddot{\boldsymbol{x}}^{*}_{k+1}\right) = \underbrace{\ddot{\boldsymbol{x}}^{des}_{k+1} + PD(\boldsymbol{x}_k, \boldsymbol{x}^{des}_{k+1})}_{\ddot{\boldsymbol{x}}^{*}_{k+1}} - \boldsymbol{J}(\boldsymbol{q}_k)\ddot{\boldsymbol{q}}_{k+1} - \dot{\boldsymbol{J}}(\boldsymbol{q}_k)\dot{\boldsymbol{q}}_k$$

Constraints compliance as a control feature : the teleoperation case

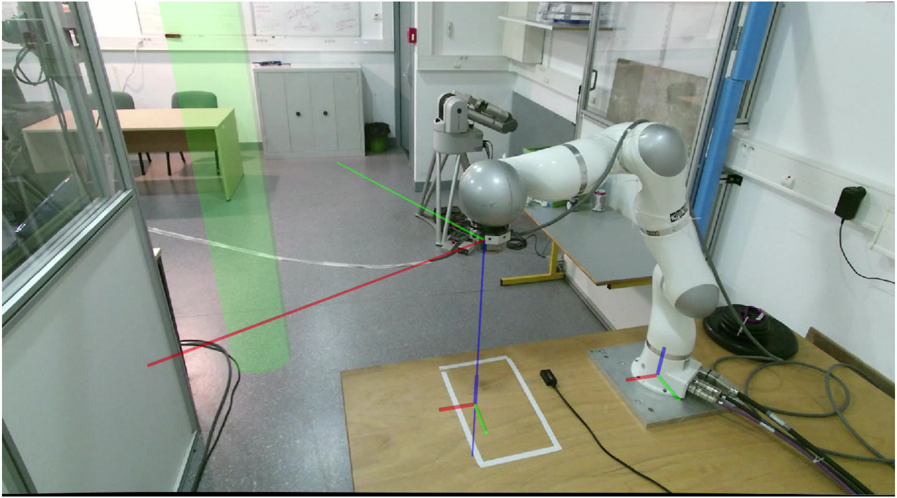
- PhD thesis Sébastien Rubrecht, ANR TELEMACH, CIFRE Bouygues Construction [Rubrecht 2010, Rubrecht 2011, Rubrecht 2012a]
- Context : Teleoperation in tunnel boring machine cutter-heads
- Static environment, interactive task definition





Constraints compliance as a control feature

- PhD work of Lucas Joseph, CIFRE GE Healthcare [Joseph 2018c]
- Dynamic environment : perception in the loop and reactive constraints adaptation



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Viability – Do not plan to do what you cannot do.

- Existence of a solution to the control problem over an ∞ time horizon ?
  [Fraichard 2004],[Wieber 2008]

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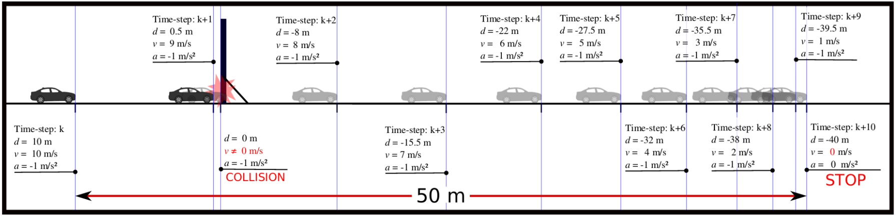

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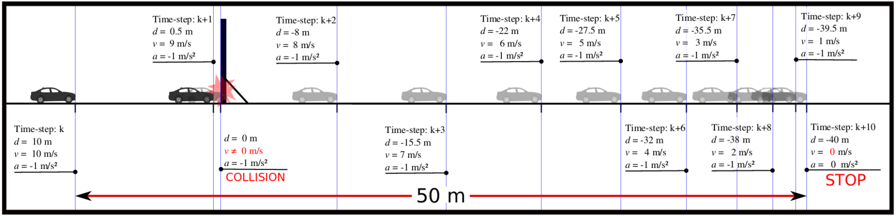

- Modify the constraints expression to ensure compatibility [Rubrecht 2012b]

$$\boldsymbol{q}'_{min}(\boldsymbol{q}_k, \boldsymbol{\nu}_k, \dot{\boldsymbol{\nu}}_{min}, \dot{\boldsymbol{\nu}}_{max}) \leq \boldsymbol{q}_{k+1} \leq \boldsymbol{q}'_{max}(\boldsymbol{q}_k, \boldsymbol{\nu}_k, \dot{\boldsymbol{\nu}}_{min}, \dot{\boldsymbol{\nu}}_{max})$$

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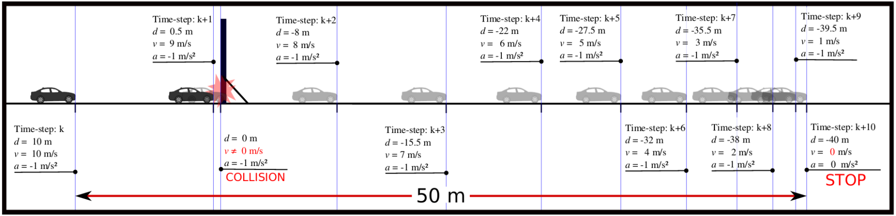

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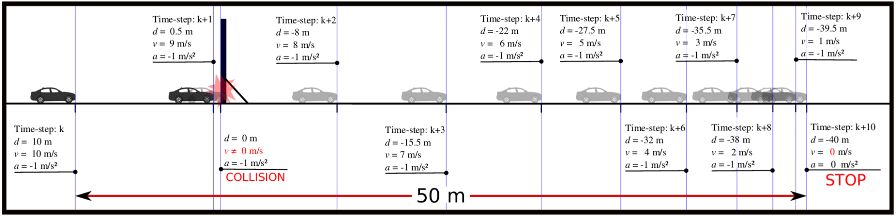
$\boldsymbol{q}'_{min}(\boldsymbol{q}_k, \boldsymbol{\nu}_k, \dot{\boldsymbol{\nu}}_{min}, \dot{\boldsymbol{\nu}}_{max}) \leq \boldsymbol{q}_{k+1} \leq \boldsymbol{q}'_{max}(\boldsymbol{q}_k, \boldsymbol{\nu}_k, \dot{\boldsymbol{\nu}}_{min}, \dot{\boldsymbol{\nu}}_{max})$

- Unfortunately $\dot{\boldsymbol{\nu}}_{k+1} = \boldsymbol{M}^{-1}(\boldsymbol{q}_k)(\boldsymbol{S}^T(\boldsymbol{q}_k)\boldsymbol{\tau}_{k+1} - \boldsymbol{b}(\boldsymbol{q}_k, \boldsymbol{\nu}_k))$ $\quad \rightarrow \dot{\boldsymbol{\nu}}_{max,k+n} = ?$

Viability – Do not plan to do what you cannot do.

- Existence of a solution to the control problem over an ∞ time horizon ?
  [Fraichard 2004],[Wieber 2008]



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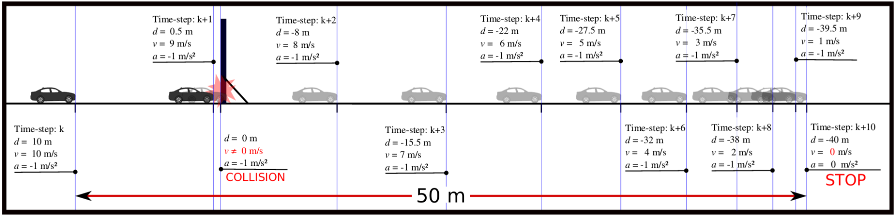

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- Look for a minorant of the joint space acceleration capabilities
  [Meguenani 2017c], [Del Prete 2018b]
- The problem gets even more complex when looking in the task space ?
  $\ddot{\boldsymbol{x}}_{k+1} = \boldsymbol{J}(\boldsymbol{q}_k)\boldsymbol{M}^{-1}(\boldsymbol{q}_k)(\boldsymbol{S}^T(\boldsymbol{q}_k)\boldsymbol{\tau}_{k+1} - \boldsymbol{b}(\boldsymbol{q}_k, t\boldsymbol{\nu}_k)) + \dot{\boldsymbol{J}}(\boldsymbol{q}_k)\boldsymbol{\nu}_k \quad \rightarrow \ddot{\boldsymbol{x}}_{max,k+n} = ?$

Model Predictive Control

- Global optimality does not exist

↪ Try to be optimal given the current state othe world and its close future predicted evolution

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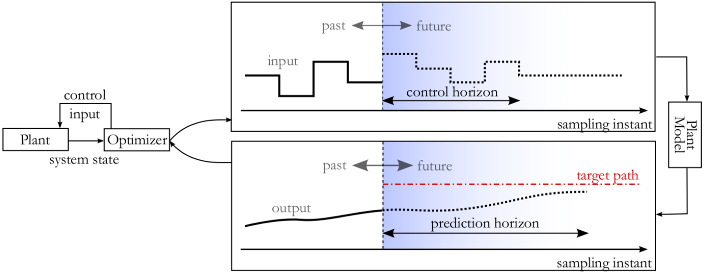
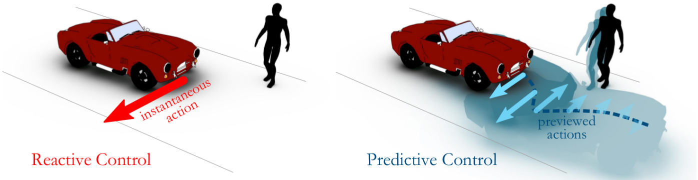




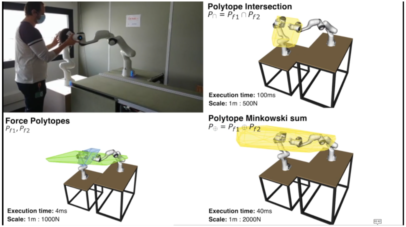
The key ingredient to planning and model predictive control is ...

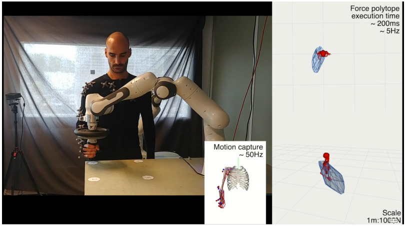
- ... a very good estimation of your motor capabilities in task space
- Complex : state dependant, polytopes

↪ MPC based motion replanning with state dependant robot capabilities

- PhD of Nicolas Torres (Cifre PSA) and Antun Skuric (Lichie Airbus)

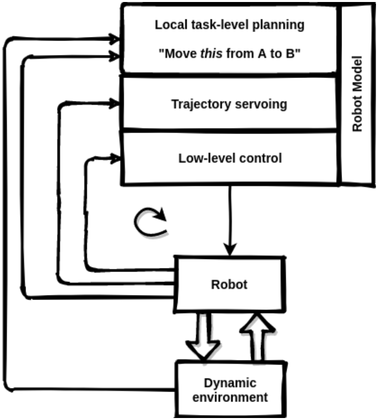
  [Skuric 2021] [Pickard 2021] [Skuric 2022]



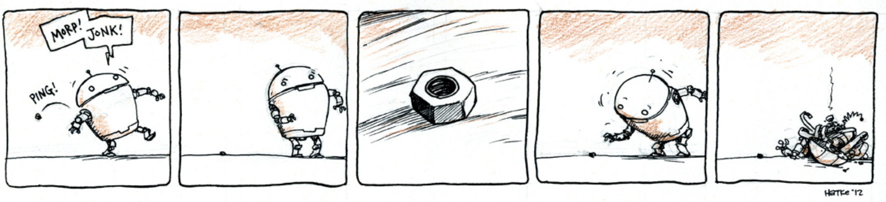


Conclusions

- Global optimality does not exist a priori
  - ! Solving accurately for the full control trajectory does not make sense ...
  - ! ... and is hardly doable in a closed-loop way
  - Closed-loop local planning at high level with low-level capabilities in mind
  - Solve reactively at low-level with constraints
- Human modeling is a key prerequesite to human-robot interaction
  - Ergonomics [Maurice 2017], Motor variability [Savin 2020]
  - Physical capabilities [Benhabib 2020], [Skuric 2022]
  - Cognitive abilities (e.g. expertise) and biases



– Thank you for your attention –



References

Nassim Benhabib, Vincent Padois and David Daney.
Securing industrial operators with collaborative robots : simulation and experimental validation for a carpentry task.
In In proceedings of the IEEE International Conference on Robotics and Automation., Paris, France, May 2020.
IEEE/RAS Best Paper Award in Automation.

Karim Bouyarmane and Abderrahmane Kheddar.
Using a multi-objective controller to synthesize simulated humanoid robot motion with changing contact configurations.
In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 4414–4419. IEEE, 2011.

S. Chiaverini.
Singularity-robust task-priority redundancy resolution for real-time kinematic control of robot manipulators.
Robotics and Automation, IEEE Transactions on, vol. 13, no. 3, pages 398–410, 1997.

Andrea Del Prete.
Joint Position and Velocity Bounds in Discrete-Time Acceleration/Torque Control of Robot Manipulators.
IEEE Robotics and Automation Letters, vol. 3, no. 1, pages pp.281–288, January 2018.

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Joint Position and Velocity Bounds in Discrete-Time Acceleration/Torque Control of Robot Manipulators.
IEEE Robotics and Automation Letters, vol. 3, no. 1, pages 281–288, January 2018.

Adrien Escande, Nicolas Mansard and Pierre-Brice Wieber.
Hierarchical quadratic programming : Fast online humanoid-robot motion generation.
The International Journal of Robotics Research, 2014.

F. Flacco, A. De Luca and O. Khatib.
Prioritized multi-task motion control of redundant robots under hard joint constraints.
In IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), pages 3970–3977, 2012.

Thierry Fraichard and Hajime Asama.
Inevitable collision states — a step towards safer robots ?
Advanced Robotics, vol. 18, no. 10, pages 1001–1024, January 2004.

C. Gaudez, M.A. Gilles and J. Savin.
Intrinsic movement variability at work. How long is the path from motor control to design engineering ?
Applied Ergonomics, vol. 53, pages 71–78, March 2016.

A. Ibanez, P. Bidaud and V. Padois.
Emergence of humanoid walking behaviors from mixed-integer model predictive control.
In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 4014–4021, Chicago, USA, September 2014.

A. Ibanez, P. Bidaud and V. Padois.
Optimization-based control approaches to humanoid balancing.
In Ambarish Goswami and Prahlad Vadakkepat, editeurs, Humanoid Robotics : a Reference, pages 1–27. Springer Netherlands, 2017.

ISO.
ISO TS-15066, Robots and robotic devices - Collaborative robots, 2016.

L. Joseph, V. Padois and G. Morel.
Experimental validation of an energy constraint for a safer collaboration with robots.
In Proceedings of the International Symposium on Experimental Robotics, Buenos Aires, Argentina, November 2018.

L. Joseph, V. Padois and G. Morel.
Towards X-ray medical imaging with robots in the open : safety without compromising performances.
In Proceedings of the IEEE International Conference on Robotics and Automation, pages 6604–6610, Brisbane, Australia, May 2018.

Lucas Joseph.
An energetic approach to safety in robotic manipulation.
Theses, Sorbonne Université, December 2018.

Lucas Joseph, Joshua Pickard, Vincent Padois and David Daney.
Online velocity constraint adaptation for safe and efficient human-robot workspace sharing.
In In Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, Las Vegas, USA, October 2020.

Oussama Kanoun, Florent Lamiraux, Pierre-Brice Wieber, Fumio Kanehiro, Eiichi Yoshida and Jean-Paul Laumond.
Prioritizing linear equality and inequality systems : application to local motion planning for redundant robots.
In Proceedings of the IEEE International Conference on Robotics and Automation, pages 2939–2944, 2009.

O. Khatib.
A unified approach for motion and force control of robot manipulators : The operational space formulation.
IEEE Journal of Robotics and Automation, vol. 3, no. 1, pages 43–53, 1987.

A. Liégeois.
Automatic Supervisory Control of the Configuration and Behavior of Multibody Mechanisms.
IEEE Transactions on Systems, Man and Cybernetics, vol. 7, no. 12, pages 868–871, dec. 1977.

M. Liu, Y. Tan and V. Padois.
Generalized hierarchical control.
Autonomous Robots, vol. 40, no. 1, pages 17–31, 2016.

R. Lober, V. Padois and O. Sigaud.
Efficient Reinforcement Learning for Humanoid Whole-Body Control.
In Proceedings of the IEEE-RAS International Conference on Humanoid Robots, Cancun, Mexico, November 2016.

R. Lober, O. Sigaud and V. Padois.
Task Feasibility Maximization using Model-Free Policy Search and Model-Based Whole-Body Control.
Frontiers in Robotics and AI, May 2020.

N. Mansard, O. Khatib and A. Kheddar.
A Unified Approach to Integrate Unilateral Constraints in the Stack of Tasks.
IEEE Transactions on Robotics, vol. 25, no. 3, pages 670–685, june 2009.

P. Maurice.
Virtual ergonomics for the design of collaborative robots.
PhD thesis, Université Pierre et Marie Curie-Paris VI, 2015.

Pauline Maurice, Vincent Padois, Yvan Measson and Philippe Bidaud.
Human-oriented design of collaborative robots.
International Journal of Industrial Ergonomics, vol. 57, pages 88–102, January 2017.

A. Meguenani, V. Padois, J. Da Silva, A. Hoarau and P. Bidaud.
Energy-based control for safe Human-robot physical interactions.
In D. Kulic, G. Venture, Y. Nakamura and O. Khatib, editeurs, Springer Proceedings in Advanced Robotics - The 2016 International Symposium on Experimental Robotics. Springer International Publishing AG, 2017.

Anis Meguenani.
Safe control of robotic manipulators in dynamic contexts.
Theses, Université Pierre et Marie Curie - Paris VI, October 2017.

Anis Meguenani.
Safe control of robotic manipulators in dynamic contexts.
PhD thesis, Université Pierre et Marie Curie - Paris VI, October 2017.

Joshua K. Pickard, Milan Hladík, Vincent Padois and David Daney.
Efficient Set-Based Approaches for the Computation of Robot Capabilities.
Submitted to IEEE TRO, 2021.

S. Rubrecht, V. Padois, P. Bidaud and M. de Broissia.
Constraint Compliant Control for a Redundant Manipulator in a Cluttered Environment.
In Jadran Lenarčič and Michael M. Stanisic, editeurs, Advances in Robot Kinematics : Motion in Man and Machine, pages 367–376. Springer, 2010.

S. Rubrecht.
Contributions to the control of constrained robots.
PhD thesis, Université Pierre et Marie Curie - Paris VI, September 2011.

S. Rubrecht, V. Padois, P. Bidaud, M. de Broissia and M. Da Silva Simoes.
Motion safety and constraints compatibility for multibody robots.
Autonomous Robots, vol. 32, no. 3, pages 333–349, 2012.

Sébastien Rubrecht, Vincent Padois, Philippe Bidaud, Michel de Broissia and Max Da Silva Simoes.
Motion safety and constraints compatibility for multibody robots.
Autonomous Robots, vol. 32, no. 3, pages 333–349, April 2012.

J. Salini, V. Padois and P. Bidaud.
Synthesis of Complex Humanoid Whole-Body Behavior : a Focus on Sequencing and Tasks Transitions.
In Proceedings of the IEEE International Conference on Robotics and Automation, pages 1283–1290, Shanghai, China, May 2011.

Jonathan Savin, Martine Gilles, Clarisse Gaudez, Vincent Padois and Philippe Bidaud.
Movement Variability and Digital Human Models : Development of a Demonstrator Taking the Effects of Muscular Fatigue into Account.
In Vincent G. Duffy, editeur, Advances in Applied Digital Human Modeling and Simulation, volume 481, pages 169–179. Springer International Publishing, Cham, 2017.

Jonathan Savin.
Simulation de la variabilité du mouvement induite par la fatigue musculaire pour la conception ergonomique de postes de travail.
PhD thesis, Sorbonne Université, November 2019.

Jonathan Savin, Clarisse Gaudez, Martine Gilles, Vincent Padois and Philippe Bidaud.
Evolution of movement variability patterns during a repetitive pointing task until exhaustion.
Submitted to Applied Ergonomics, 2020.

B. Siciliano and J.-J.E. Slotine.
A general framework for managing multiple tasks in highly redundant robotic systems.
In Fifth International Conference on Advanced Robotics, pages 1211 –1216 vol.2, june 1991.

Antun Skuric, Vincent Padois and David Daney.
On-line force capability evaluation based on efficient polytope vertex search.
In Proceedings of the 2021 IEEE International Conference on Robotics and Automation, 2021.

Antun Skuric, Vincent Padois, Nasser Rezzoug and David Daney.
On-line feasible wrench polytope evaluation based on human musculoskeletal models : an iterative convex hull method.
Submitted to IEEE Robotics and Automation Letters, 2022.

Divya Srinivasan and Svend Erik Mathiassen.
Motor variability in occupational health and performance.
Clinical Biomechanics, vol. 27, no. 10, pages 979–993, December 2012.

P.-B. Wieber.
Viability and predictive control for safe locomotion.
In 2008 IEEE/RSJ International Conference on Intelligent Robots and Systems, pages 1103–1108, Nice, September 2008. IEEE.