Task, hardware, and control: challenges in legged-robot design

Margot Vulliez

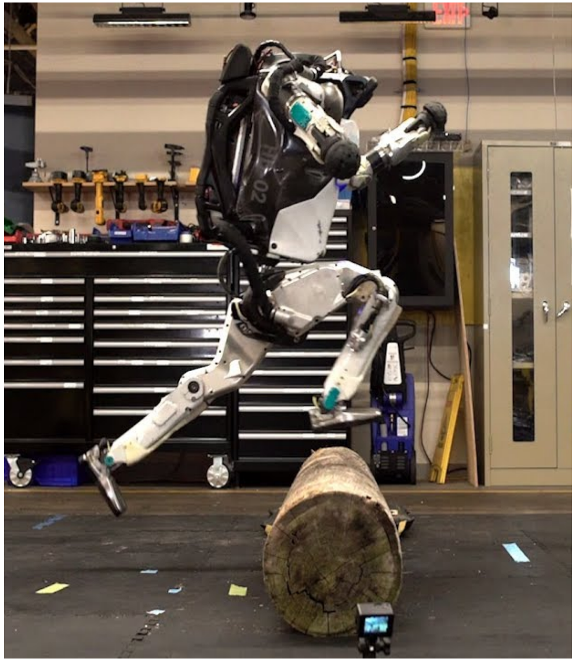
Virgile Batto

AUCTUS –

Gepetto –

JNRH 2023

Robot mobility, on the importance of the design



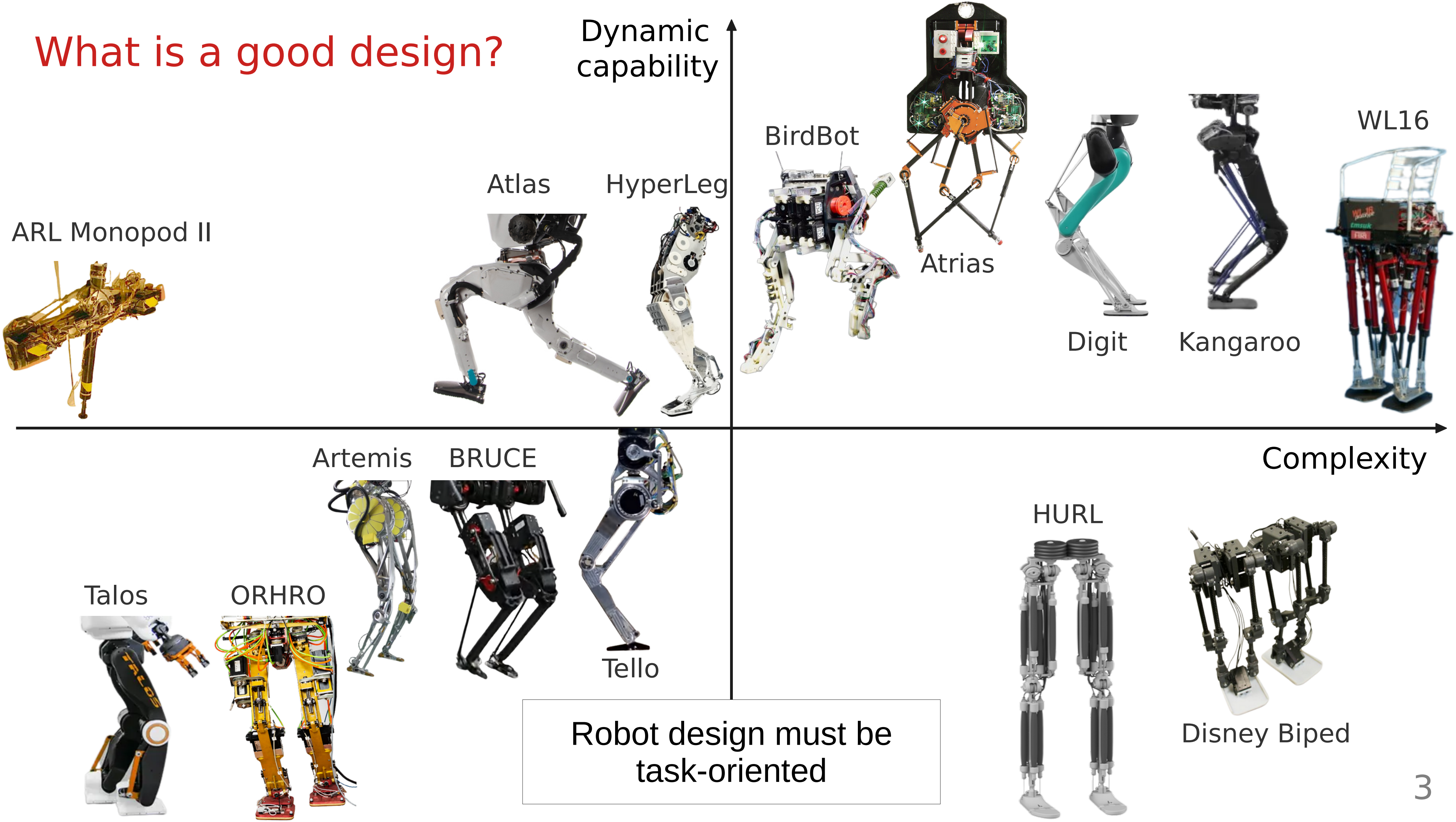
Why robot mobility ?

- Ground locomotion tasks
- Dynamic and unstructured environment
- Physical interactions + compliance

A good design is fundamental for robot mobility

Humanoid robots?
A roboticist ideal but complex

What is a good design?



Robot design must be task-oriented

On the importance of mechatronic design

Task

Performances

Constraints

Task-based requirements

Structural design

Modeling

Actuation

Sensors & electronics

Integration

Optimization

Electromechanical components

Controller

Perception

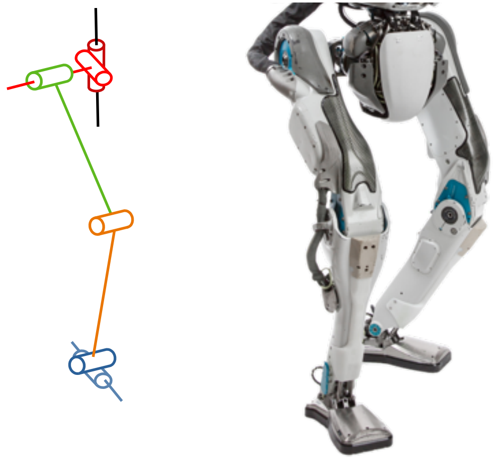
Constraints

Control objectives

Structural design

Serial legs

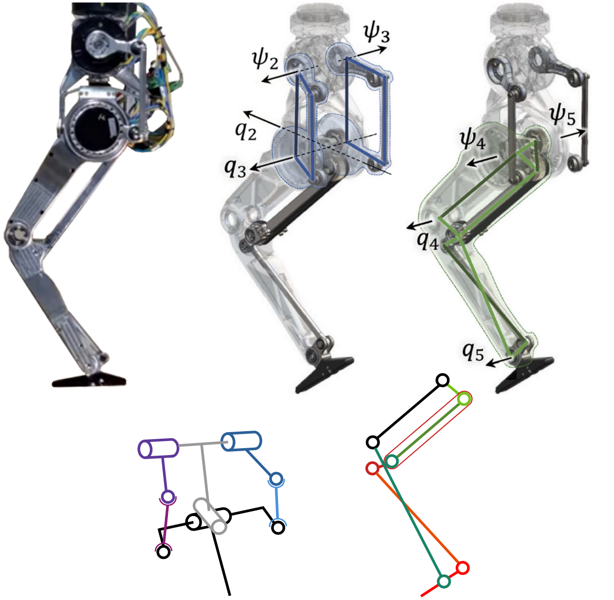
Revolute/prismatic joints



- Large workspace
- High effective inertia
- Reduced force capability
- Structural flexibility
- Small footprint

Hybrid legs

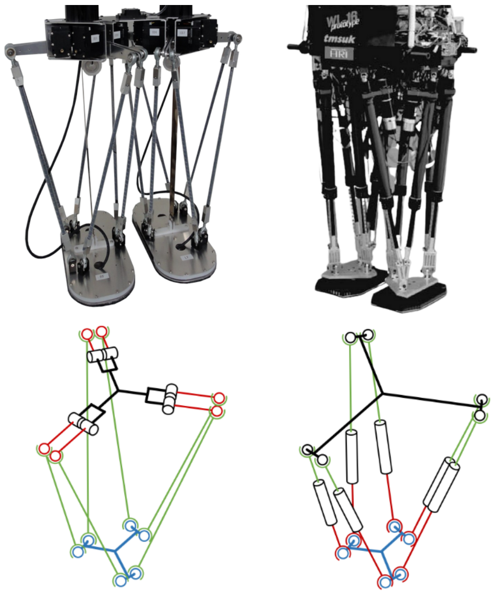
Bar linkage, differential mechanism



- Large workspace
- Low effective inertia
- High force capability
- Improved stiffness
- Small footprint

Parallel legs

Delta, HEXA, Stewart-Gough



- Limited workspace
- Low effective inertia
- High force capability
- High stiffness
- Large footprint

Dynamic modeling

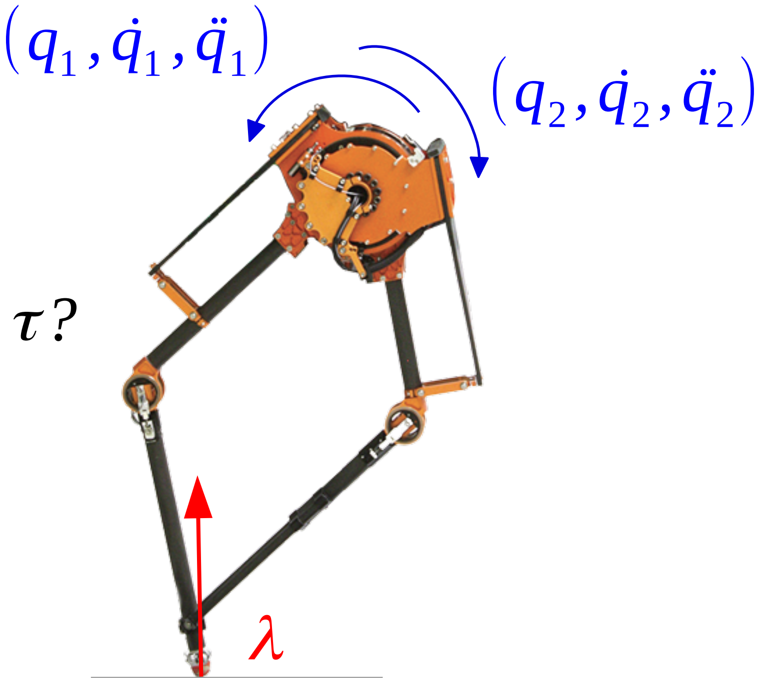
- Robot Dynamics libraries

  Robot dynamics through Recursive Newton-Euler Algorithm (Pinocchio)
  Symbolic model of tree structures (Modélisation Dynamique d'Arborescences)

- Robot description: URDF, SDF

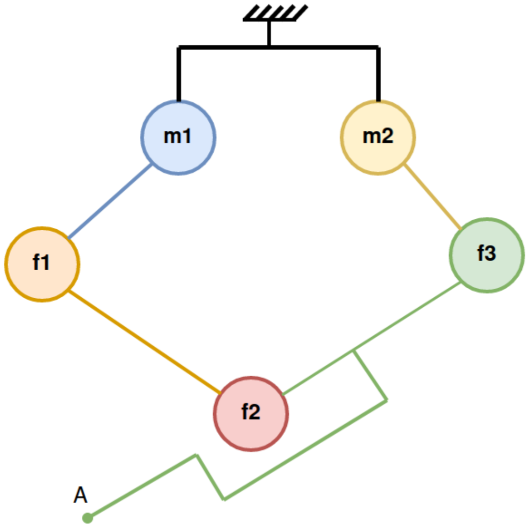
- Closed-loop modeling ?

$$M(q)\ddot{q}+b(q,\dot{q})+g(q)+G^T\lambda=\tau$$

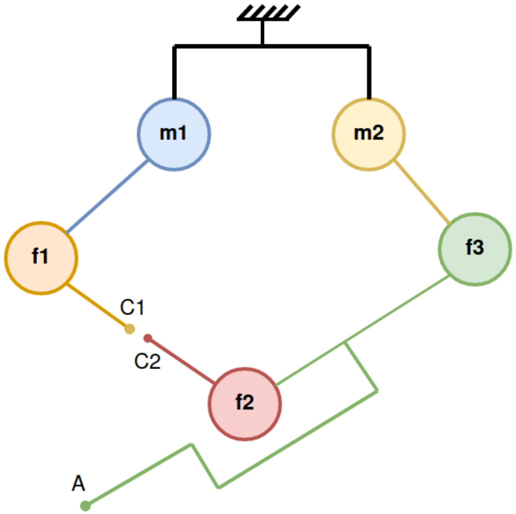


Closed-loop modeling

Description of closed loop structure



SDF files
Any number of
parent joint by link



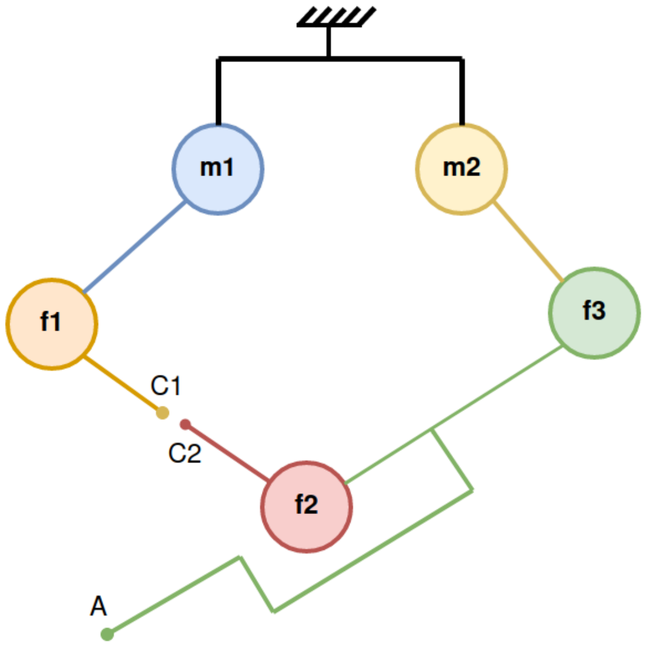
URDF files
One parent joint by
link

SDF files led to parsing issue => Inertia of the link distribued to the joint

URDF files used : Robust and reliable result for open-loop, contact constraint generated after

Closed-loop modeling

Closed loop jacobian



Contact constraint between c₁ and c₂

With an open loop robot with a contact constraint , define by :
-q its configuration vector
-q_mot and q_free the configuration vector of the motor and free joint
-Jc the contact Jacobian (Jc=JC₁ -JC₂)
-Jc=[Jcmot,Jcfree]

We obtain :

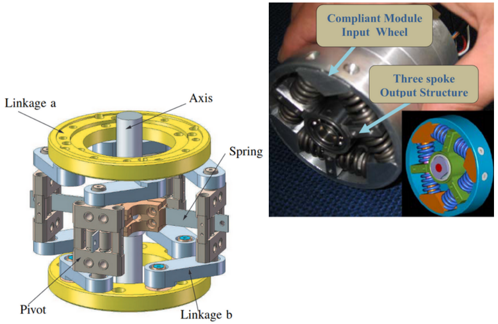
$$\frac{\partial q}{\partial q_{mot}} = \begin{bmatrix} \mathbb{I} \\ -J_{cfree}^{\dagger} J_{cmot} \end{bmatrix}$$

This led to Jcl, the closed loop jacobian, here in A :

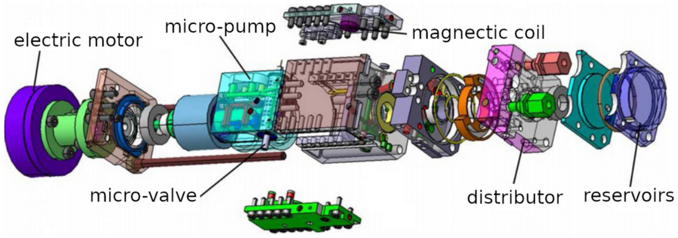
$$J_{cl} = \frac{\partial {}^{o}M_A(q)}{\partial q} \frac{\partial q}{\partial q_{mot}}$$

Actuation

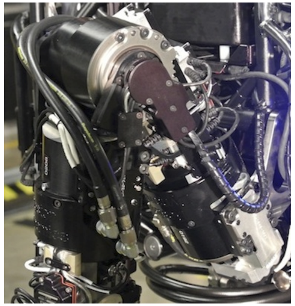

Electric motors (DC brushless)



Elastic actuators (SEA, VSJ)

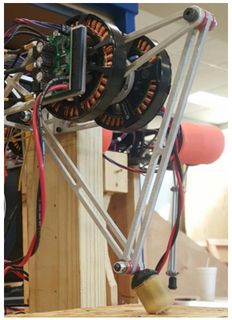


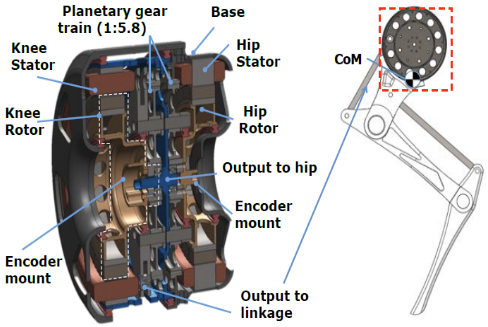
Electro-hydraulic actuators (IEHA)


Hydraulic units

High torque, high power to mass ratio, compactness, smooth motion/torque...

Transmission system – Mechanical transparency, ratio, flexibility/stiffness

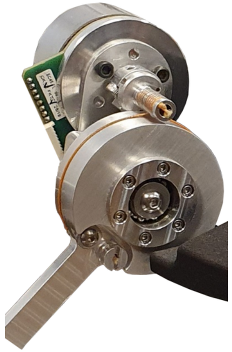

Direct drive (Minitaur)



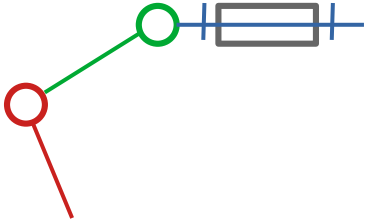
Geared transmission (Cheetah) harmonic, planetary, cycloïdal

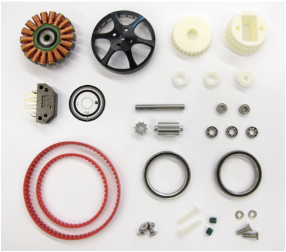

Ball-screw (Orhro)

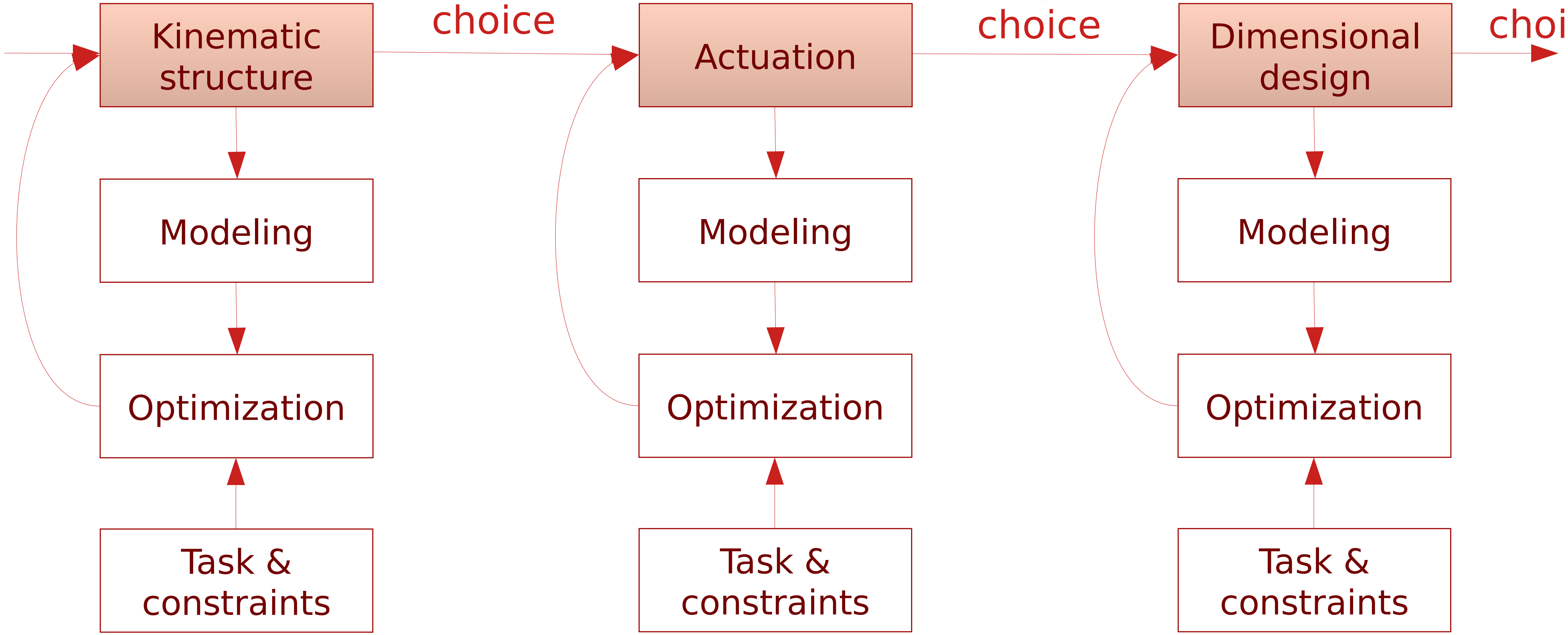

Pulley-Belt (Solo)


Cable-driven system

An iterative optimization process







Kinematic structure

Modeling

Optimization

Task & constraints

designer choice

Actuation

Modeling

Optimization

Task & constraints

designer choice

Dimensional design

Modeling

Optimization

Task & constraints

designer choice

Common optimization criteria

Workspace

Velocity ellipsoid $q^T q = v^T (J J^T)^{-1} v = 1$

Kinematic Manipulability $\omega_c = \sqrt{det(J J^T)}$

Kinematic Isotropy/Dexterity

$$\eta_c = \frac{\sigma_{min}(J J^T)}{\sigma_{max}(J J^T)}$$

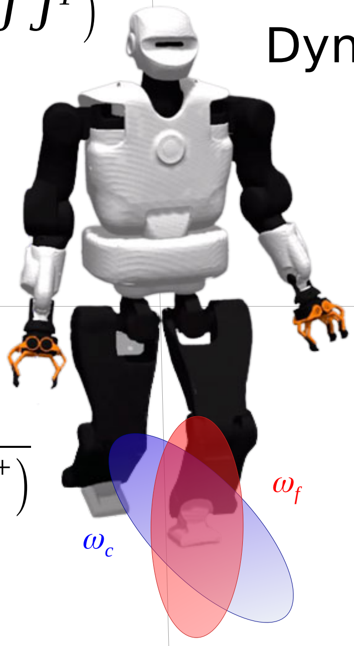
Effective Inertia $\Lambda = J^{+T} M J^{+}$

Dynamic ellipsoid $a^T a = F^T (\Lambda \Lambda^T)^{-1} F = 1$

Dynamic Manipulability $\omega_d = \sqrt{det(\Lambda \Lambda^T)}$

Dynamic Isotropy/Dexterity

$$\eta_d = \frac{\sigma_{min}(\Lambda \Lambda^T)}{\sigma_{max}(\Lambda \Lambda^T)}$$



Force ellipsoid $\tau^T \tau = F^T (J J^T) F = 1$

Force Manipulability $\omega_f = \sqrt{det(J^{+T} J^{+})}$

Force Isotropy/Dexterity

$$\eta_f = \frac{\sigma_{min}(J^{+T} J^{+})}{\sigma_{max}(J^{+T} J^{+})}$$

Footprint

Joint stiffness $K_a = k J^{-T} J^{-1}$

Structural stiffness K

Force/motion capability through convex polytopes?

Leg design criteria

Formulation

Kinematics criteria

Rotation Manipulability :

$$RM = det(Jr_{cl} Dr^2 Jr_{cl}^T)$$

Translation Manipulability :

$$TM = det(Jt_{cl} Dt^2 Jt_{cl}^T)$$

Z Reduction Ratio :

$$ZRR = ||Jt_{cl}^T \vec{z}||$$

Inertial criteria

Foot inertia :

$$\Lambda_{foot} = (J_{closedloop} M_{mot}^{-1} J_{closedloop}^T)^{-1}$$

Foot inertia projeted on the z-axis :

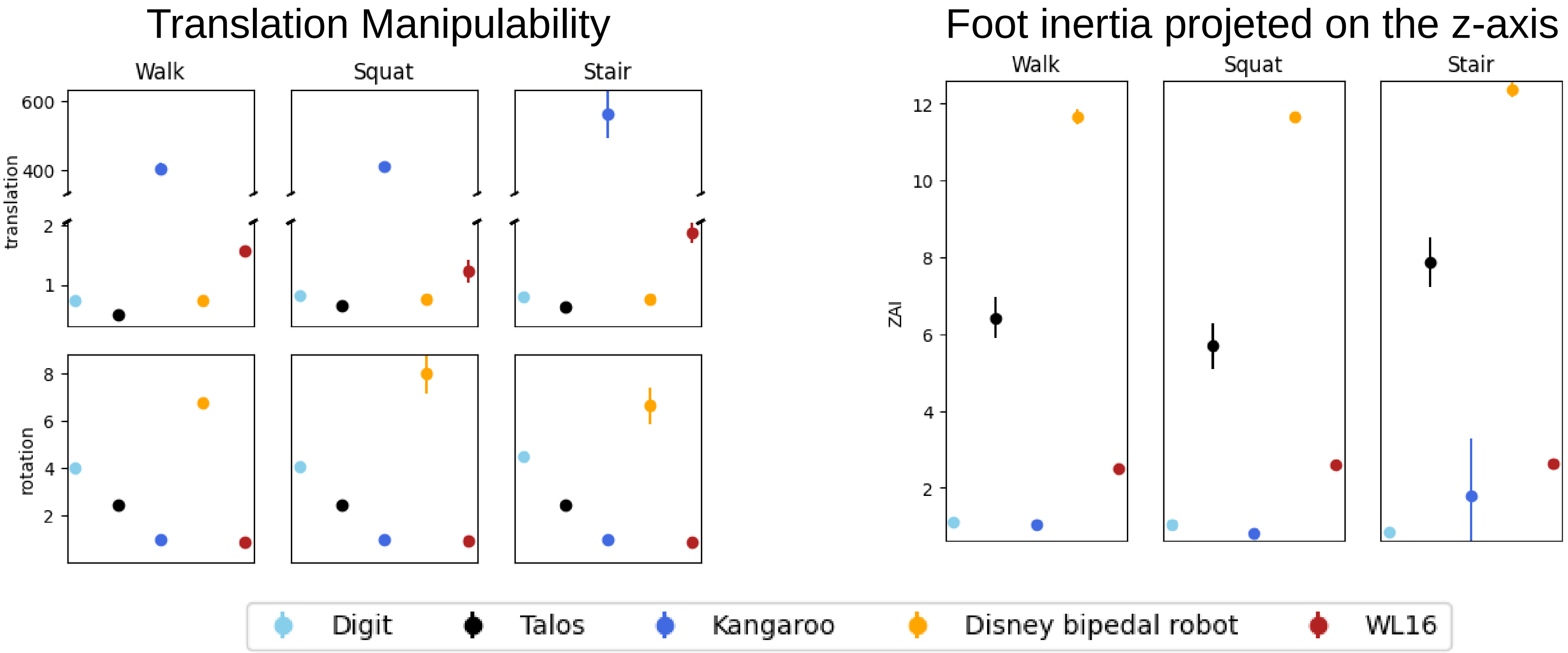
$$ZAI = [z,0] \Lambda_{foot} [z,0]^T$$

Impact mitigation factor :

$$IMF = det(\mathbb{I} - \Lambda_{foot} \Lambda_{Lfoot})$$

Leg design criteria

Application


Translation Manipulability

Foot inertia projeted on the z-axis

Optimization problem

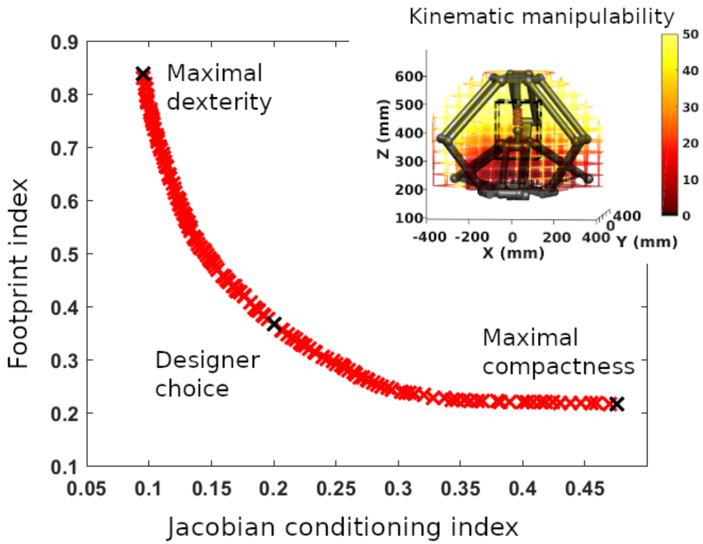
Problem formulation

$$\underset{x}{\text{minimize}} \quad \sum_i \alpha_i f_i(x) \qquad \text{subject to} \quad \begin{array}{l} g_j(x) \leq 0 \quad \text{for} \quad j=1\dots m \\ h_k(x)=0 \quad \text{for} \quad k=1\dots p \end{array}$$

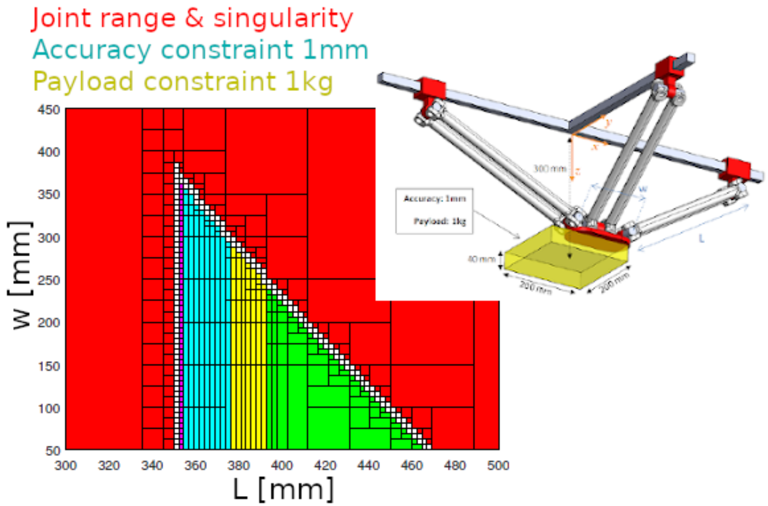
objective functions, weight/penalty,constraints

Aiming at a set of optimal solutions

Pareto front of optimal solutions



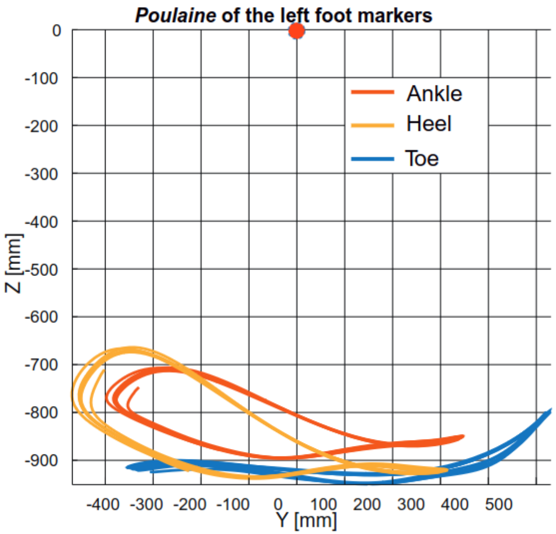
Interval-analysis set of feasible solutions



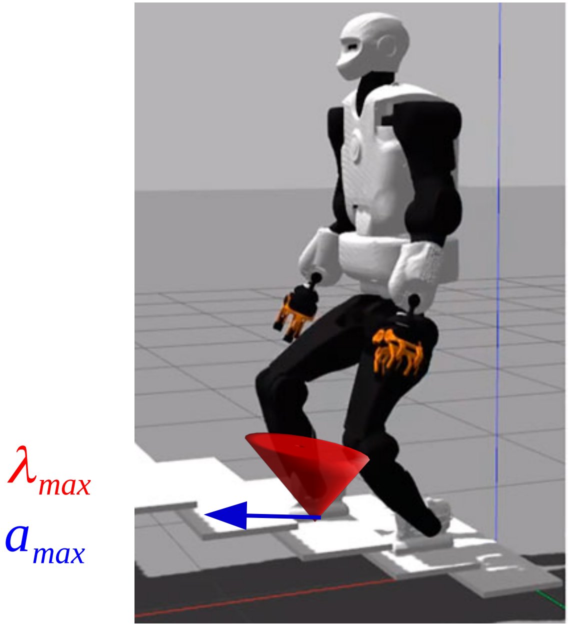
Locomotion tasks: performances and constraints

Required performances (task trajectories and force)
Task constraints (workspace, minimal force-motion capability)

Poulaines of walking

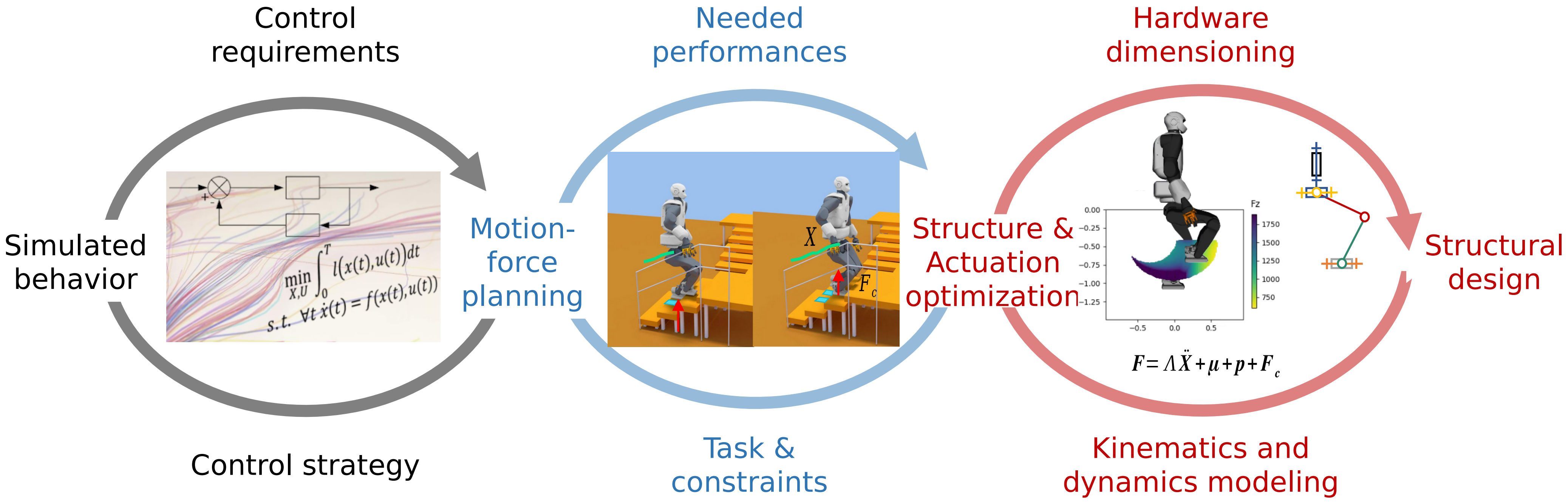


Climbing stairs performances



Task variability ?

Building upon simulation, a codesign approach



Control requirements

Simulated behavior

Control strategy

Needed performances

Motion-force planning

Task & constraints

Hardware dimensioning

Structure & Actuation optimization

Structural design

$$F = \Lambda \ddot{X} + \mu + p + F_c$$

Kinematics and dynamics modeling

Predicted controlled behavior

Simulated task

Mechatronic design