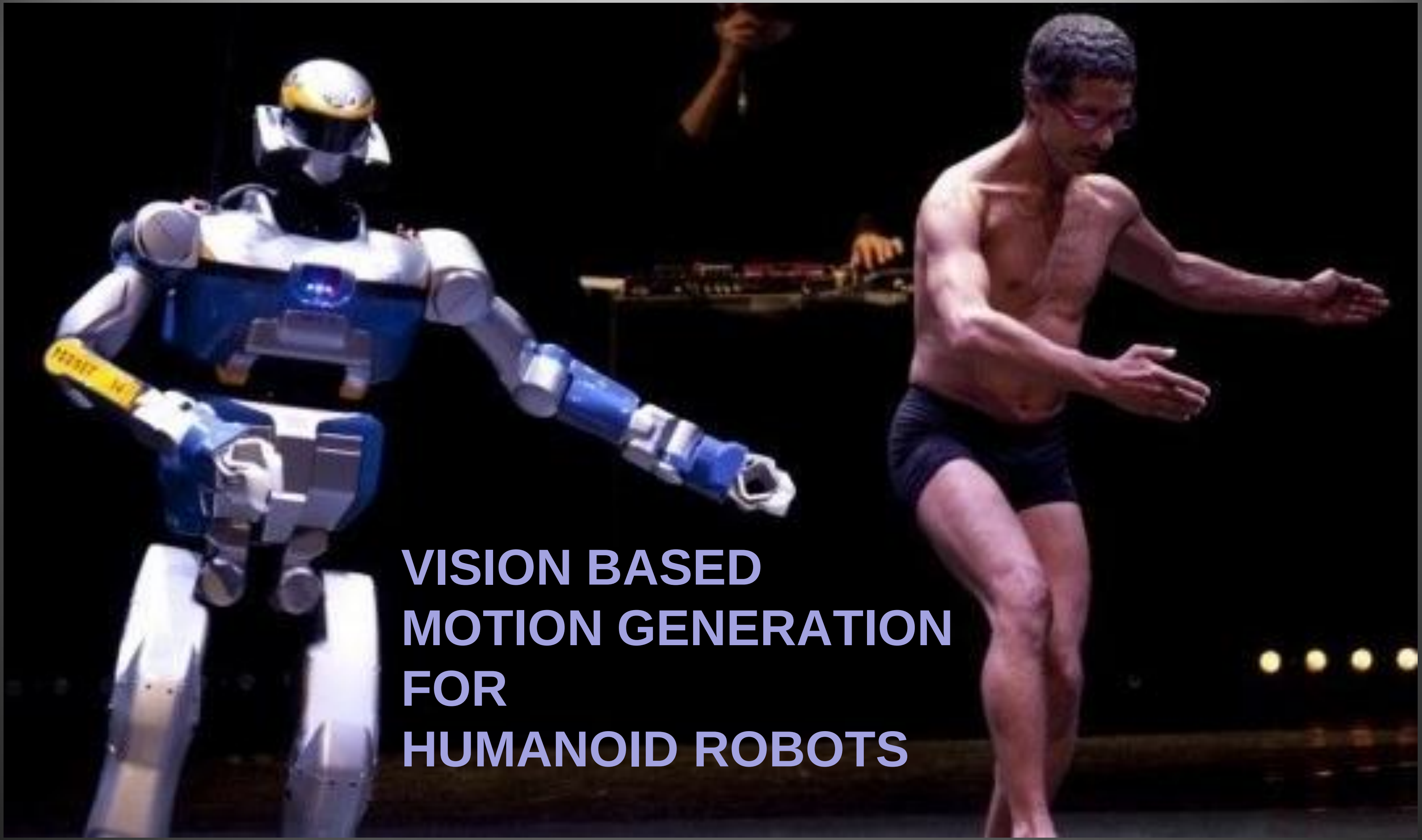


VISION BASED MOTION GENERATION FOR HUMANOID ROBOTS

O. Stasse
Gepetto TEAM, LAAS, Toulouse, France

Habilitation à Diriger des Recherches
4th April 2013

CNRS-AIST JRL (Joint Robotics Laboratory) UMI 3218/CRT

Bio sketch

Start	End	Laboratory	Status
2011	-	LAAS, UPR 8001 CNRS	Researcher at CNRS,
2003	2011	CNRS/AIST, Joint Robotics Laboratory (UMI), ISR	Researcher at CNRS, Assistant Professor
2000	2003	IUT de Villetaneuse, L2TI (EA),LISV	Assistant Professor, ATER
1997	2000	Paris 6 (UPMC) AIST, Japan	PhD

Motivations

Long term scientific goal

Motion generation for complex sensory based behaviors
Application: Service and Rescue Robotics

Difficulties

- Planning: trajectory, tasks
- Control: balance, limits
- Curse of dimensionality

Behavior - Game Theory

Behavior: An optimization problem

$$B \begin{cases} \min_{\mathbf{q}(t),\mathbf{v}(t)} \mathbf{f}(\mathbf{q}(t),\mathbf{v}(t)) \\ \mathbf{h}(\mathbf{q}(t),\mathbf{v}(t)) < \mathbf{0} \\ \mathbf{g}(\mathbf{q}(t),\mathbf{v}(t)) = \mathbf{0} \end{cases}$$

The game score $\mathbf{f}(\mathbf{t})$

Game & Other Agent Representation $\mathbf{v}(\mathbf{t})$

Rules of the game to constrain the actions

$\mathbf{h}(\mathbf{t}) \leq 0,\ \mathbf{g}(\mathbf{t}) = \mathbf{0}$

Actions

$\mathbf{q}(\mathbf{t})$

Approach

What are the necessary and meaningful constraints ?

How to build the cost function for the behavior of interest ?

Behavior: An optimization problem

$$B \begin{cases} \min_{\mathbf{q}(t),\mathbf{v}(t)} \mathbf{f}(\mathbf{q}(t),\mathbf{v}(t)) \\ \mathbf{h}(\mathbf{q}(t),\mathbf{v}(t)) < \mathbf{0} \\ \mathbf{g}(\mathbf{q}(t),\mathbf{v}(t)) = \mathbf{0} \end{cases}$$

How do we deal with such a huge search space ?

How to build an efficient world representation ?

Approach

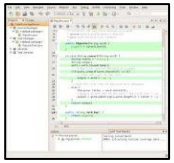
Behavior: An optimization problem

$$B\begin{cases}\min_{\mathbf{q}(t),\mathbf{v}(t)} \mathbf{f}(\mathbf{q}(t),\mathbf{v}(t)) \\ \mathbf{h}(\mathbf{q}(t),\mathbf{v}(t)) < \mathbf{0} \\ \mathbf{g}(\mathbf{q}(t),\mathbf{v}(t)) = \mathbf{0}\end{cases}$$

Finding a solution

Complexity is NP-Hard

How can we break the complexity ?



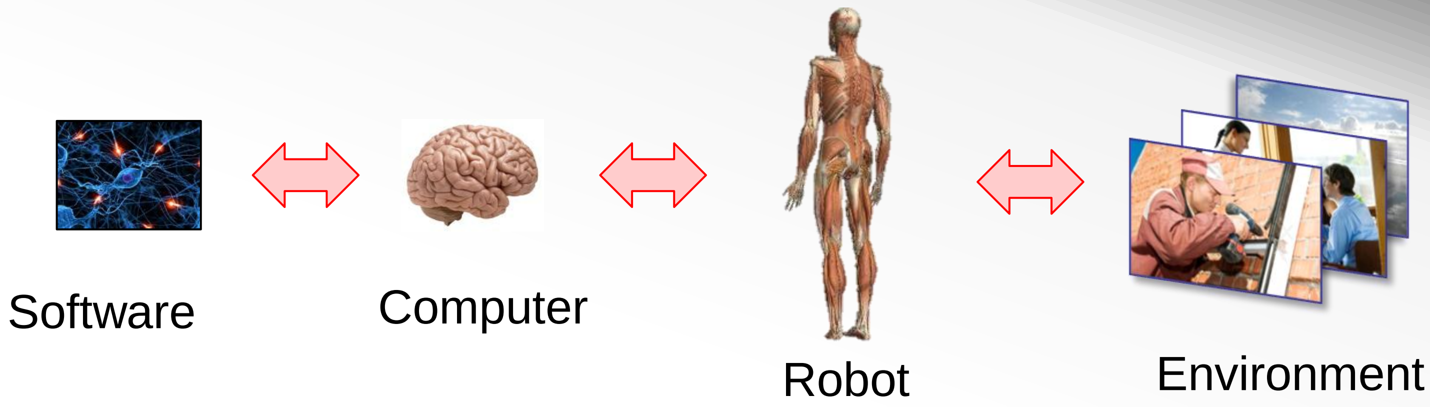
Software

Computer

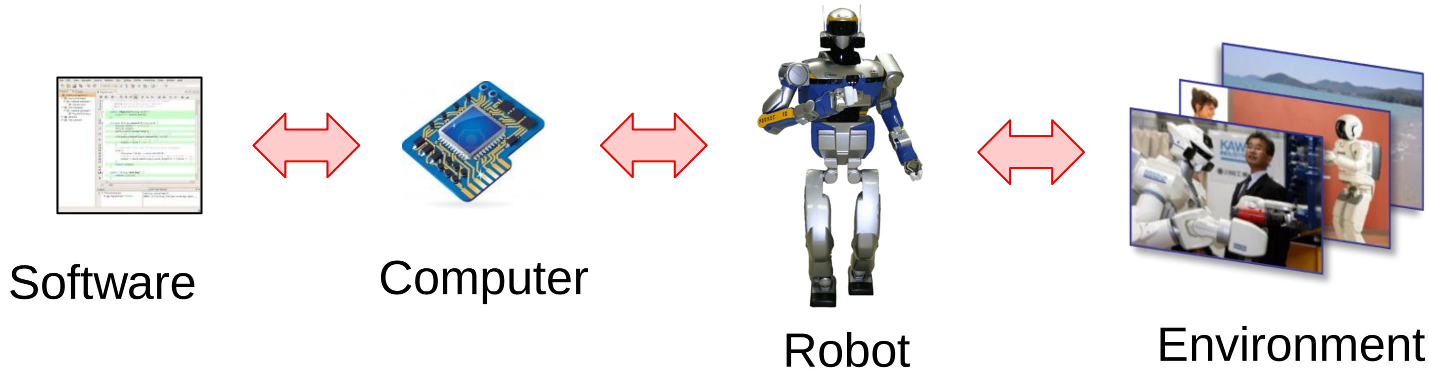
Robot

Environment

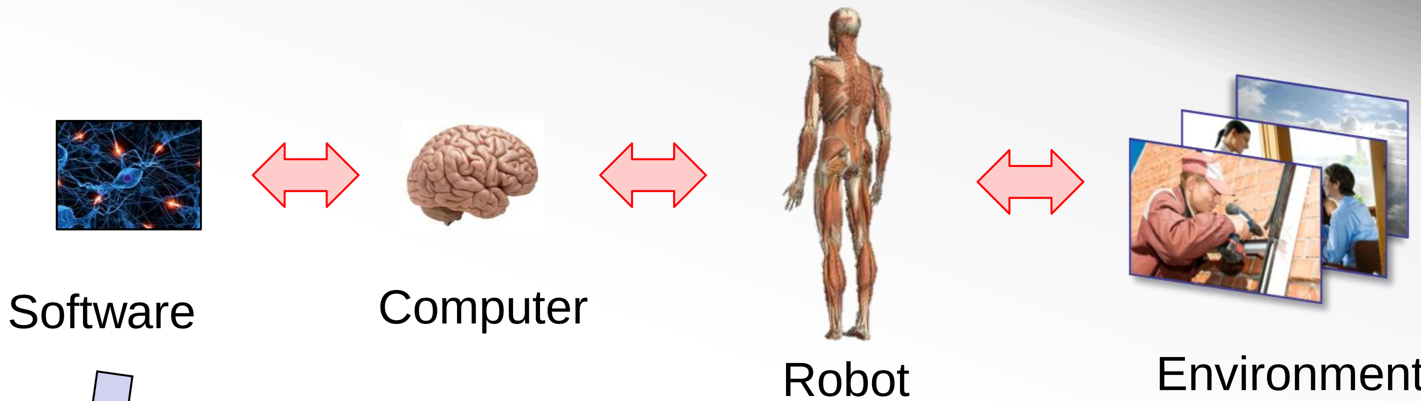
Approach



Humans routinely solve NP-Hard problems !

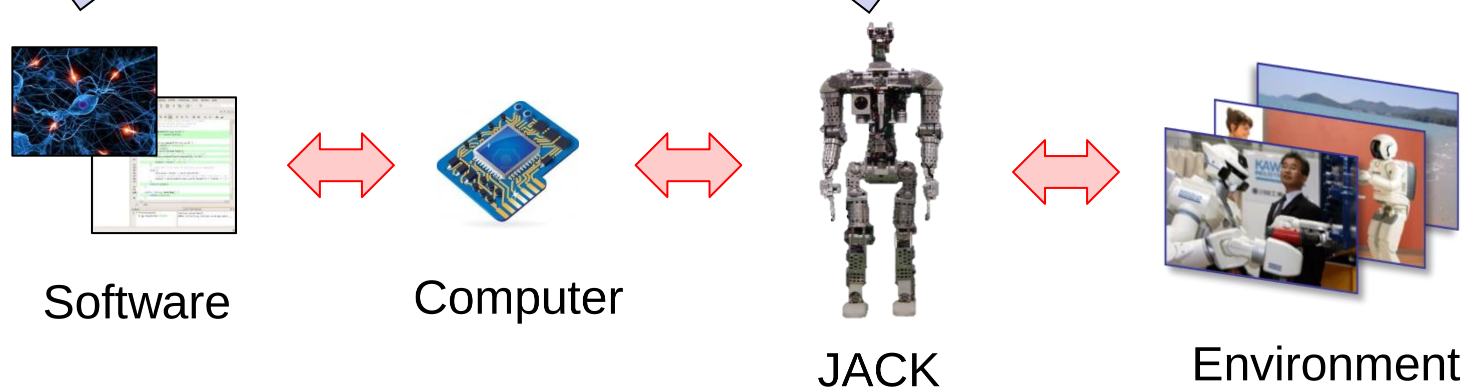


Approach : Human software



Simulating Human Software on Robots:
Complexity returns on simulation cost
and difficulty on analysis

[Phd, 2000]



Approach: Embodiment-application

Software

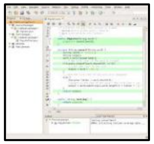
Computer

Robot

Environment

[2000-2003]

Robots can exhibit complex sensory based behaviors such as soccer with two limitations:
Scaling is costly (building f is increasingly complex) and too specific
Computational and decisional autonomy are constraining



Software

Computer

AIBO

Robocup

Approach: Analog computers

Software

Computer

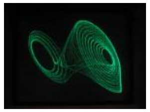
Robot

Environment

Exotic computers with possible more computational powers are VERY difficult to analyze and are limited in their applicability

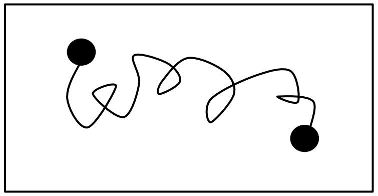
[Syroco, 2003]

Non linear control



Chua Oscillator

Point



2D Plane

Approach: JRL 2003-

Behavior: An optimization problem

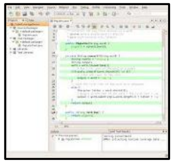
$$
B \begin{cases} \min_{\mathbf{q}(t),\mathbf{v}(t)} \mathbf{f}(\mathbf{q}(t),\mathbf{v}(t)) \\ \mathbf{h}(\mathbf{q}(t),\mathbf{v}(t)) < \mathbf{0} \\ \mathbf{g}(\mathbf{q}(t),\mathbf{v}(t)) = \mathbf{0} \end{cases}
$$

Efficient formulation of the problems (NL → QP)

Using general constraints to limit the search space

Composition of generic motion capabilities

Forget about Human Analogy ! (for now)



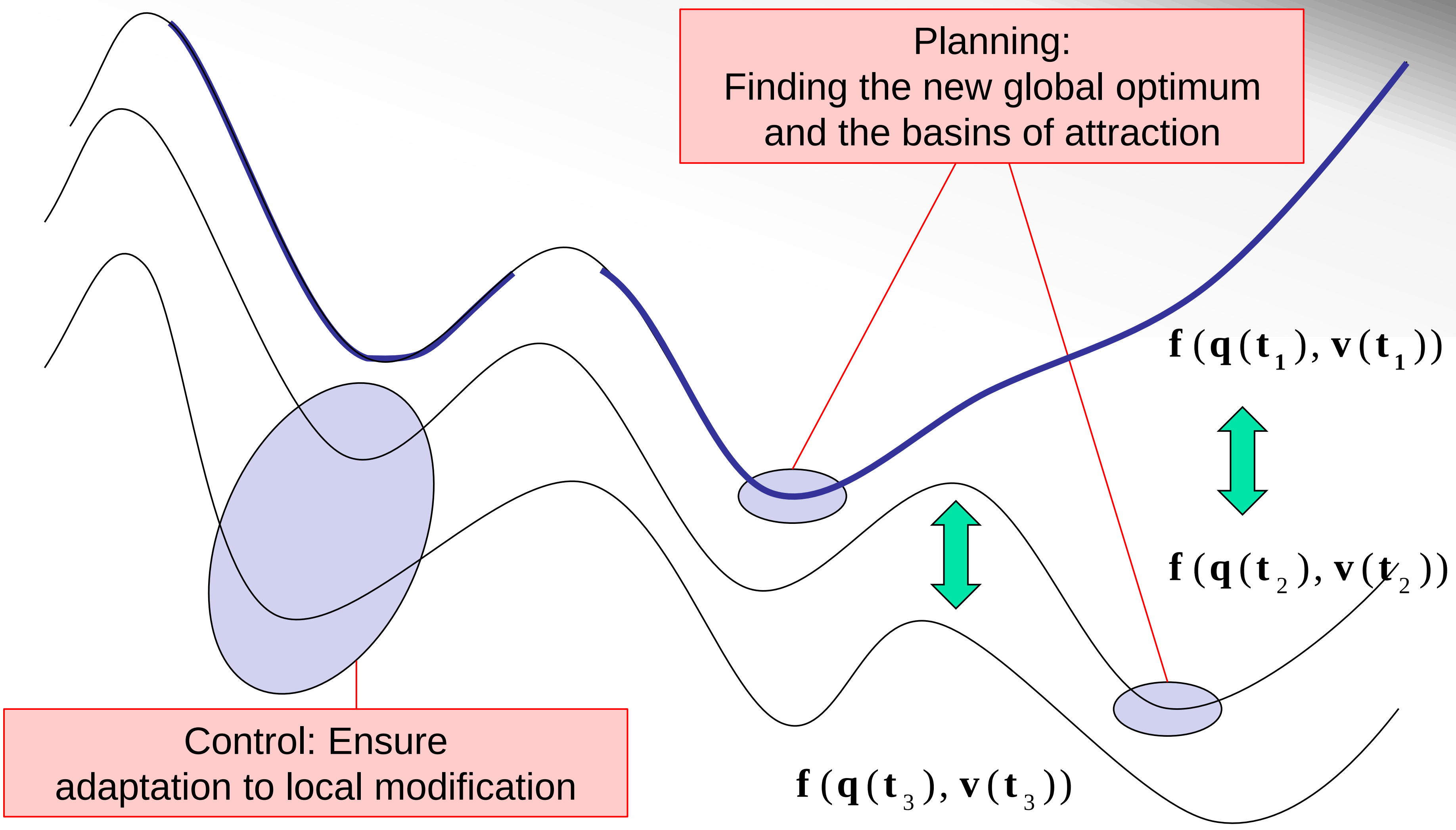
Software

Computer

Robot

Environment

Approach: JRL 2003-



Approach: Software only

What are the necessary and meaningful constraints ?

- Dynamics
- Physical Limits
- Balance
- Tasks

How to build the cost function for the behavior of interest ?

- Motion cost
- Distance to goal
- Approximation

Behavior: An optimization problem

$$B\begin{cases}\min_{\mathbf{q}(t),\mathbf{v}(t)} \mathbf{f}(\mathbf{q}(t),\mathbf{v}(t))\\ \mathbf{h}(\mathbf{q}(t),\mathbf{v}(t)) < \mathbf{0}\\ \mathbf{g}(\mathbf{q}(t),\mathbf{v}(t)) = \mathbf{0}\end{cases}$$

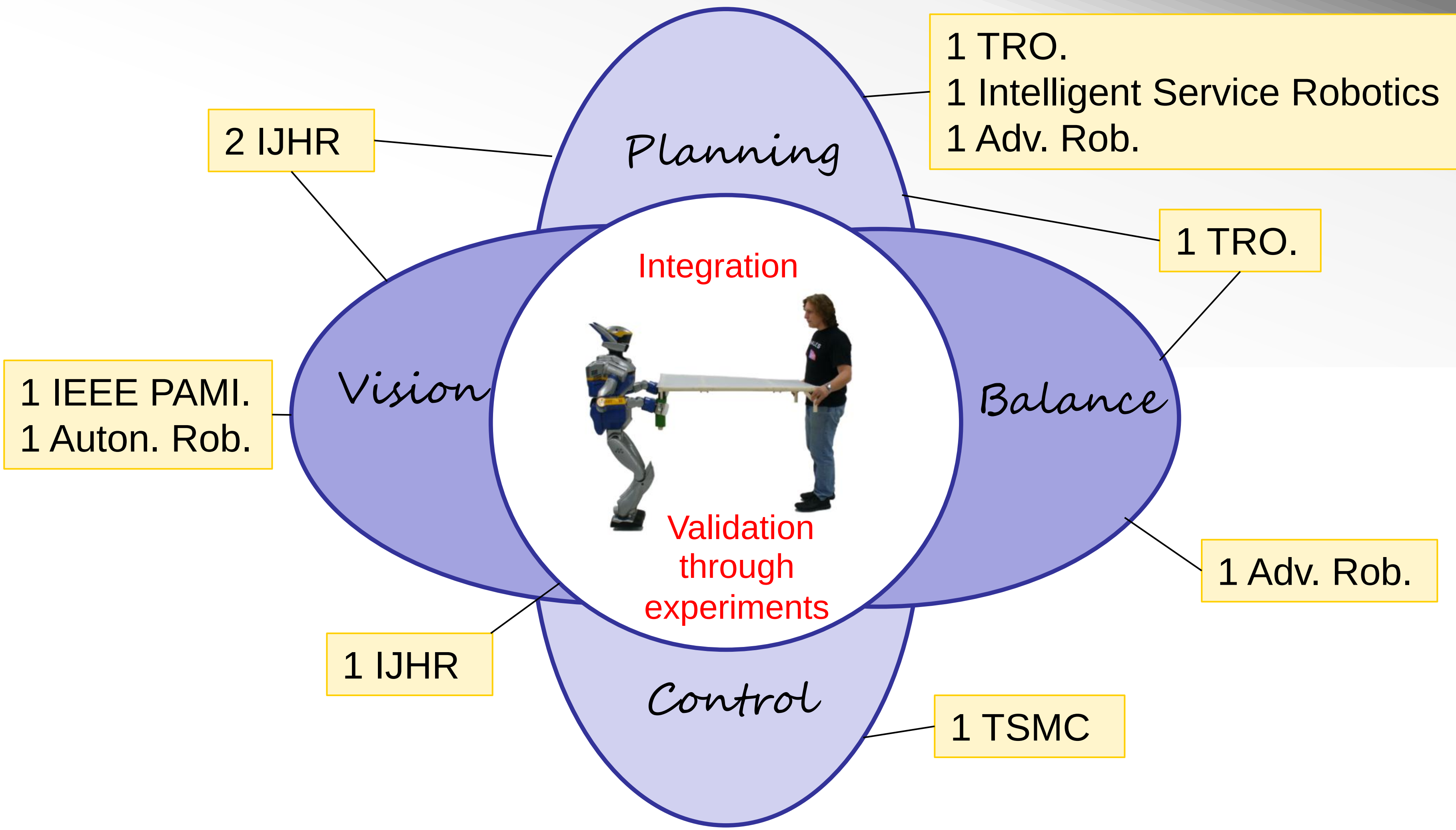
How do we deal with such a huge search space ?

- Planning
- Control

How to build an efficient world representation ?

- SLAM
- Object recognition
- Tracking

Contributions



Manuscript Organization

Walking
With Simplified Model

Whole Body
Motion

Motion Generation
Planning (Hybrid Models)

Motion Generation

Interval Analysis for
Triangulation

Visual Object Models
for Seeing Far Away

Self Localization and
Map Building

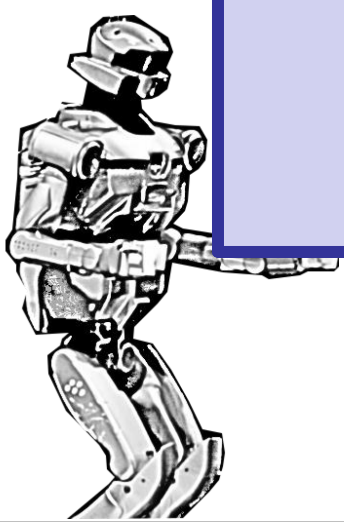
Visual Search

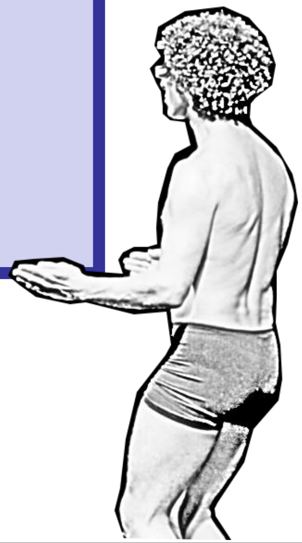
Object Visual Model
Construction

Computer Vision

Overview

- Context – Problem statement
- Computer Vision
  - Next Best View
  - Visual Search
- Motion generation
  - Walking
  - Whole-Body Motion
  - Planning





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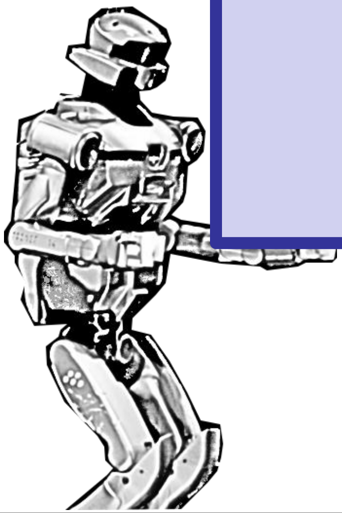
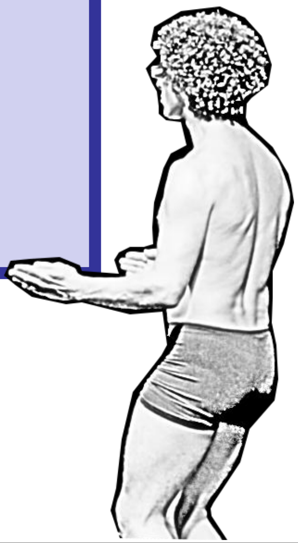




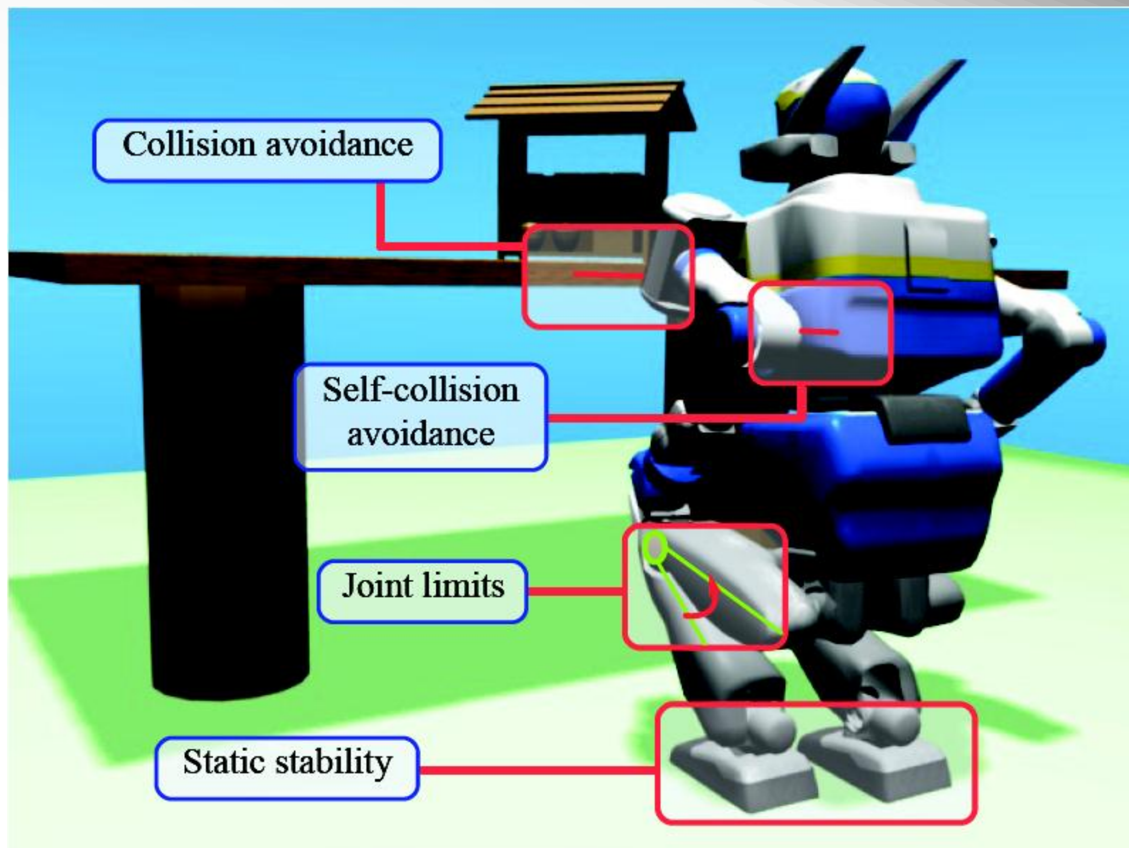
Next Best View & Body Pose

Goal

HRP-2 should maximize the unknown projected into its vision system.

Constraints

- Respecting the joint limits;
- Having both feet on the floor;
- Being statically stable;
- Keeping a sufficient number of landmarks visibles ;
- Avoid self-collision and collision with the environment.



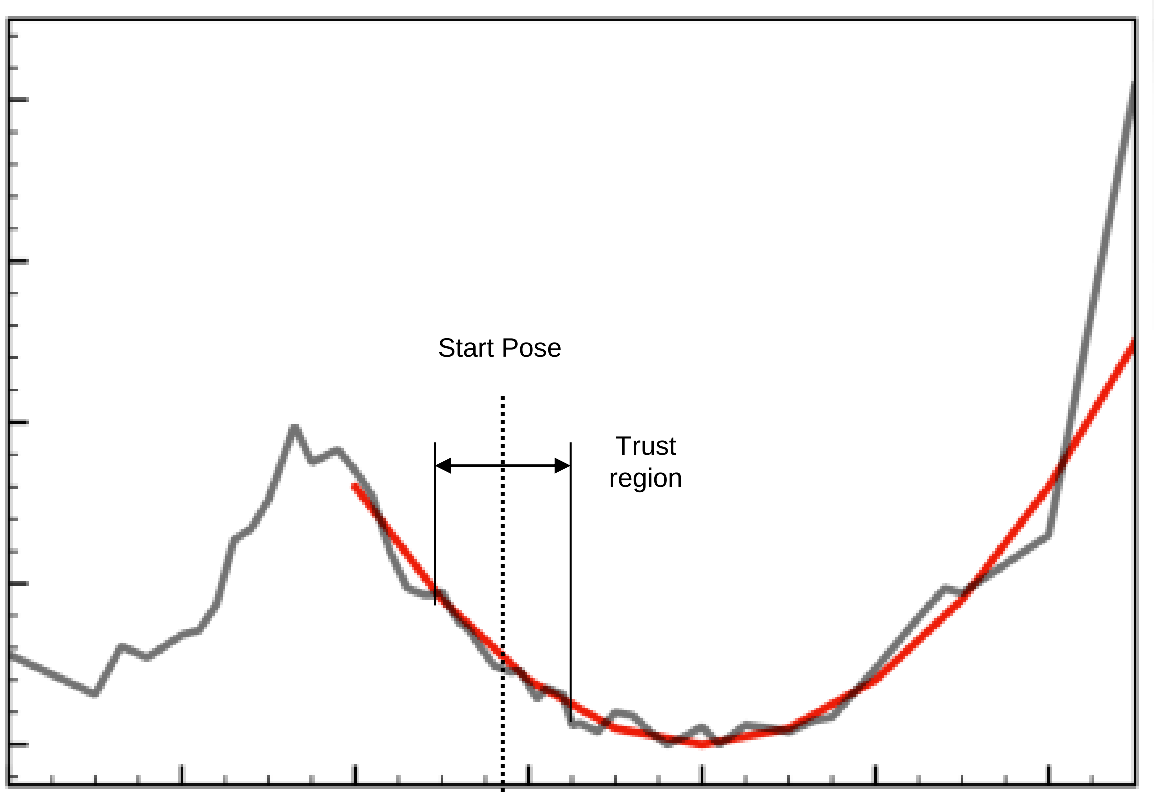
NBV: NewUOA

Optimization Problem

Solved using CFSQP.
Needs for a C-1 objective function

Contributions

- Proposing such a function;
- Shows that its evaluations with discrete measurement do not behave well with FSQP;
- The image discretization introduce local minima.



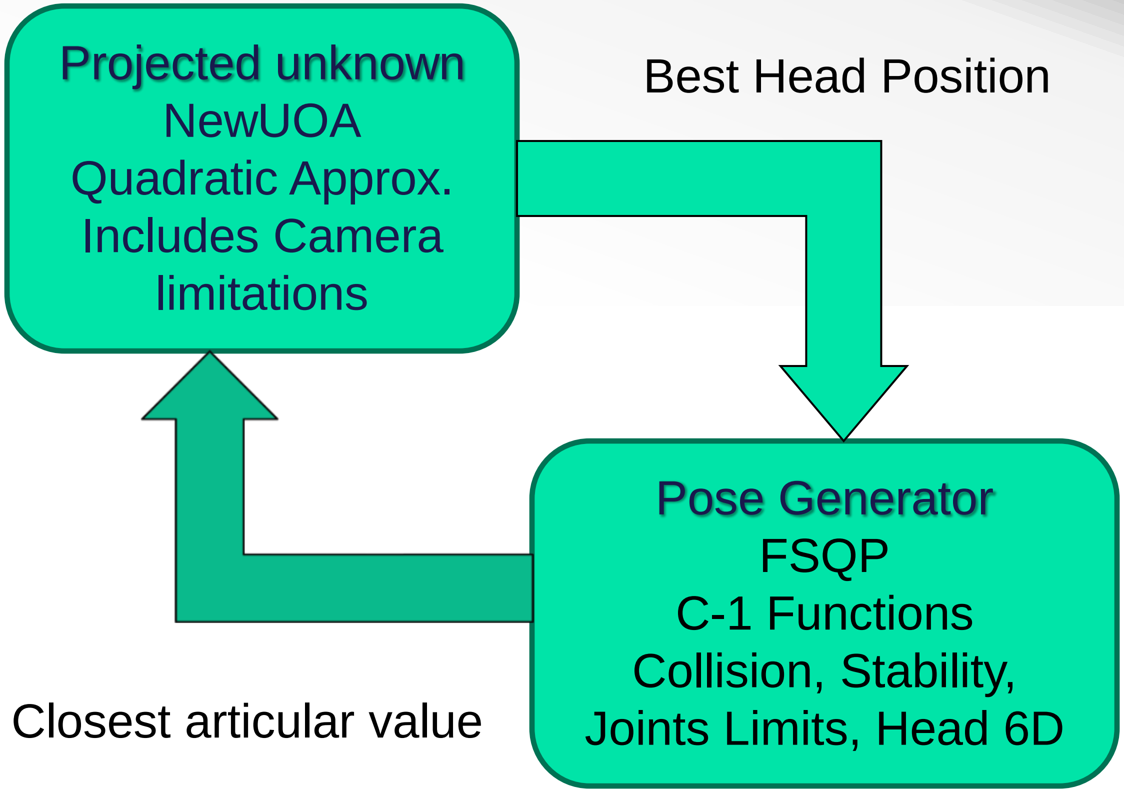
NBV: A 2-stage approach

Optimization Problem

Projected unknown:
NEWUOA.
Pose:
FSQP.

Contributions

- Using an optimization algorithm which do not need derivability of the objective function;
- Iterate between several approximations while keeping a feasible pose;
- Stop when having a fixed point



NBV: A 2-stage approach

Optimization Problem

Projected unknown:
NEWUOA.
Pose:
FSQP.

Contributions

- Using an optimization algorithm which do not need derivability of the objective function;
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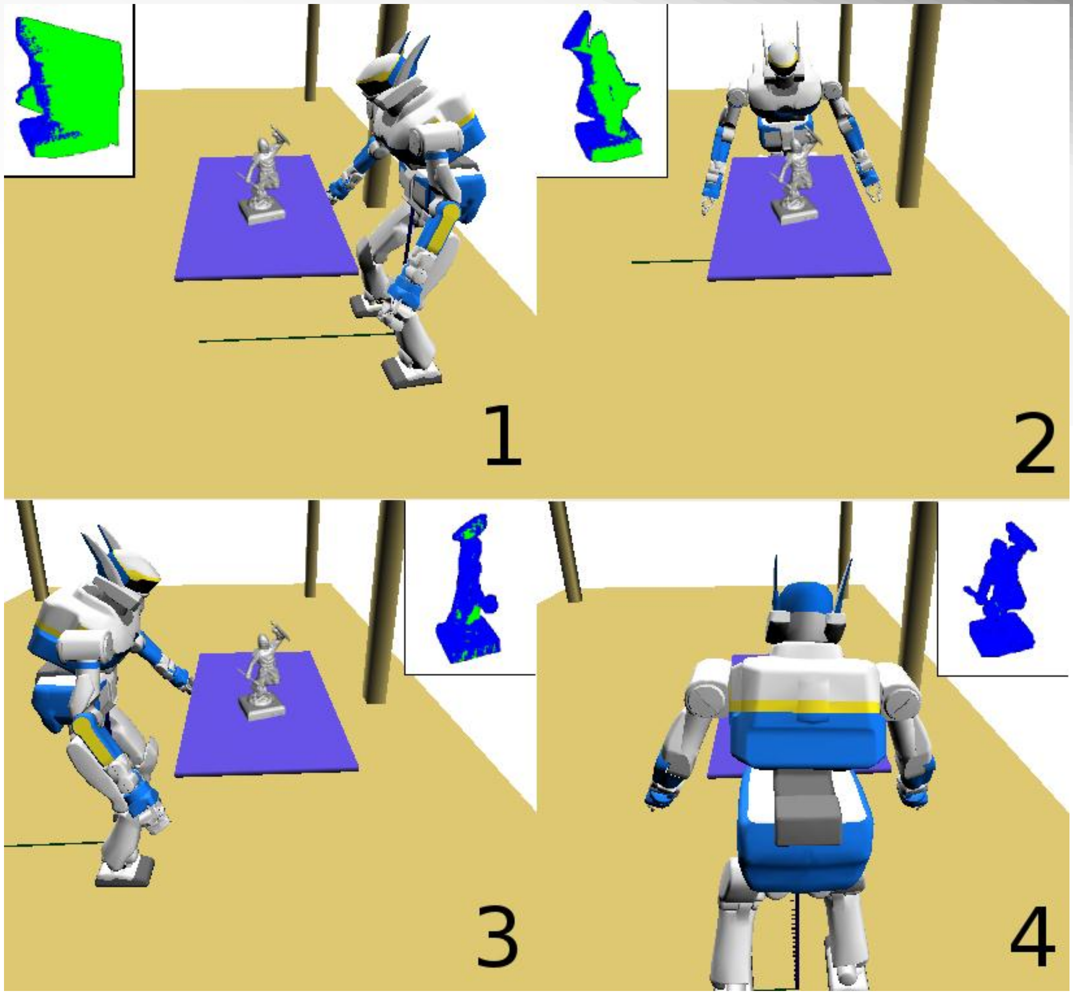
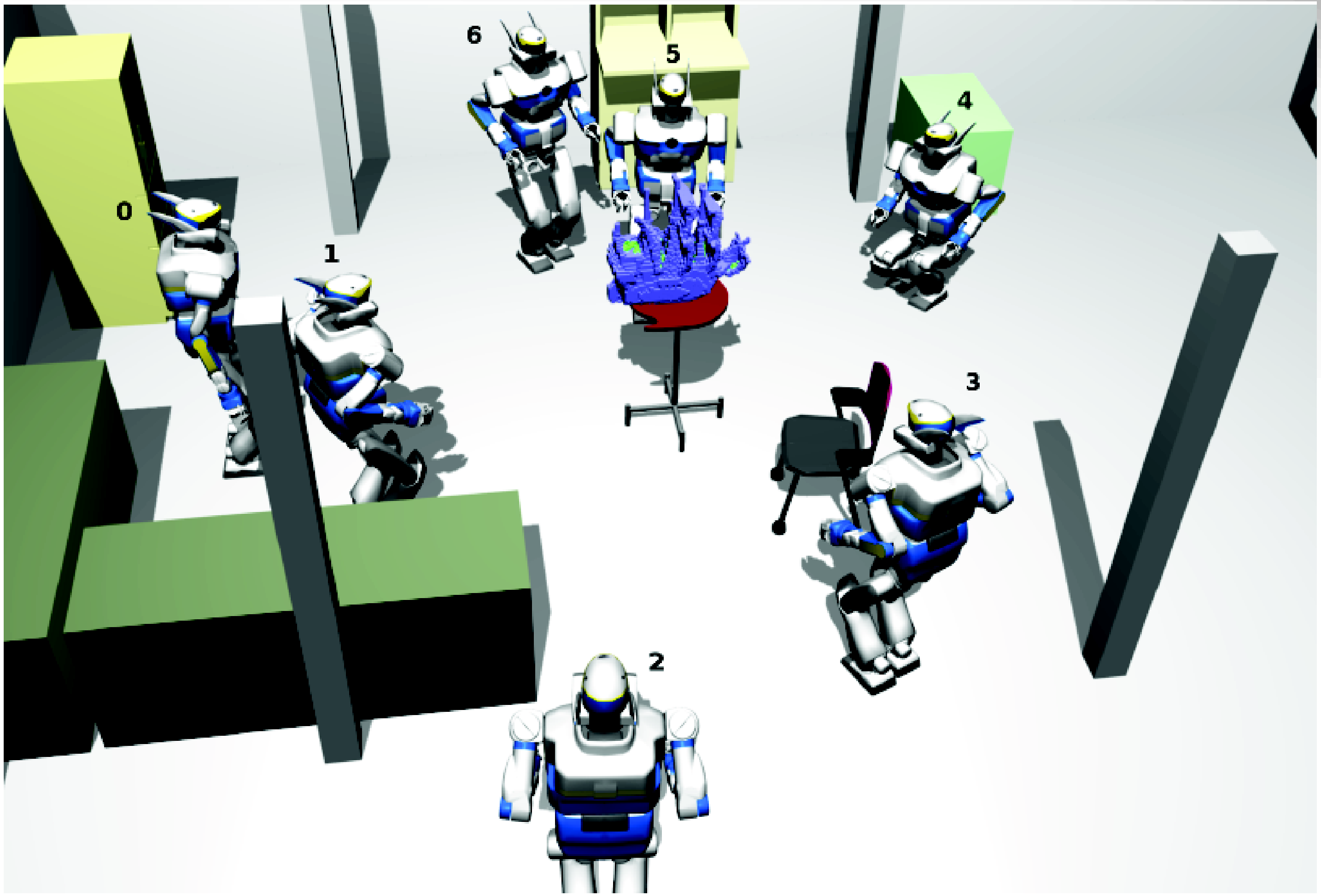
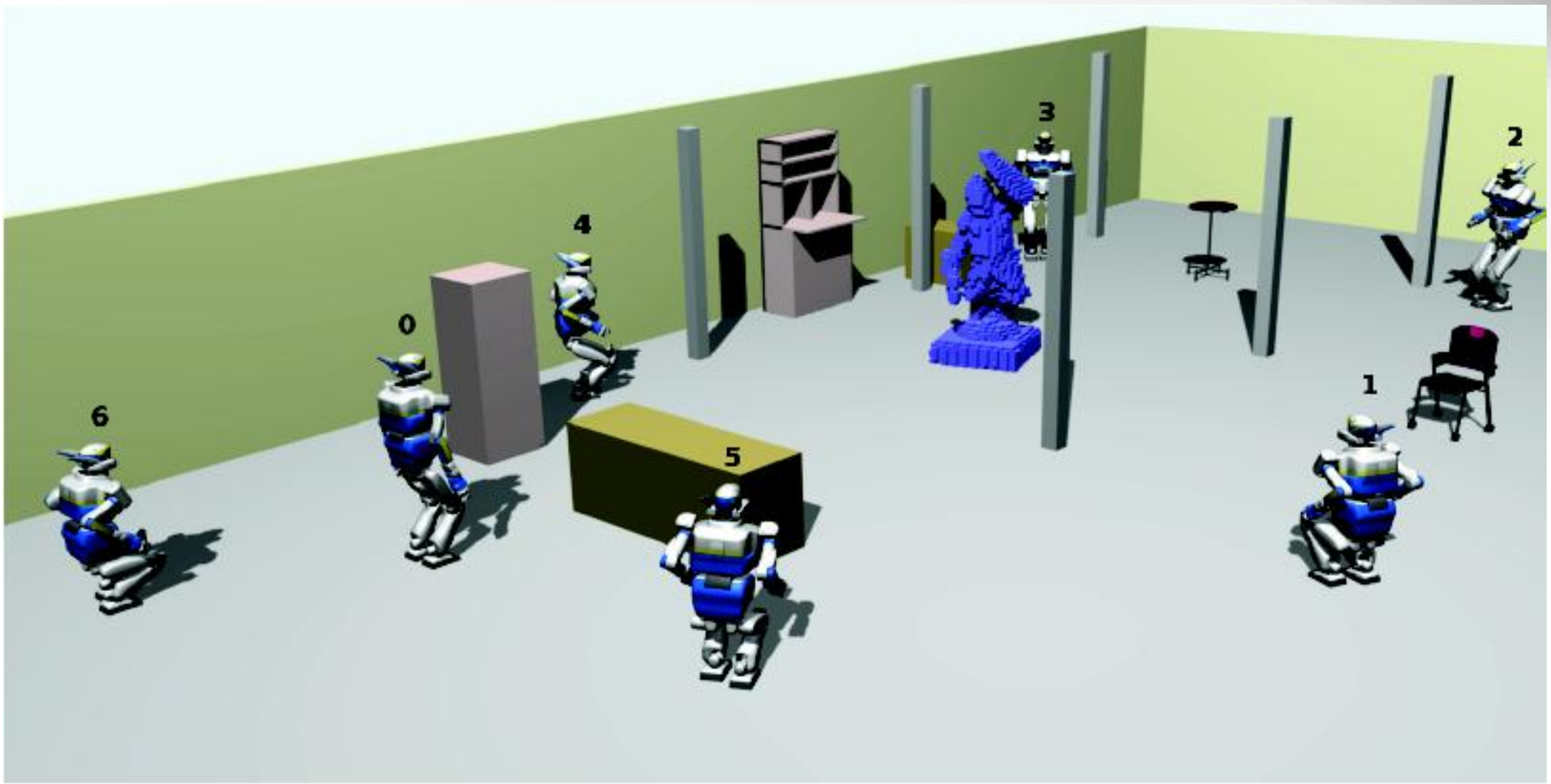


[Foissotte, Stasse, Wieber, Kheddar, ICRA 2009]

Non convex objects



Non convex objects



Overview

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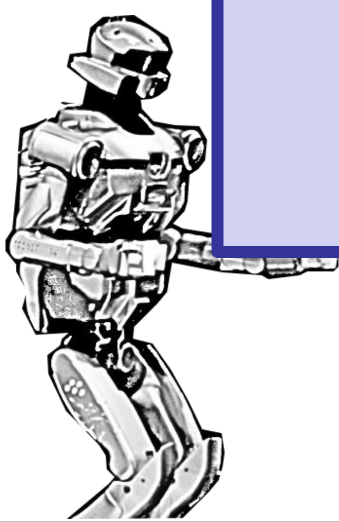
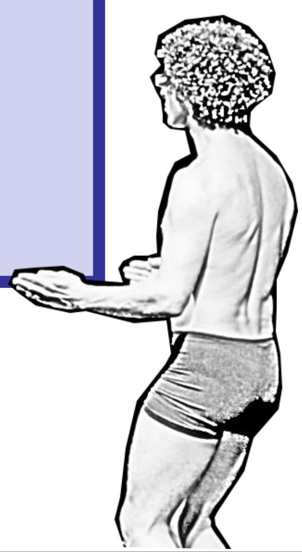




Problem statement

Formulated as a discrete optimization problem

- Falls in the field of sensor planning problem (6 D.O.F) proven to be NP-complete [Tsotsos AIM 1996]
  - → A heuristic strategy is needed
- Because of the limited field of view, limited depth, lighting condition, occlusion
  - → Active vision is necessary

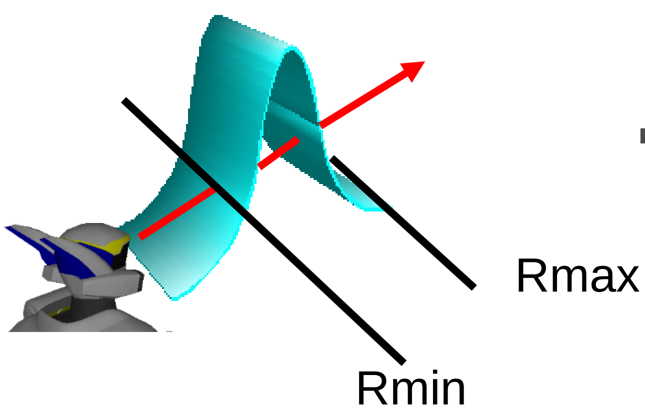
The Rating function to evaluate the interest of a potential next view is costly

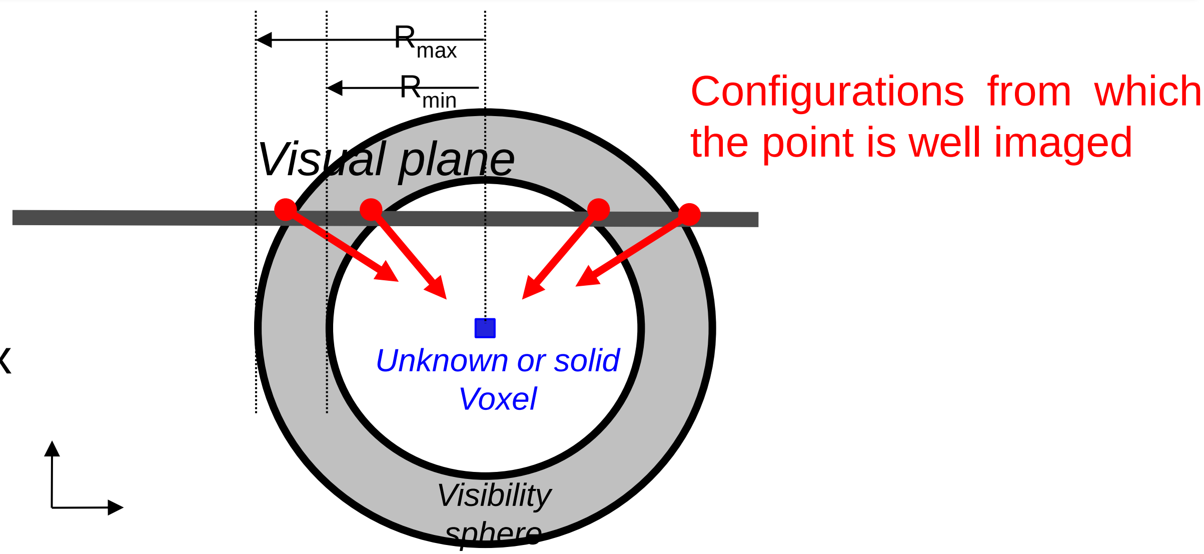
→ Need to formalize constraints on the sensor to speed up the search

Visibility map (1/2)

A statistical accumulator in the sensor configuration space

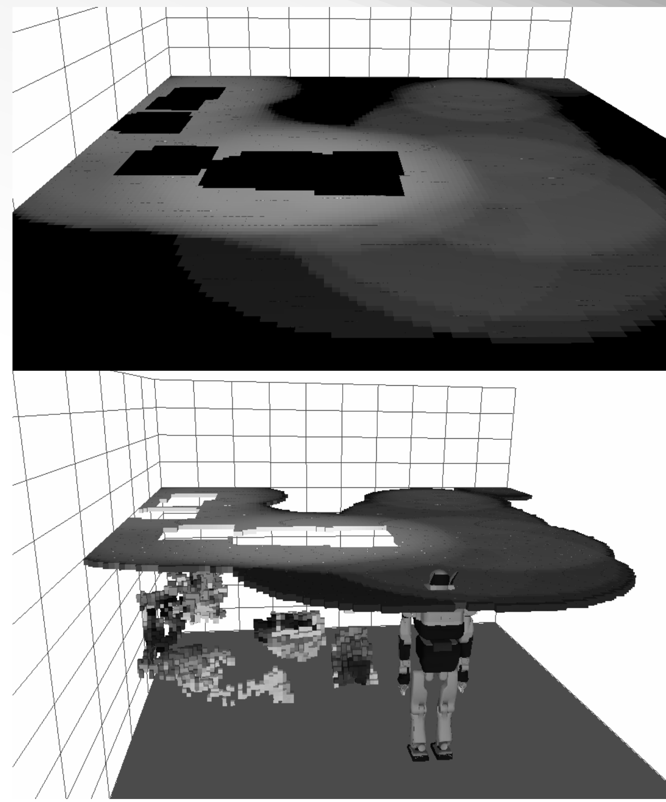
- Takes into account the limitation of the recognition algorithm (each point can be well recognized when viewed at a distance lying between Rmin and Rmax).
- Each point of interest (unknown or solid) vote for all configurations from which it can be well imaged.





Visibility Map (2/2)

- The contribution of all points of interest are summed up in what we call the visibility map.
- The figures on show a 2D projection of the 4D visibility map.
- Clear areas represents interesting configuration (in which many points are visible under good recognition condition)
- Computation time 380 ms



Experiments

An Exploration behavior with HRP-2 Humanoid Robot

Francois Saidi*
Olivier Stasse*
Kazuhito Yokoi*
Fumio Kanehiro**

*AIST-CNRS Joint Japanese-French Laboratory (JRL)
**Intelligent System Institute AIST

[Finalist for the Best Paper Award, ICAR 2007][IROS 2007, LCNS 2007]

Conclusion on Next Best View

- Pro
  - Generic
  - Autonomous
- Con
  - Slow…
  - Slow…
  - Slow…

Overview

- Context – Problem statement
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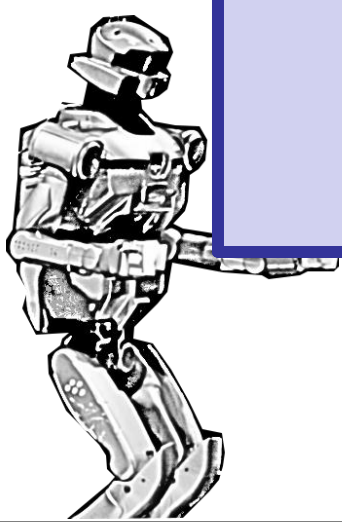

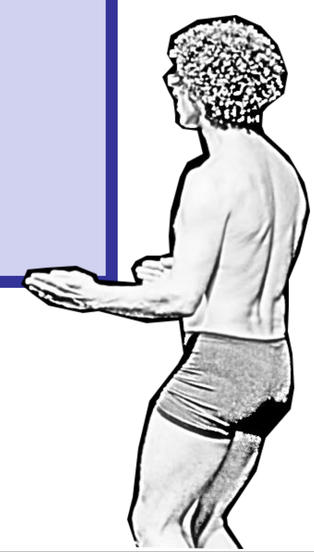

Constraints for a feasible motion

Motion Constraint Satisfaction Problem

$$MCSP_{\mathbf{u}} \begin{cases} \text{Robot Dynamics} \\ \text{Friction cone} \\ \text{Torque Limits} \\ \text{Joint Limits} \\ \text{Self-Collision} \end{cases}$$

Overview

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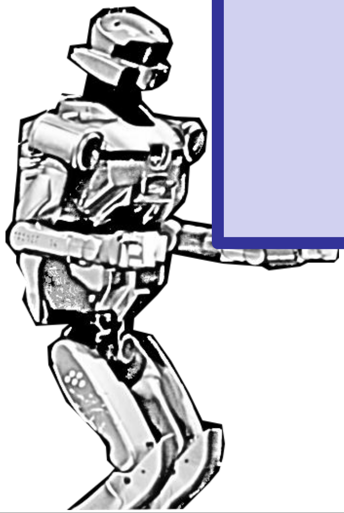
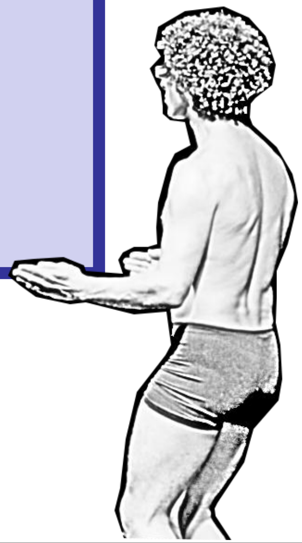
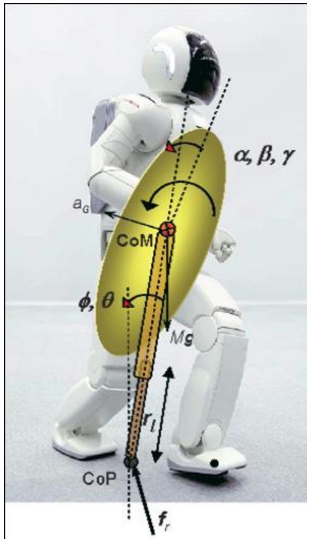




General balance constraints



Necessary CoM constraints

$$\begin{cases}\begin{bmatrix} m\ddot{\mathbf{c}} - m\mathbf{g} \\ \mathbf{W}_{\mathbf{R}}\end{bmatrix} = \mathbf{C}_{1c}^{\top}(\mathbf{q}_c)\lambda \\ \lambda_j \in \mathcal{C}_j\end{cases}$$

Assume the contact points chosen.
Can we use the constraints to find a feasible CoM trajectory ?

If **c** and $\mathbf{W}_{\mathbf{R}}$ are unknown
the problem dimension is only 6.
Also called the
Inertia Shaping Problem.

Dealing with such constraints on a time horizon:
Model Predictive Control

A solution for the Inertia Shaping Problem may NOT be feasible !

Coplanar contact forces

Inverted Pendulum – X axis

$$\mathbf{p}_{\mathbf{x}} = \frac{m\,\mathbf{c}_{\mathbf{x}}(\ddot{\mathbf{c}}_{\mathbf{z}} + g) - m(\mathbf{c}_{\mathbf{z}} - \mathbf{p}_{\mathbf{z}})\ddot{\mathbf{c}}_{x} - \mathbf{W}_{\mathbf{R}}^{\mathbf{y}}}{m(g + \ddot{\mathbf{c}}_{\mathbf{z}})}$$

Acceleration along Z axis equal to zero

Momentum Derivative set to Zero

Linear Inverted Pendulum

$$\mathbf{p}_{\mathbf{x}} = \mathbf{c}_{\mathbf{x}} - \frac{\mathbf{c}_{\mathbf{z}}\ddot{\mathbf{c}}_{x}}{g}$$

Problem:
How to find **c** knowing the constraints on **p** ?

Finding the CoM trajectory

When the CoP reference is given – LQR approach

$$
PC \begin{cases} \min \sum_{i=k}^{k+N-1} \frac{1}{2} Q\left(p_x(i+1) - p_x^{ref}(i+1)\right)^2 + \frac{1}{2} R\,\dddot{\mathbf{c}}_{\mathbf{x}}^2(i) \\ \mathbf{c}_{\mathbf{x}}(k+1) = \mathbf{A}\,\mathbf{c}_{\mathbf{x}}(k) + \mathbf{B}\,\dddot{\mathbf{c}}_{\mathbf{x}}(k) \\ p_x(k) = \mathbf{C}\,\mathbf{c}_{\mathbf{x}}(k) \end{cases}
$$

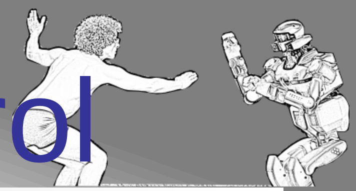
[Kajita, 2003]

$$
\mathbf{c}_{\mathbf{x}}(k) \equiv [c_x(k)\ \dot{c}_x(k)\ \ddot{c}_x(k)]^{\top},
$$

$$
\mathbf{A} \equiv \begin{bmatrix} 1 & T & T^2/2 \\ 0 & 1 & T \\ 0 & 0 & 1 \end{bmatrix}, \mathbf{B} \equiv \begin{bmatrix} T^3/6 \\ T^2/2 \\ T \end{bmatrix}, \mathbf{C} \equiv \begin{bmatrix} 1 & 0 & -\frac{c_z}{g} \end{bmatrix}
$$

No guarantee that the generated solution is not going out the support polygon !

Constrained Preview Control



QP with linear constraints

$$
PC_c \begin{cases} \min_{\dddot{\mathbf{C}}_x(k)} \frac{1}{2}\dddot{\mathbf{C}}_x^2(k) \\ \mathbf{P_x c_x}(k) + \mathbf{P_u}\dddot{\mathbf{C}}_{\mathbf{x}}(k) \leq \mathbf{Z}^{\mathbf{max}}(k) \\ -\mathbf{P_x c_x}(k) - \mathbf{P}_u\dddot{\mathbf{C}}_{\mathbf{x}}(k) \leq -\mathbf{Z}^{\mathbf{min}}(k) \end{cases}
$$

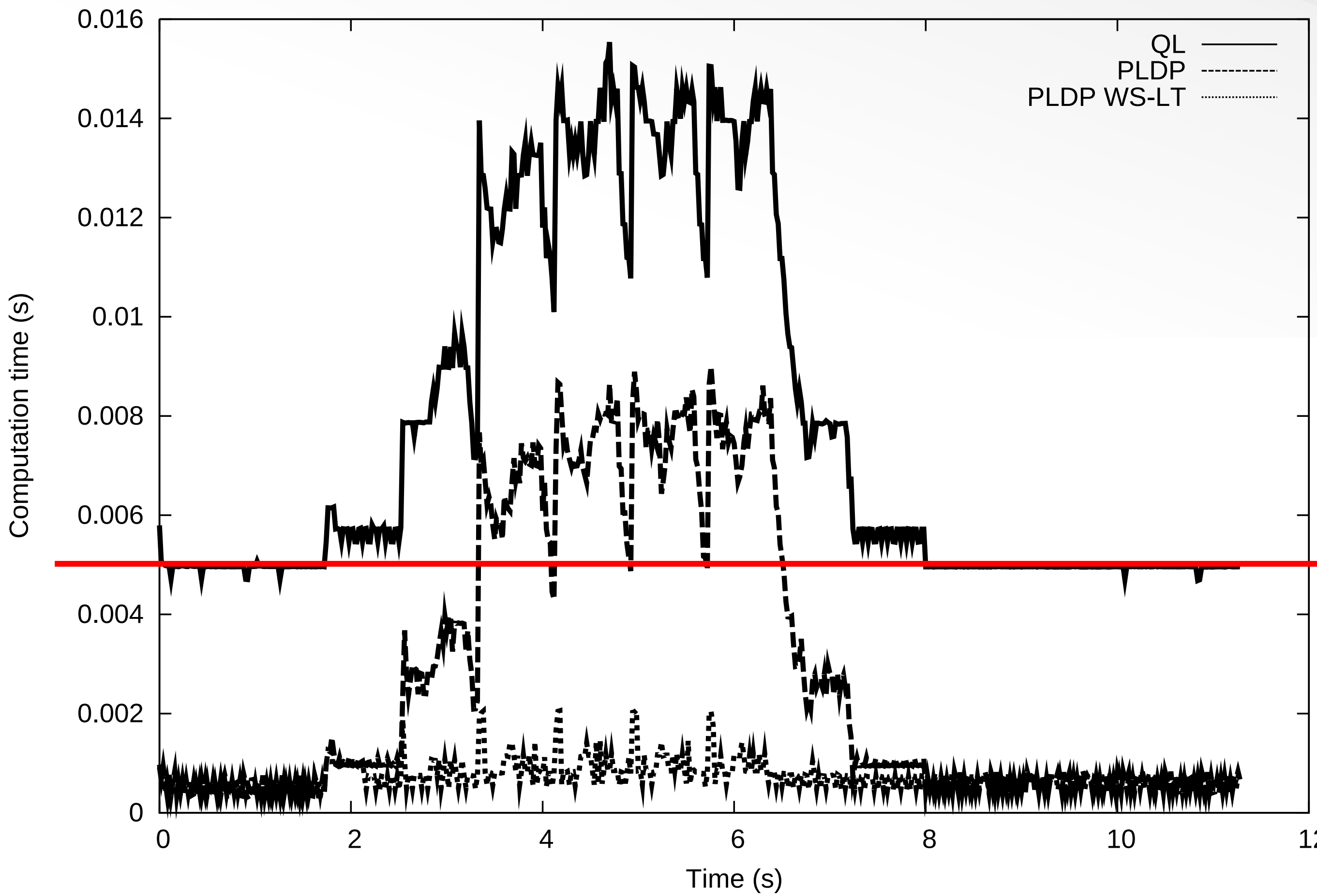
[Wieber, 2006]

$$
PC_c^{ref} \begin{cases} \min_{\dddot{\mathbf{C}}_x(k)} (\frac{1}{2}\dddot{\mathbf{C}}_x^2(k) + \alpha \dot{\mathbf{C}}_{\mathbf{x}}^2(\mathbf{k}) + \beta(\mathbf{Z}_{\mathbf{k}}(k) - \mathbf{Z}^{\mathbf{ref}}(k))^2) \\ \mathbf{P_x c_x}(k) + \mathbf{P_u}\dddot{\mathbf{C}}_{\mathbf{x}}(k) \leq \mathbf{Z}^{\mathbf{max}}(k) \\ -\mathbf{P_x c_x}(k) - \mathbf{P}_u\dddot{\mathbf{C}}_{\mathbf{x}}(k) \leq -\mathbf{Z}^{\mathbf{min}}(k) \end{cases}
$$

Constraints almost never deactivated

Computation cost

Computation time for QL, PLDP, with Warm Start (WS), with Limited Time (LT) on HRP-2



Control Period For HRP-2

Automatic Foot placement

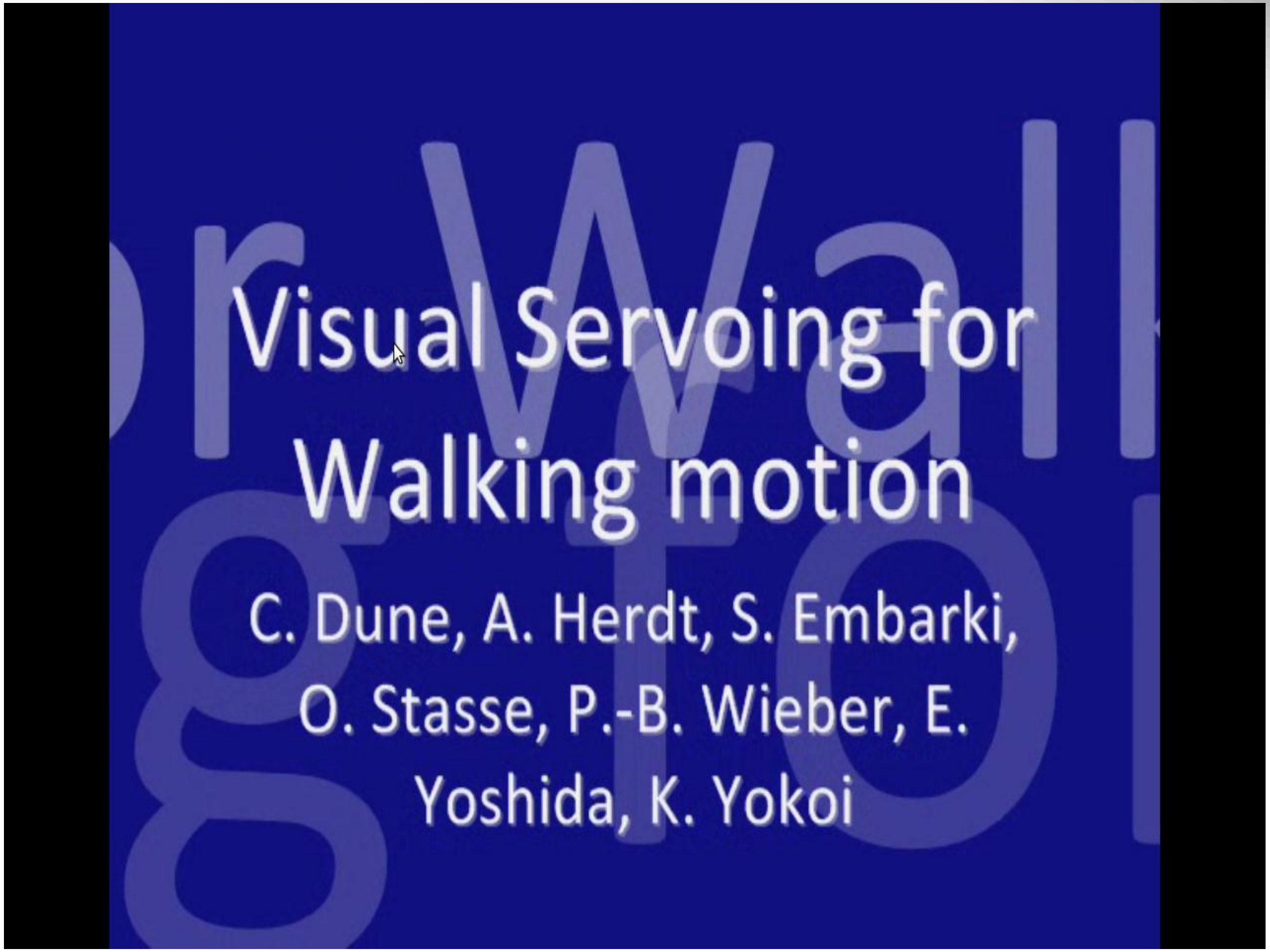
New free variables: feet positions/ Walking without Thinking

$$
WwT \begin{cases}
\min_{\mathbf{u}(k)} \frac{\beta}{2}\left\| \dot{\mathbf{X}}(k+1) - \dot{\mathbf{X}}^{ref}(k+1) \right\|^2 + \frac{\beta}{2}\left\| \dot{\mathbf{Y}}(k+1) - \dot{\mathbf{Y}}^{ref}(k+1) \right\|^2 \\
\text{linear constraints on ZMP} \\
\text{linear constraints on Foot Position} \\
with\ \mathbf{u}(k) = \begin{pmatrix} \dots \\ \mathbf{X}(k) \\ \mathbf{X}^{f}(\mathbf{k}) \\ \dots \\ \mathbf{Y}(\mathbf{k}) \\ \mathbf{Y}^{f}(k) \end{pmatrix}
\end{cases}
$$

→ Learning Feasibility Foot Steps Transitions [N. Perrin, TRO, 2012]

[Herdt, A.R., 2010],[Herdt, IROS, 2010]

Visual servoing



Angular momentum ?

Inverted Pendulum – X axis

$$\mathbf{p}_x = \frac{m\,\mathbf{c}_x(\ddot{\mathbf{c}}_z + g) - m(\mathbf{c}_z - \mathbf{p}_z)\ddot{\mathbf{c}}_x - \mathbf{W}_R^y}{m(g + \ddot{\mathbf{c}}_z)}$$

In practice not zero

CoP_{ref}

Foot steps

Preview Control + GIK

$\mathbf{q}_1$

RNEA

$\mathbf{W}_R$

$\Delta CoP = CoP_{MB} - CoP_{ref}$

$\mathbf{q}_2$

Preview Control + GIK

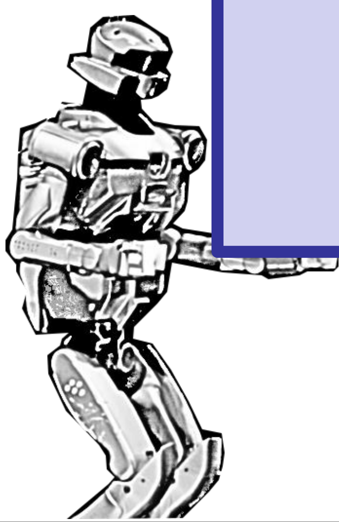
Dynamic filter

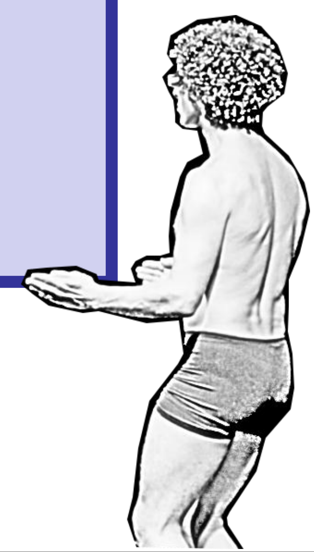
A very efficient way of compensating the perturbation induced by the upper body imposed motion

Stepping over obstacles

Overview

- ❑ Context – Problem statement
- ❑ Computer Vision
  - Next Best View
  - Visual Search
- ➢ Motion generation
  - Walking
  - ➢ Whole-Body Motion
  - Planning





Stacks of Tasks

Task definition

Error between current and desired sensor values: $\mathbf{e} = \mathbf{s}^* - \mathbf{s}$

Reference behavior of the error: $\mathbf{e} = -\lambda \, \mathbf{e}$

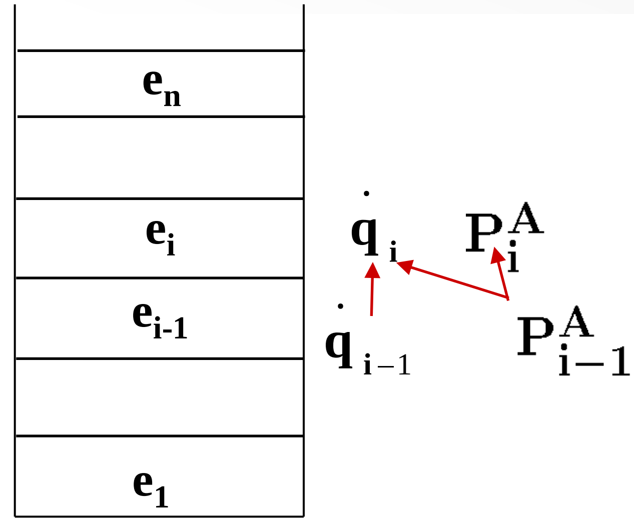
The associated Jacobian matrix: $\dot{\mathbf{e}} = \mathbf{J}\dot{\mathbf{q}}$ $\qquad \mathbf{J} = \dfrac{\partial \mathbf{e}}{\partial \mathbf{q}}$

Combining Simple Controllers

- Handle mutual collaboration or exclusion of tasks
- Establish priorities

Online Optimization

- The robot moves to minimize the criteria without guarantee that it will reach the maximum

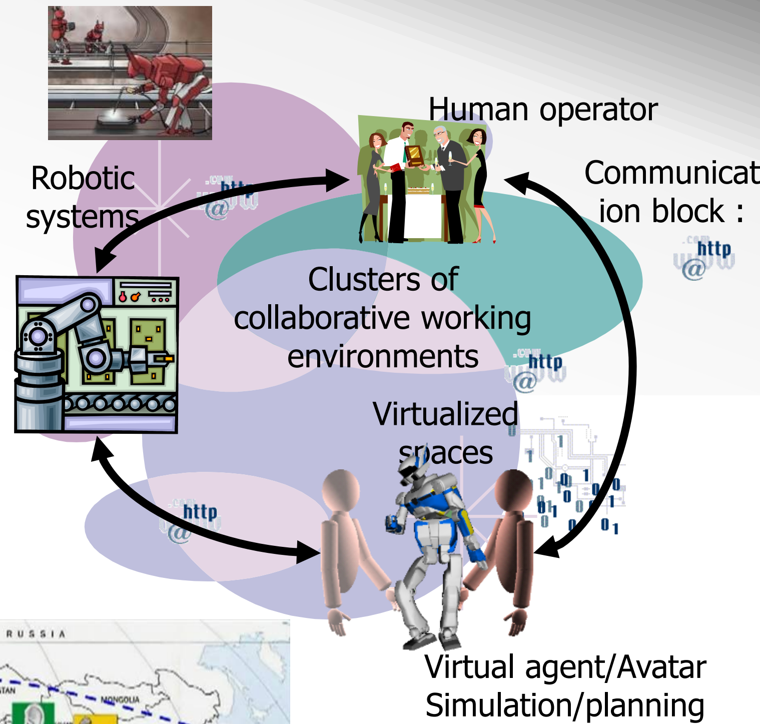


STACK

Collaborative Working Environments

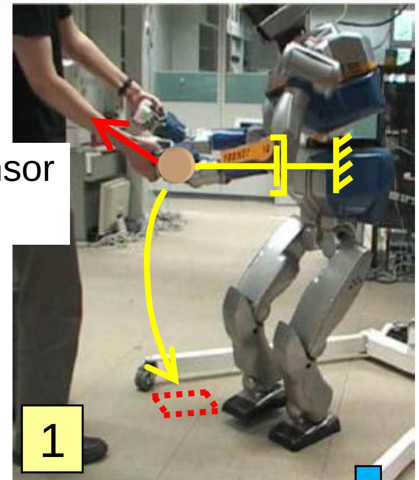
ROBOT@CWE (2006 – 2009)

- Integrating robots in CWE
- EU Project FP6
- A robot can be your agent
- Members: CNRS and AIST (JRL),
  UC3M, TUM, UNISALZ, EPFL
  DRAGADOS, HP EIC, SAS
- www.robot-at-cwe.eu



Cooperation through force interaction

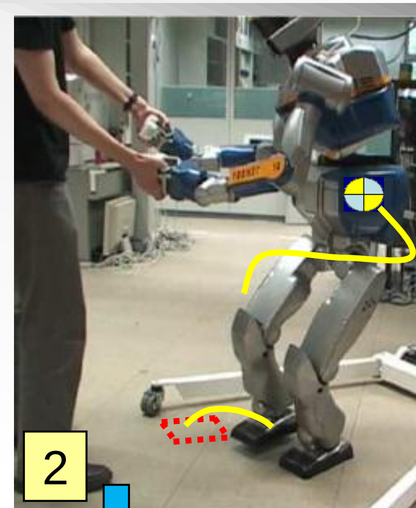
Force sensor input



Force input and footstep planning

Real-time walking pattern generation:

Stability and foot motion



Teleoperator

Compliant upper-body motion

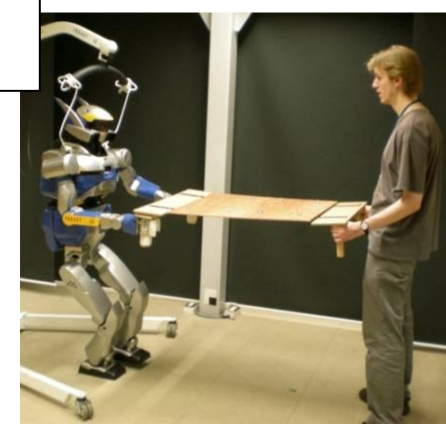
Teleoperation input

"Stack of tasks"

- CoM
- Upper body
- Legs
- Gaze
- …

Fast walking pattern generation

Real-time whole-body motion



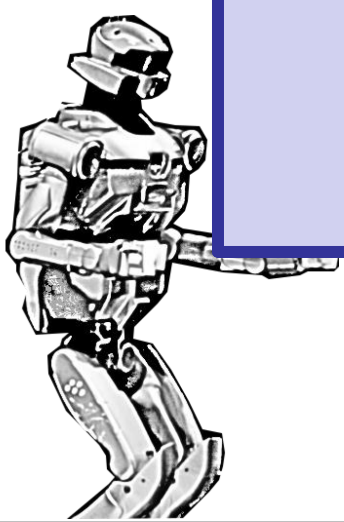
Robot@CWE final demonstrator

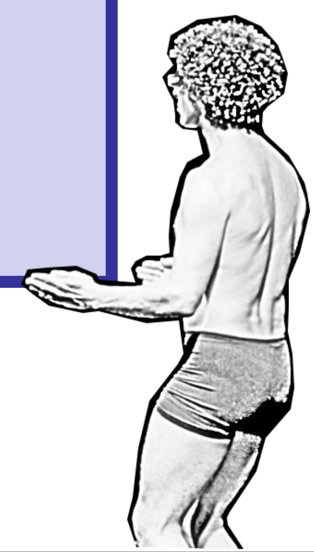
Stack of Tasks

- Pro
  - Allow combination of simple controllers
  - Integrate priority to exclude tasks when necessary
  - Take into account constraints
- Con
  - Rank deficiency is not handled properly
  - Local minima
  - Possible discontinuity between task switching without additional mechanisms

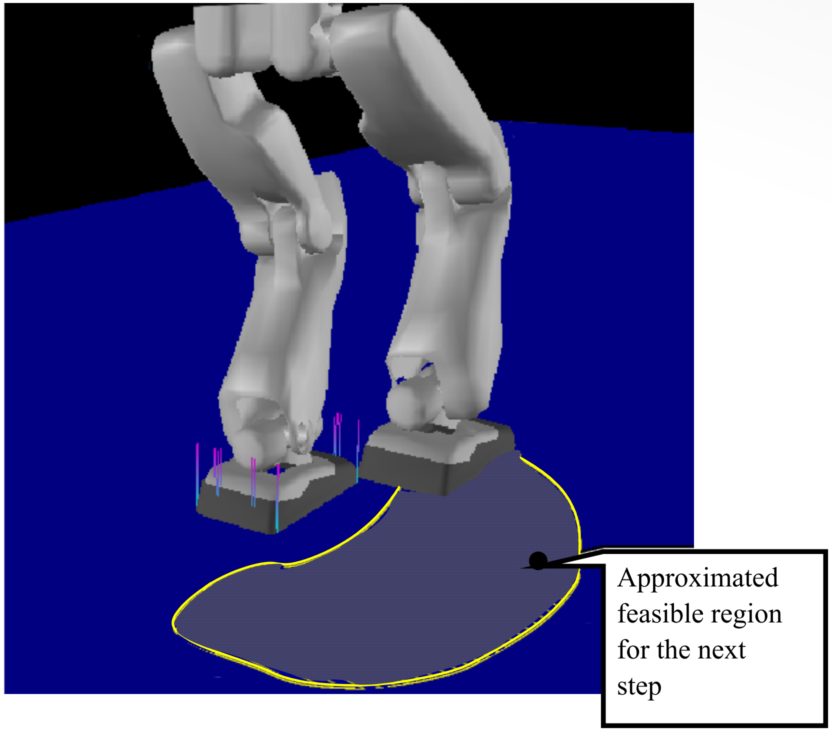
Overview

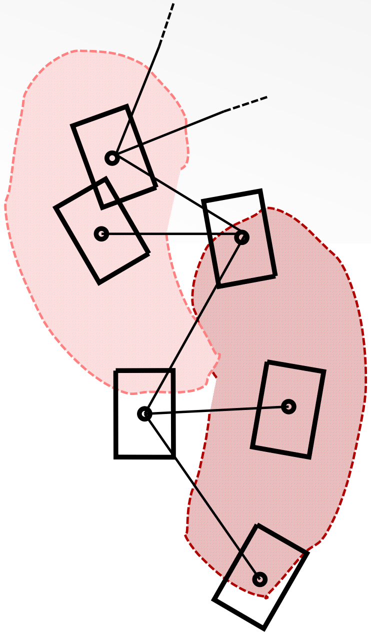
- Context – Problem statement
- Computer Vision
  - Next Best View
  - Visual Search
- Motion generation
  - Walking
  - Whole-Body Motion
  - Planning





Fast Foot-step feasibility checking



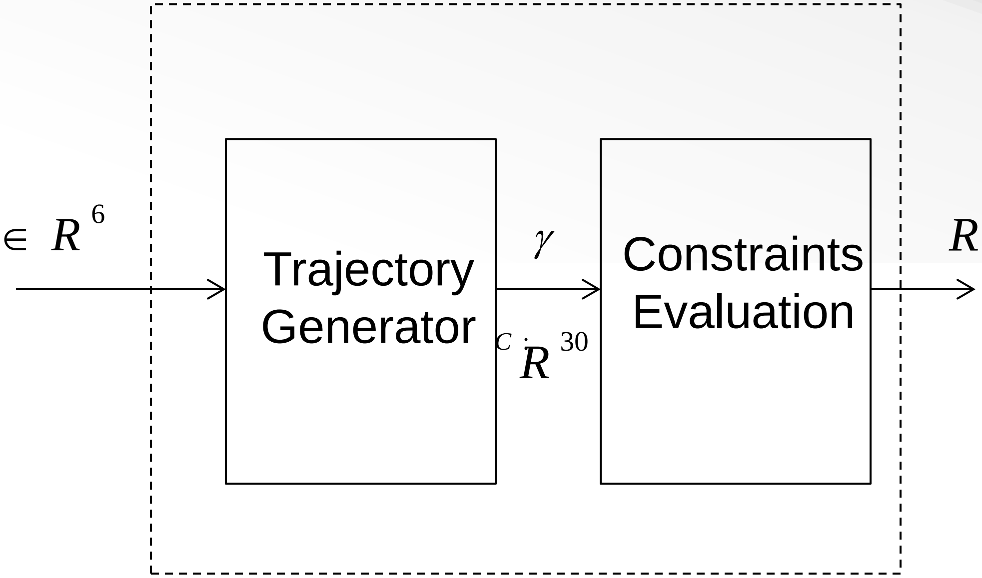


Function to approximate

Goal

Knowing in few micro seconds if a footstep is feasible. There is no real-time constraint for ***building*** the approximation.

$$(x_{right}, y_{right}, \theta_{right}, x_{left}, y_{left}, \theta_{left}) \in R^6$$

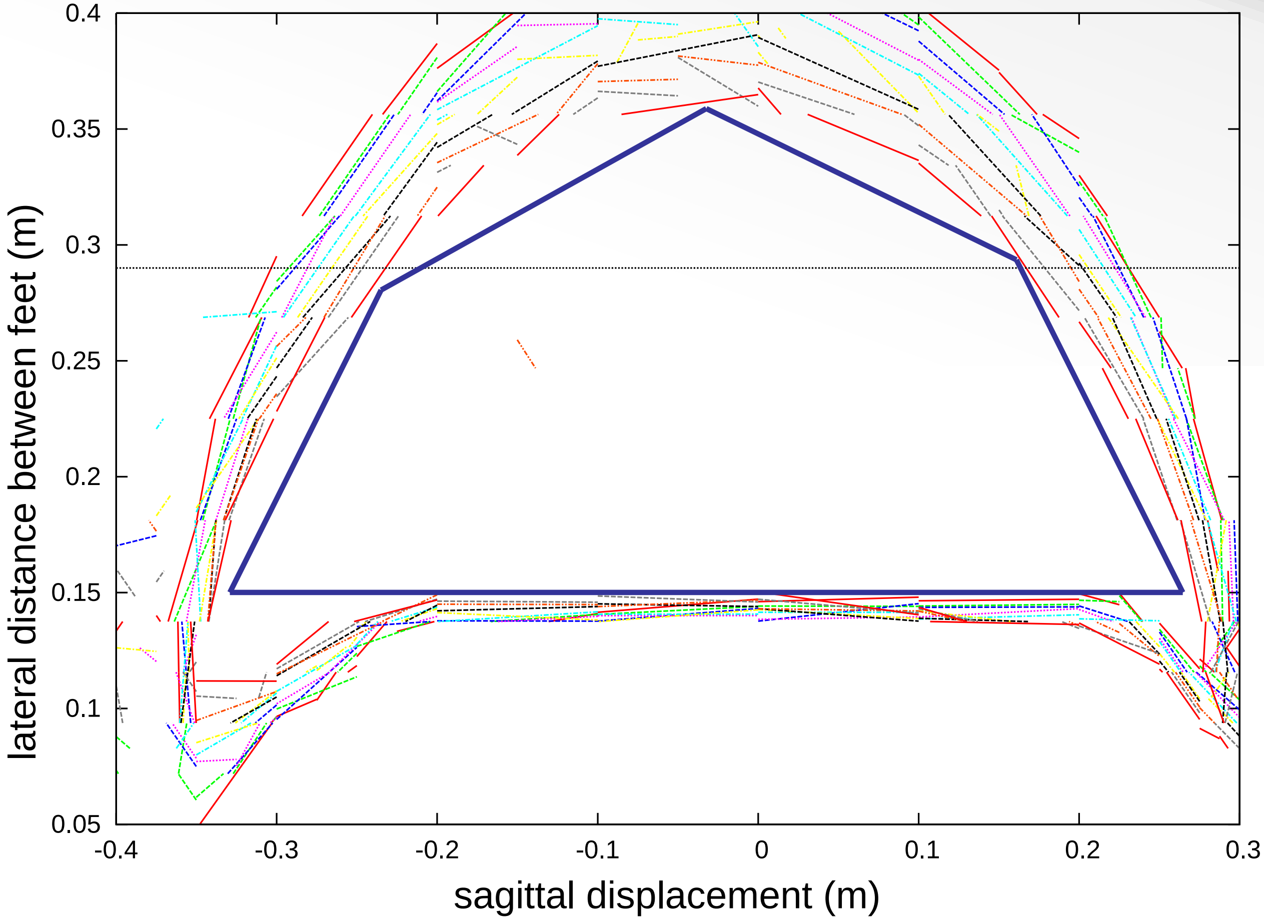


Constraints

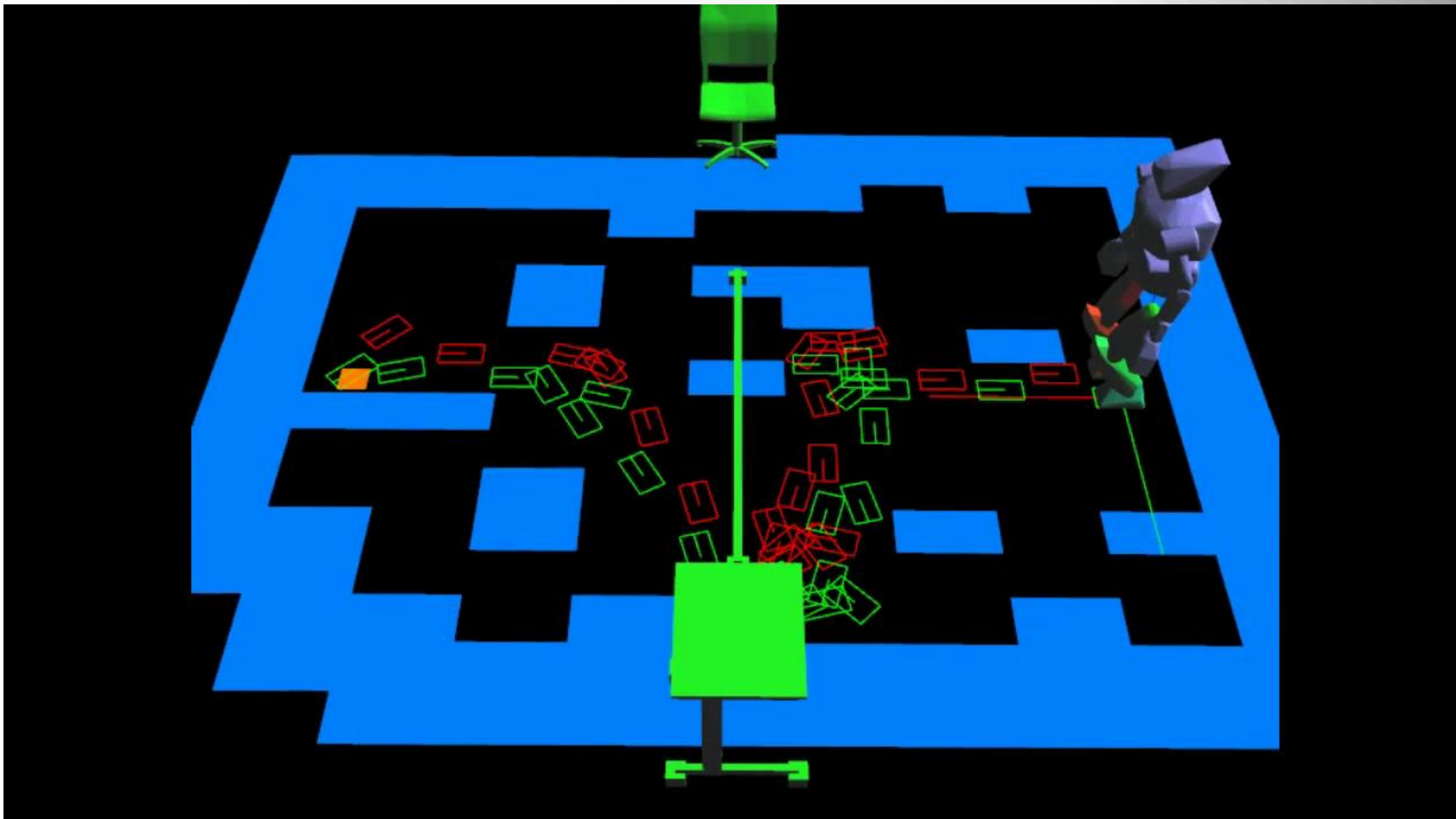
- Joint limits;
- Deviation from desired ZMP trajectory (i.e. dynamic stability);
- Self-collision;

Approximation: 11 days (4 dim.)
Evaluation: 9 micro-seconds

Approximation map



Real-time foot step replanning



[IEEE TRO Perrin 2012]

Conclusion

- Reactive motion generation
  - Possible at the control level, but generation is complex without proper tools to combine basic controllers: Stack of Tasks
  - Planning complex motion generation calls for powerful representation of steering method
- Robot such as HRP-2 have not yet been fully exploited:
  - Real-time multi-contacts motions
  - Whole body real-time generation with heavy objects
  - Extreme motions

Research Project (1/2)

Scientific Problem

Make the robot able to acquire and use *knowledge* to solve NP-hard problems.

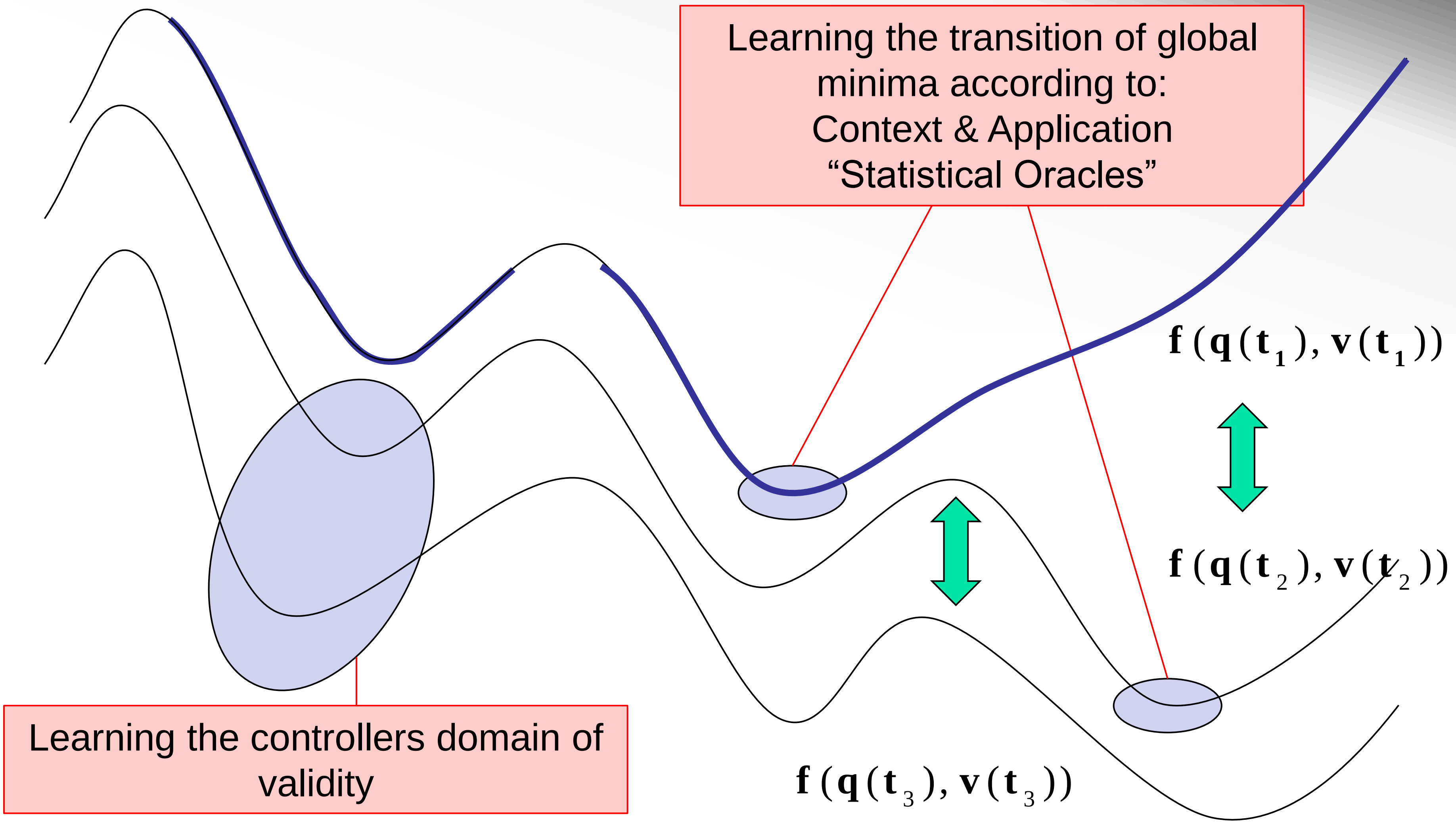
Approach

Build statistical *oracles*.

Method

- Embodiment: Take into account constraints related to the body and the control scheme.
- Making the robot aware of its body, the context, and the environment.

Approach



Learning the transition of global minima according to: Context & Application "Statistical Oracles"
$f(q(t_1), v(t_1))$
$f(q(t_2), v(t_2))$
$f(q(t_3), v(t_3))$
Learning the controllers domain of validity

More advanced controllers

Walking while Seeing – Visual Servoing – MPC and walking

$$
WwS \begin{cases} \min_{\mathbf{u}(k)} \sum_{l=0}^{M} (S_l^d - S_{l,k}^m)^\top W (S_l^d - S_{l,k}^m) \\ \text{linear constraints on ZMP} \\ \text{linear constraints on Foot Position} \\ \dots \\ with\ \mathbf{u}(k) = \begin{pmatrix} \mathbf{X}(k) \\ \mathbf{X}^f(\mathbf{k}) \\ \dots \\ \mathbf{Y}(\mathbf{k}) \\ \mathbf{Y}^f(k) \end{pmatrix} \end{cases}
$$

[Garcia, Stasse et al. IROS, 2013, submitted]

Using Human Motion

CoM

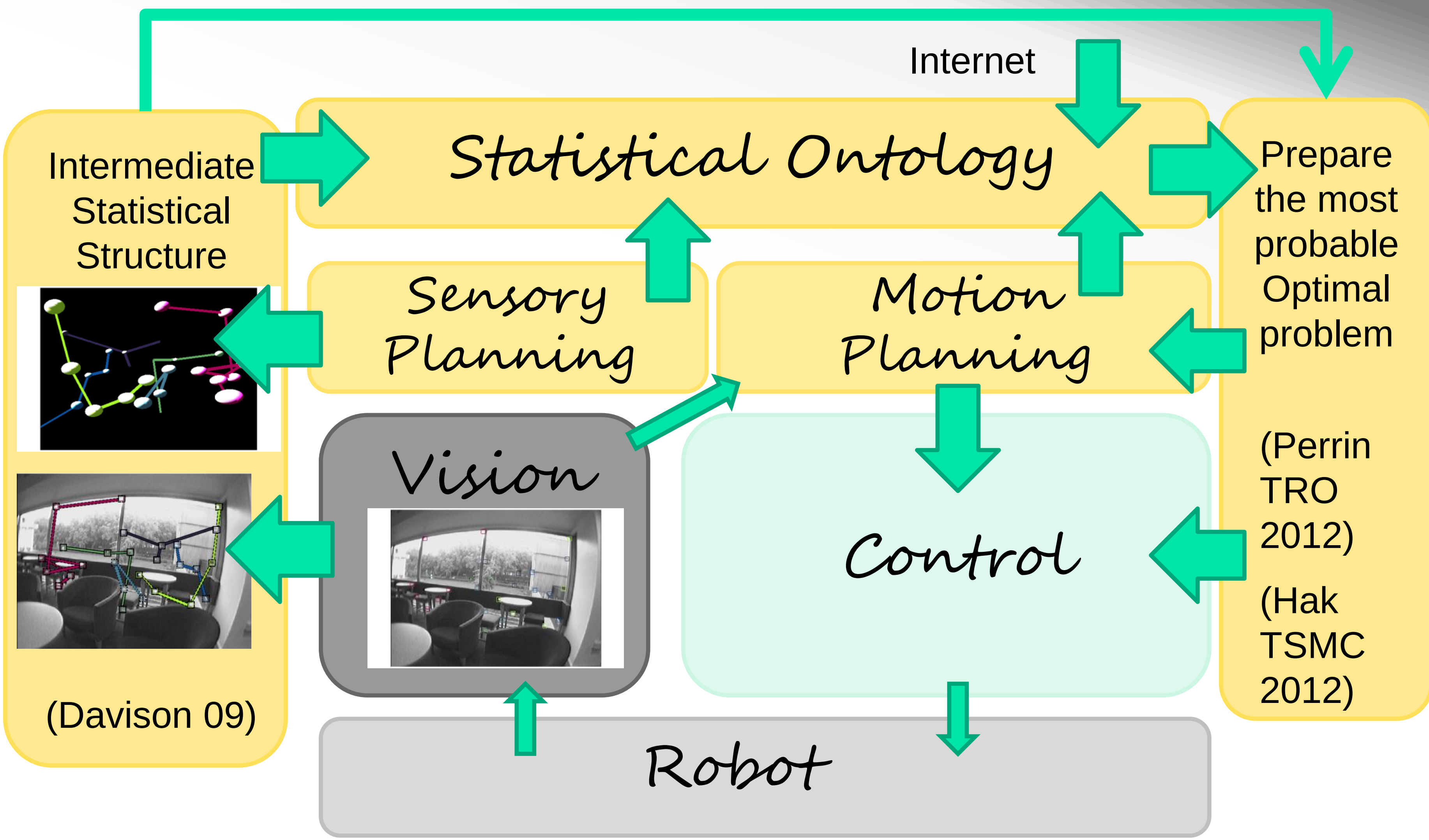
Left Hand

Right Hand

Visual Servo

[Hak, TSMC 2012]

Research Project



Challenge 1: Evolving in Factories

Humanoid Robots in Factories

- Complex but structured environment
- Possible to add additional sensors to simplify perception problems
- Handle real life variability is mandatory
- Proof-Of-Concept

(Ford Vision of Future Factory)

Challenge 2: Extreme Man

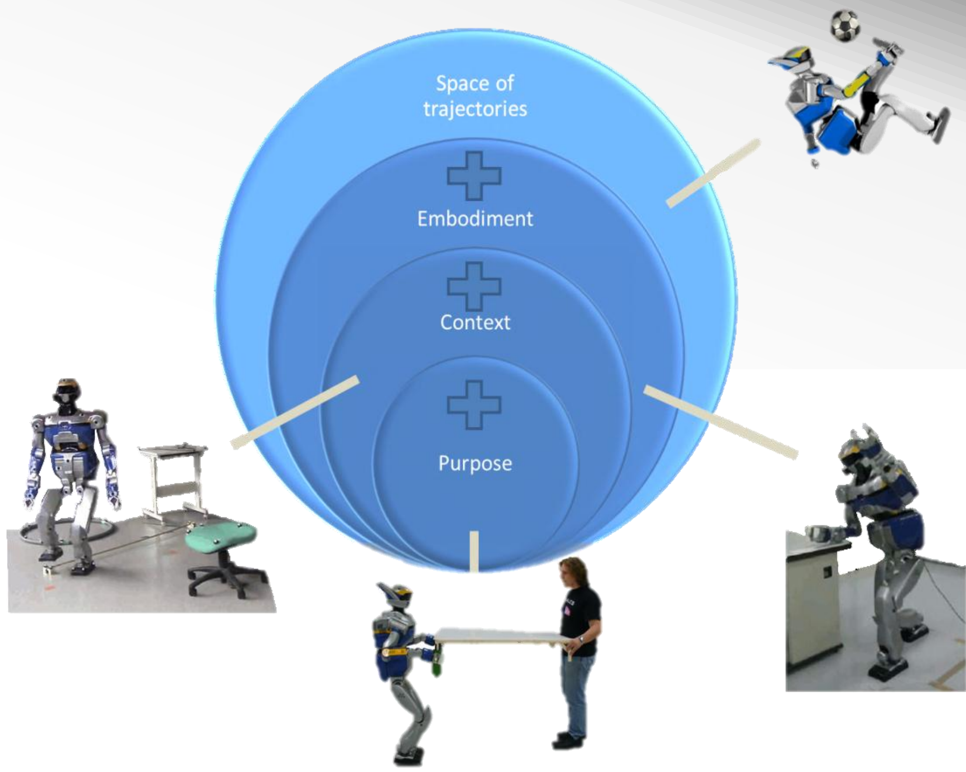
Extreme Motions: Parkour

- Calls for new mechanical mechanisms: Variable Impedance
- Make the problem even more Non-Linear
- Size of the problem is two times bigger than classical structure

Projects

Status

- Coordinator of one FP-7 project submitted in the frame of ICT call 10 – Triple A
- Leading one Proof –Of-Concept project with a Big industrial partner.
- Participation to one challenging project sponsored by an international oil company.
- Involved in a proposal for European Robotics Challenges



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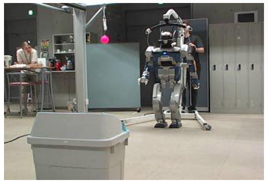

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