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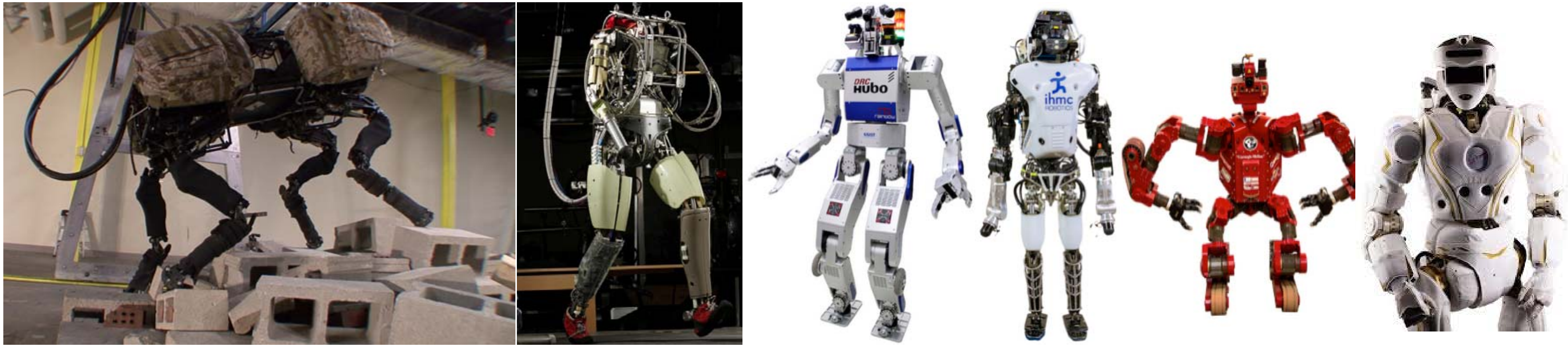


Lecture «Robot Dynamics»: Legged Robots

151-0851-00 V

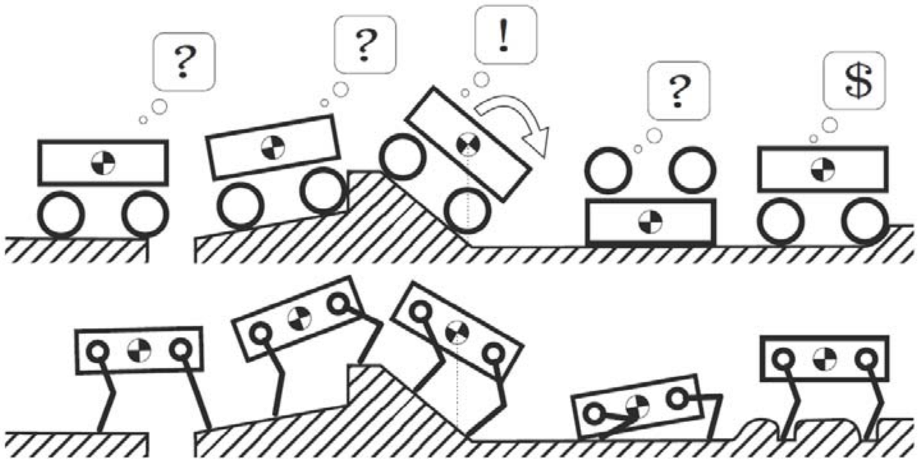
lecture:	CAB G11	Tuesday 10:15 – 12:00, every week
exercise:	HG E1.2	Wednesday 8:15 – 10:00, according to schedule (about every 2nd week)

Marco Hutter, Roland Siegwart, and Thomas Stastny

19.09.2017	Intro and Outline	Course Introduction; Recapitulation Position, Linear Velocity			
26.09.2017	Kinematics 1	Rotation and Angular Velocity; Rigid Body Formulation, Transformation	26.09.2017	Exercise 1a	Kinematics Modeling the ABB arm
03.10.2017	Kinematics 2	Kinematics of Systems of Bodies; Jacobians	03.10.2017	Exercise 1b	Differential Kinematics of the ABB arm
10.10.2017	Kinematics 3	Kinematic Control Methods: Inverse Differential Kinematics, Inverse Kinematics; Rotation Error; Multi-task Control	10.10.2017	Exercise 1c	Kinematic Control of the ABB Arm
17.10.2017	Dynamics L1	Multi-body Dynamics	17.10.2017	Exercise 2a	Dynamic Modeling of the ABB Arm
24.10.2017	Dynamics L2	Floating Base Dynamics	24.10.2017		
31.10.2017	Dynamics L3	Dynamic Model Based Control Methods	31.10.2017	Exercise 2b	Dynamic Control Methods Applied to the ABB arm
07.11.2017	Legged Robot	Dynamic Modeling of Legged Robots & Control	07.11.2017	Exercise 3	Legged robot
14.11.2017	Case Studies 1	Legged Robotics Case Study	14.11.2017		
21.11.2017	Rotorcraft	Dynamic Modeling of Rotorcraft & Control	21.11.2017	Exercise 4	Modeling and Control of Multicopter
28.11.2017	Case Studies 2	Rotor Craft Case Study	28.11.2017		
05.12.2017	Fixed-wing	Dynamic Modeling of Fixed-wing & Control	05.12.2017	Exercise 5	Fixed-wing Control and Simulation
12.12.2017	Case Studies 3	Fixed-wing Case Study (Solar-powered UAVs - AtlantikSolar, Vertical Take-off and Landing UAVs – Wingtra)			
19.12.2017	Summery and Outlook	Summery; Wrap-up; Exam			

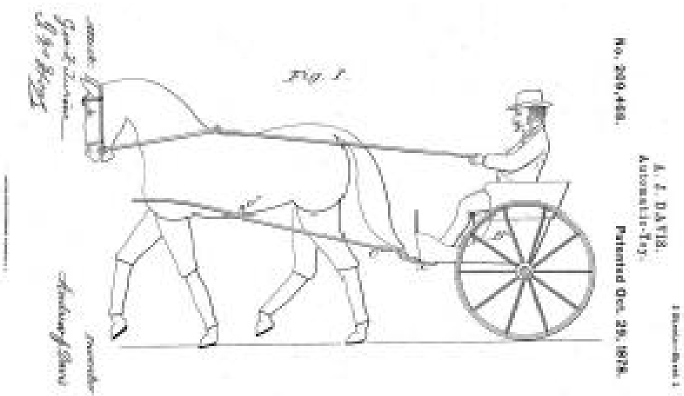
Why legged robots?

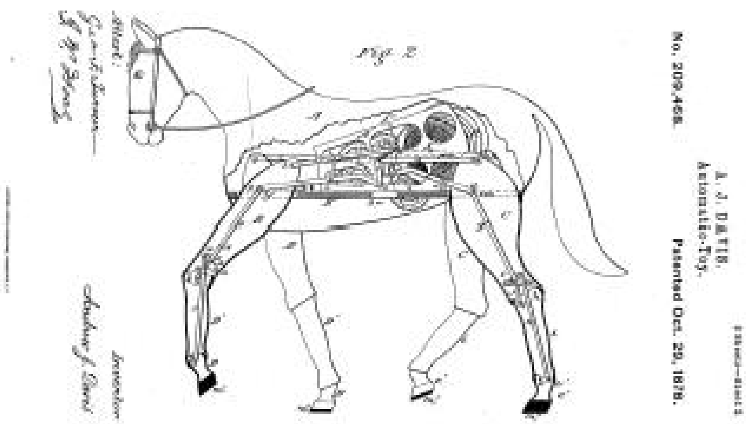
- Legged systems can overcome many obstacles



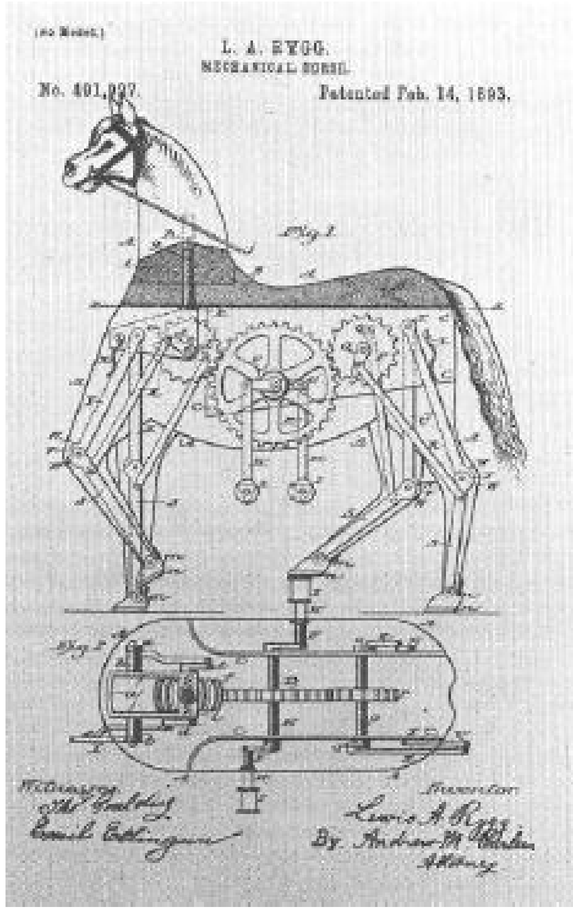
- But it is quite hard to achieve this since
  - many DOFs must be controlled in a coordinated way
  - the robot must interact with (uncertain) terrain

History of Legged Robotics
Walking Mechanism – First patents



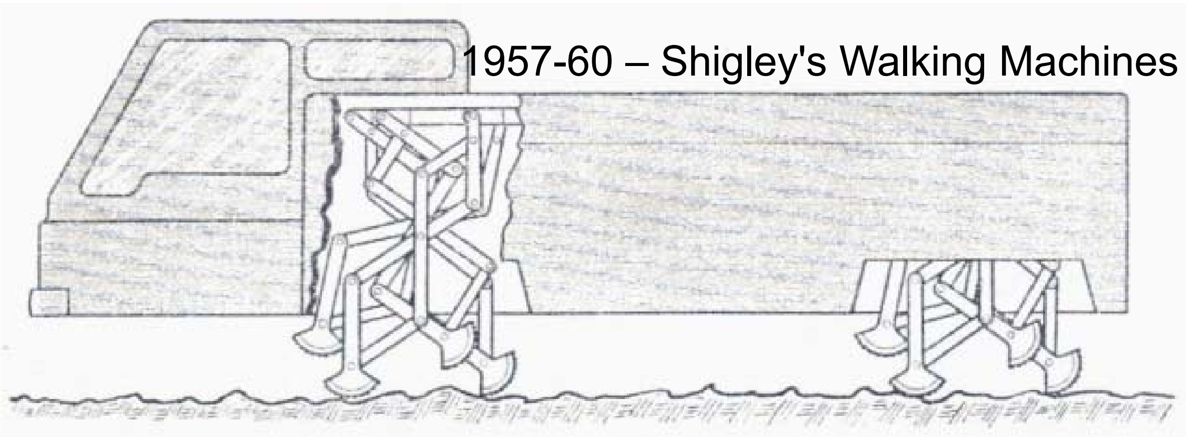


- Davis, 1878



Rygg, 1893

Walking Mechanisms



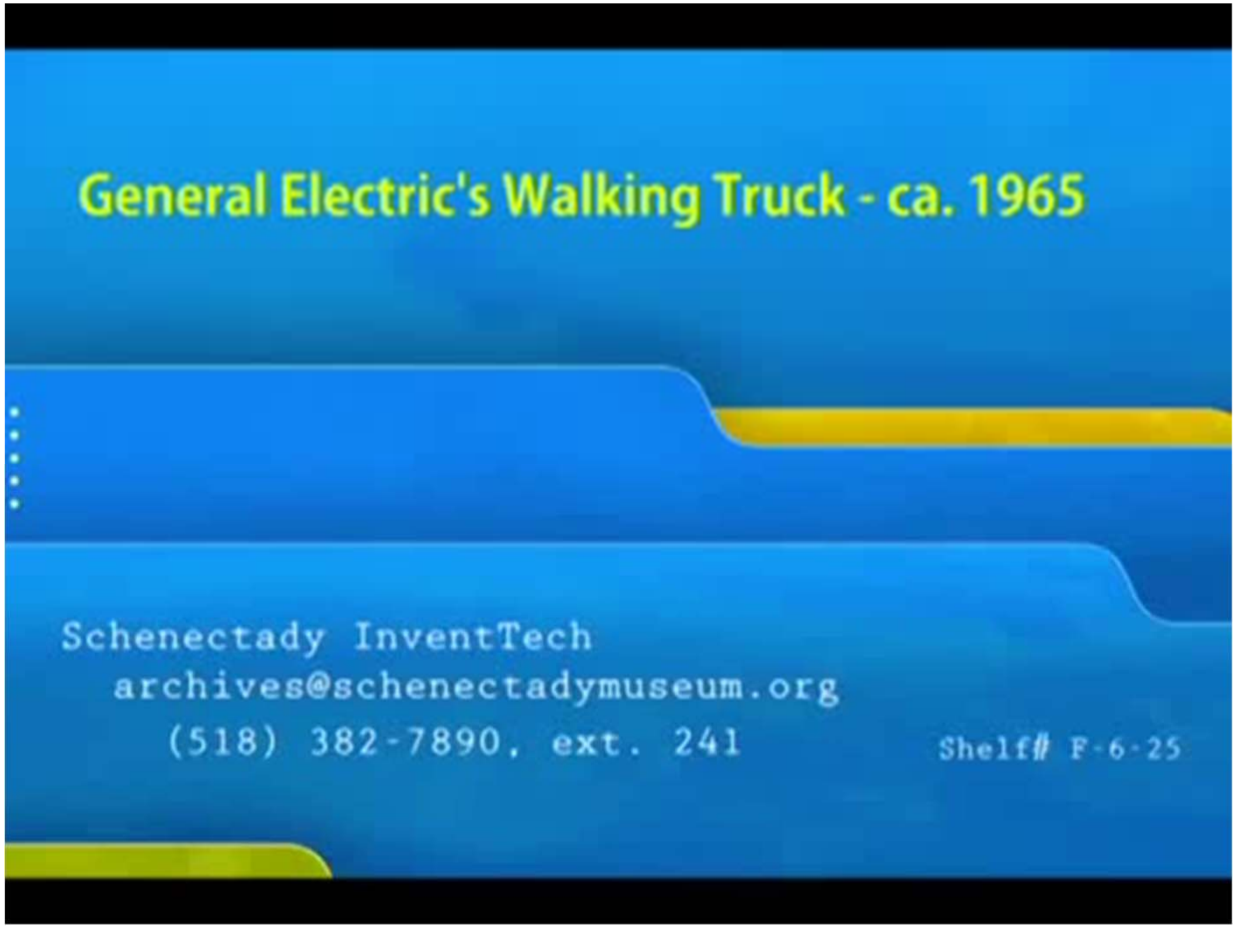
1957-60 – Shigley's Walking Machines

1984 - OSU ASV
(Adaptive Suspension Vehicle)

Walking Mechanism
Theo Jansen

History of Legged Robotics

GE Walking Truck – human controlled 4-ped



Large Scale Legged Locomotion and Manipulation

Youtube:
menzi muck extreme



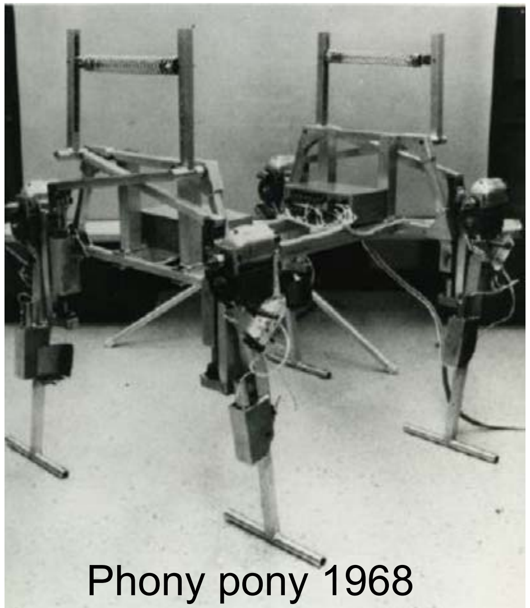




History of Legged Robotics

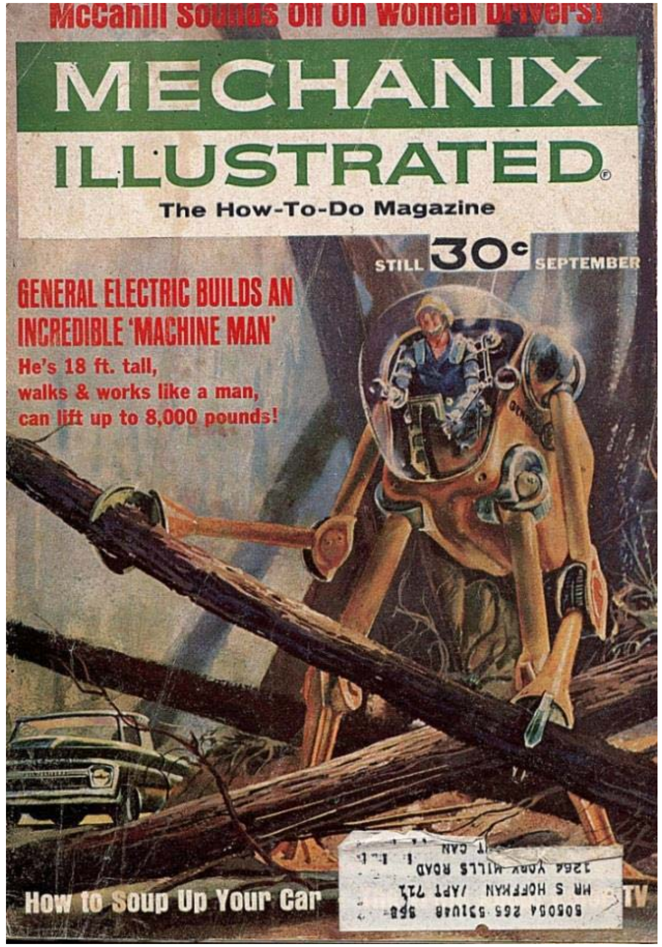
Phony Pony, GE Hardiman and many more…

- More on http://cyberneticzoo.com/
  - steam-actuated humans
  - mechanical elephants
  - …



Phony pony 1968

Hardiman1965



History of Legged Robotics
Humanoid robots after 2000

- Honda Asimo

- Toyota Humanoid

History of Legged Robotics
Humanoid robots after 2000

- Fukushima 2011

- DARPA Robotics Challenge 2012

Legged Robotics

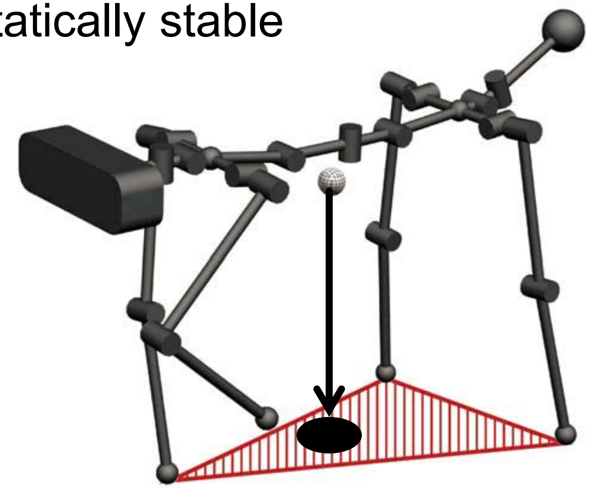
Where are we really and what are the challenges?

DARPA Robotics Challenge
... and a thing we learned after the DRC Finals

- Walking is still difficult

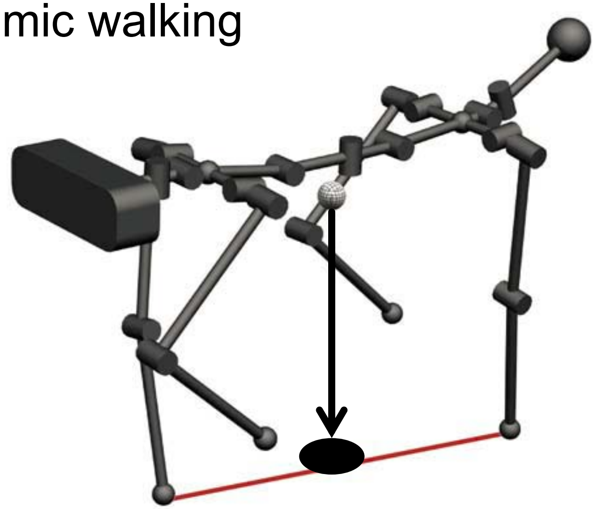
Static vs. Dynamic Stability

- Statically stable



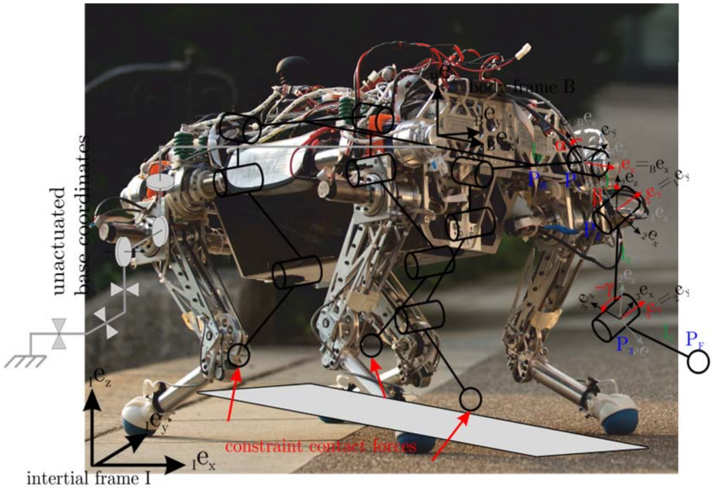
  - Bodyweight supported by at least three legs
  - Even if all joints 'freeze' instantaneously, the robot will not fall
  - Safe, slow and inefficient

- Dynamic walking



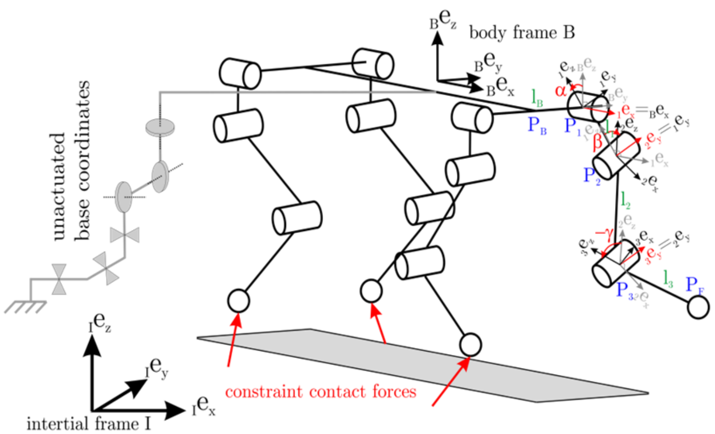
  - The robot will fall if not continuously moving
  - Less than three legs can be in ground contact
  - fast, efficient and demanding for actuation and control

Kinematics of Floating Base / Mobile Systems



- Quadrupedal robot
- Static walking
- 3 legs in stance [NR 1,2,3]
- 1 in swing [NR 4]

Kinematics of Floating Base / Mobile Systems



- Quadrupedal robot
- Static walking
- 3 legs in stance [NR 1,2,3]
- 1 in swing [NR 4]

1. How many generalized coordinates?
2. How many base coordinates?
3. How many actuated joint coordinates?
4. How many contact constraints?

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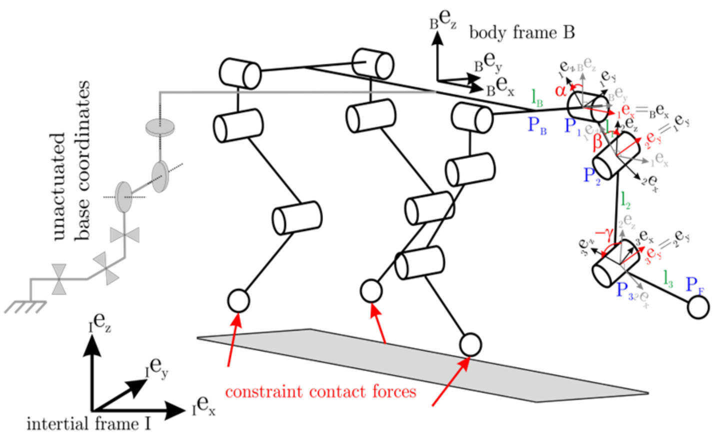
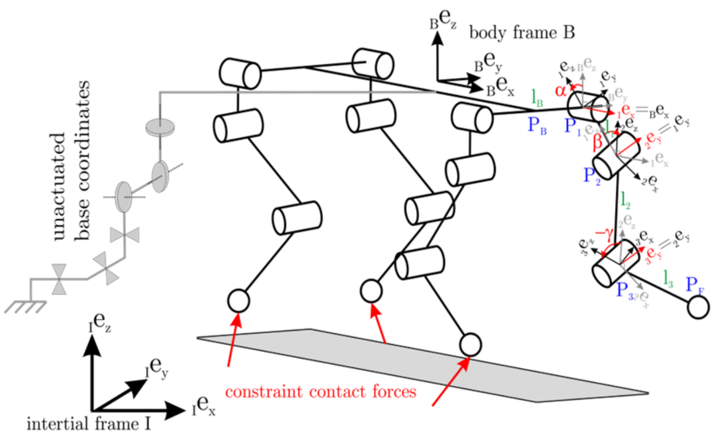
Differential Kinematics



- Quadrupedal robot
- Static walking
- 3 legs in stance [NR 1,2,3]
- 1 in swing [NR 4]

5. Write down the contact constraint
6. How many DoFs remain adjustable?
7. Which DoFs remain adjustable?

Inverse Differential Kinematics



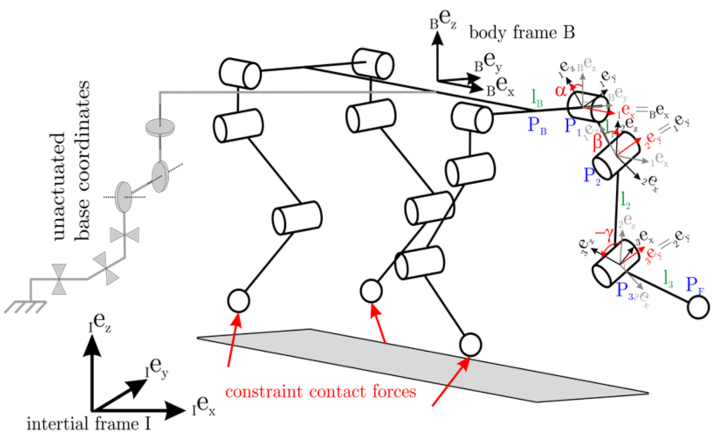
- Quadrupedal robot
- Static walking
- 3 legs in stance [NR 1,2,3]
- 1 in swing [NR 4]

8. Given a desired swing velocity $_I\dot{\mathbf{r}}_{OP_{F4}}^{des}$ what is the generalized velocity?

$$\dot{\mathbf{q}} = f\left(\mathbf{q}, {}_I\dot{\mathbf{r}}_{OP4}^{des}\right)$$

9. Is it unique?
10. Is it possible to follow the desired swing trajectory without moving the joints of leg 4? How?

Kinematic Singularity



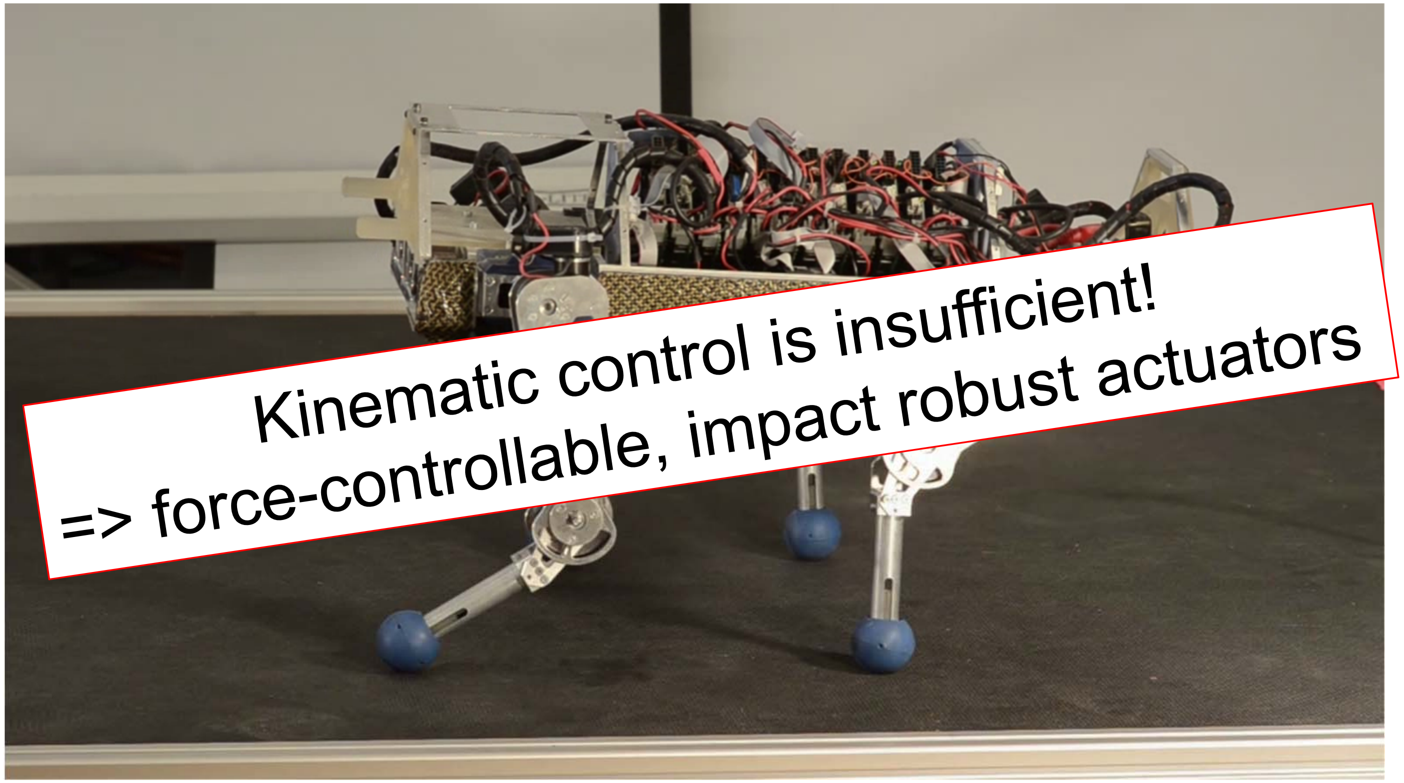
- There exist different formulations for “moving the foot (task1) while keeping the base position and orientation (task2)”. Write down the solution for A and B!
- What is the difference?
- What happens in singular configs?

Task 1:
- contact constraints
- foot motion

Task 2:
- base position
- base orientation

A) Single Task

B) Null-space motion



Kinematic control is insufficient!
=> force-controllable, impact robust actuators

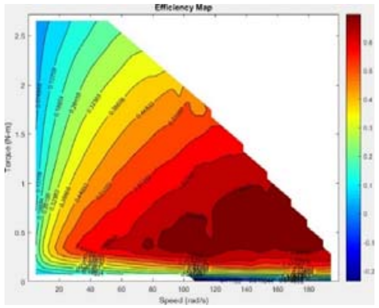
Actuation principles in legged robots

- The ideal actuator for versatile dynamic legged robots
  - Ideal Torque source (high bandwidth and versatility)
  - Energy Efficiency
  - High maximum joint torque
  - High maximum joint velocity
  - Small size and weight
  - Robustness (to impacts,failure)
  - Large range of motion
  - Low price
  - User friendliness

Actuation principles in legged robots

Geared motor

- High-geared motor with torque sensor
  - \+ Very compact
  - \+ Motor can be operated at high speed
  - – High reflected inertia
  - – Low gearbox efficiency
  - – Impact loads can destroy the gear



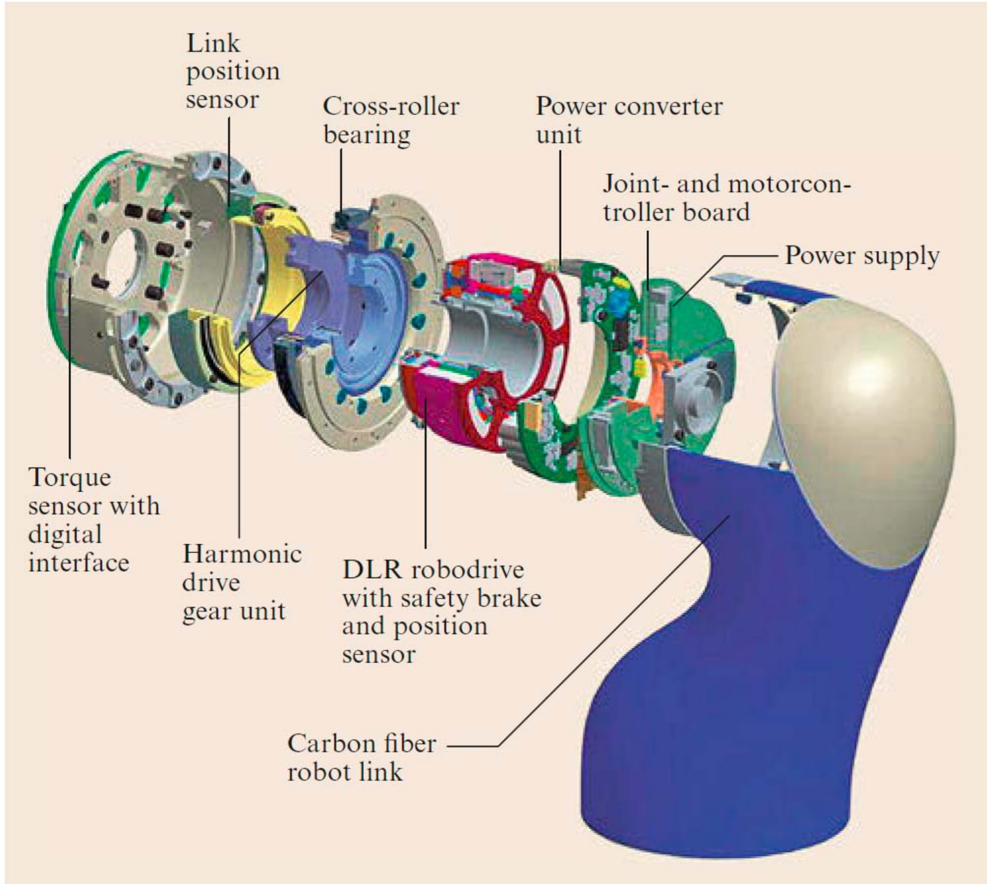
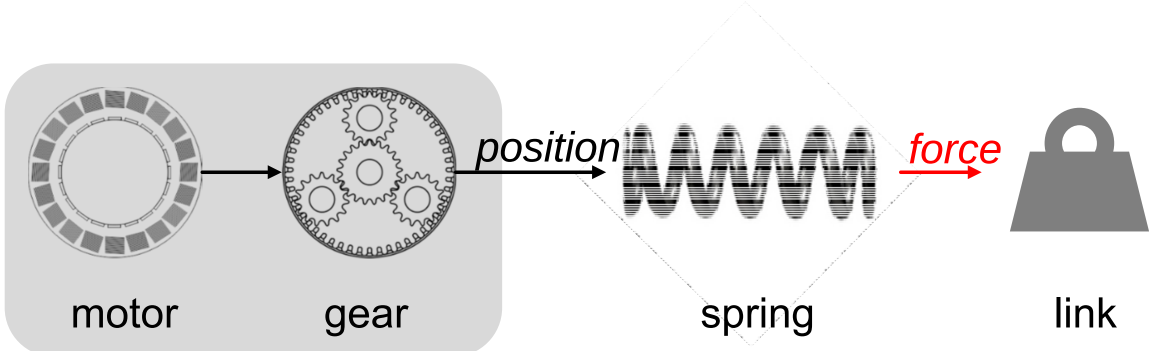


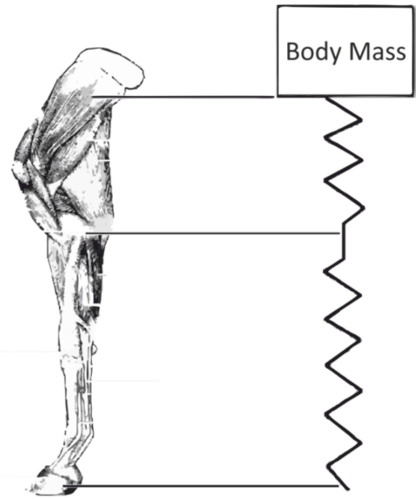
Fig. 11.8 Exploded view of a joint of the *DLR LWR-III* lightweight manipulator and its sensor suite

SCHAFT

Actuation principles in legged robots
Series Elastic Actuator

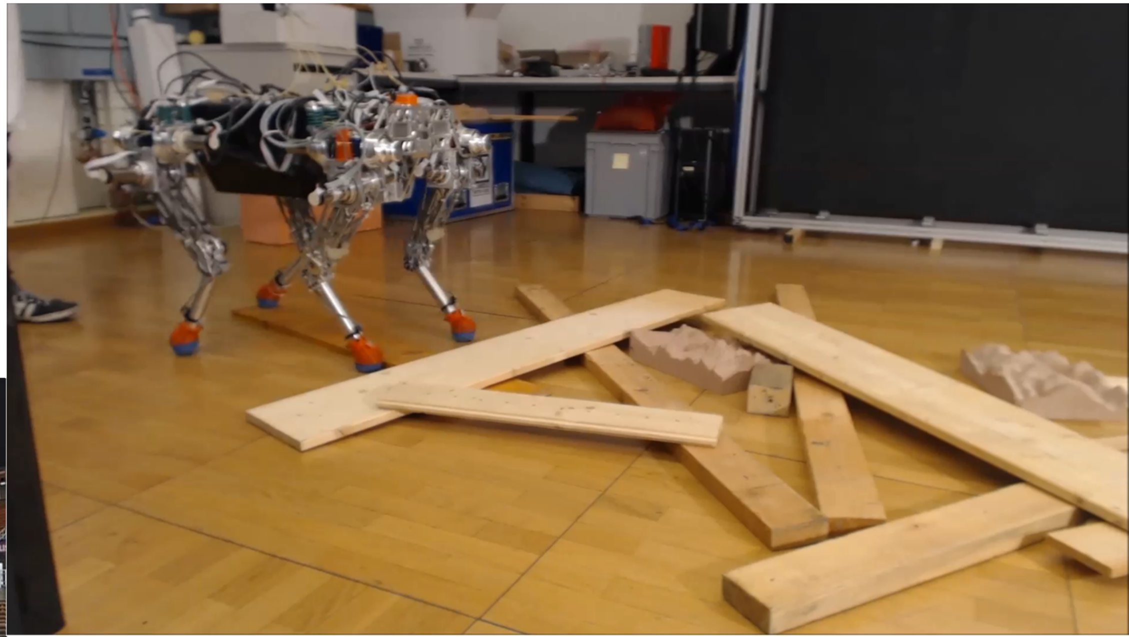
- High-geared motor with serial spring
  - \+ Very compact
  - \+ Precise torque regulation
  - \+ Decoupled actuator and link inertia
    - \+ robustness
  - Additional spring dynamics
    - Temporary energy storage
    - Power/speed amplification
  - – Low control bandwidth





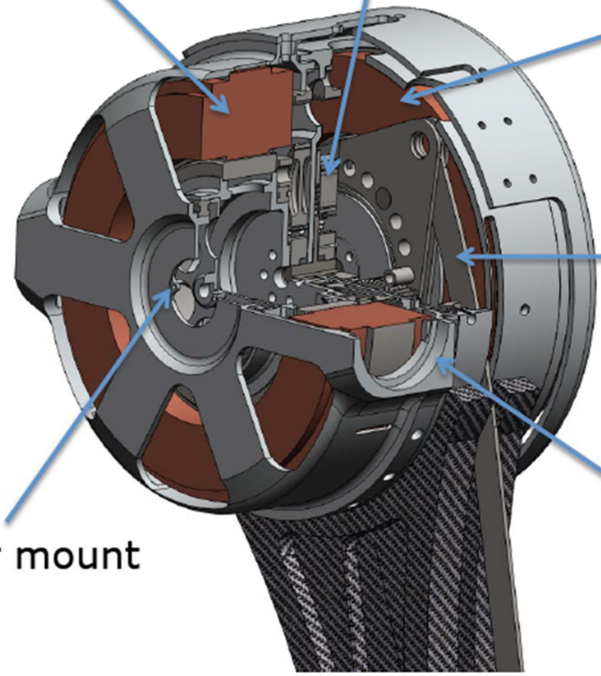
Actuation principles in legged robots

Series Elastic Actuator



Actuation principles in legged robots
Pseudo direct drive

- Low-geared high-torque motor
  - Low reflected inertia due to low gear ratio
    - Impact robust
    - High speed and power
  - High-bandwidth current control ⇔ force control
  - Relatively big, hard to integrate

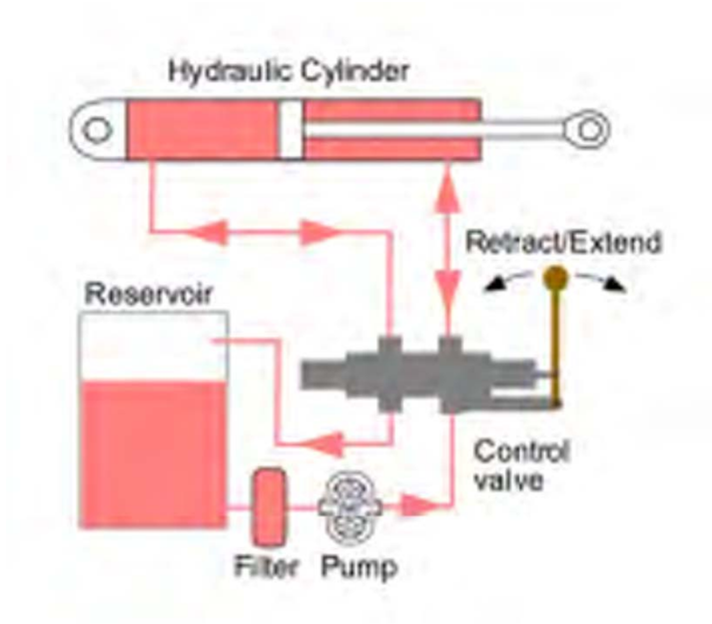


Actuation principles in legged robots
Pseudo direct drive

- Low-geared high-torque motor
  - Low reflected inertia due to low gear ratio
    - Impact robust
    - High speed and power
  - High-bandwidth current control ⇔ force control
  - Relatively big, hard to integrate

Actuation principles in legged robots
Hydraulic Actuation

- Hydraulic actuation
  - + High force at small size/weight
  - + Very rugged
  - + Pressure sensor provides direct force feedback
  - – Onboard pump required
  - – Hard to downscale
  - – Energetically inefficient
  - – Can leak



P_max = 200bar = 20N/mm
r=1cm
A=pi*r^2 = 3.14cm2=314mm2
=> Fmax = 6kN!!

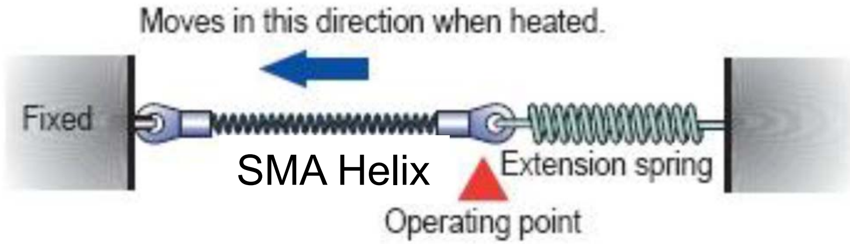
Actuation principles in legged robots
Hydraulic Actuation

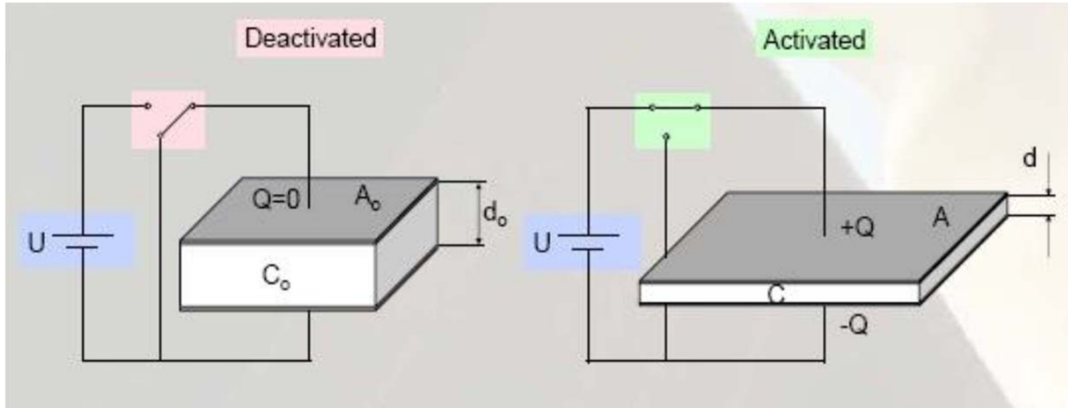
Actuation principles in legged robots
Pneumatics

- Pneumatic Muscle Actuators
  - \+ light weight
  - \+ high maximum contraction force
  - – often with off-board pump
  - – works only in contraction
  - – highly non-linear contraction-force-pressure characteristics
  - – difficult to control
  - – can be quite loud

Actuation principles in legged robots
Other types of actuators

- New, unconventional actuators types
  - Shape Memory Alloy (SMA)
  - Electro-Active Polymer (EAP)
  - Piezo-electric
- Open Issues
  - Low output force levels
  - Low displacement (strain)
  - Need kV power supplies
  - Low control bandwidth



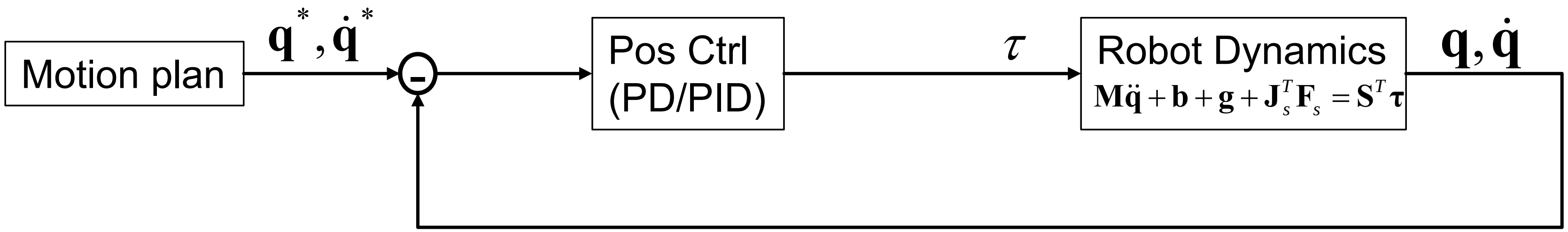


*Dielectric EAP actuator in deactivated (**left**) and activated state (**right**).*

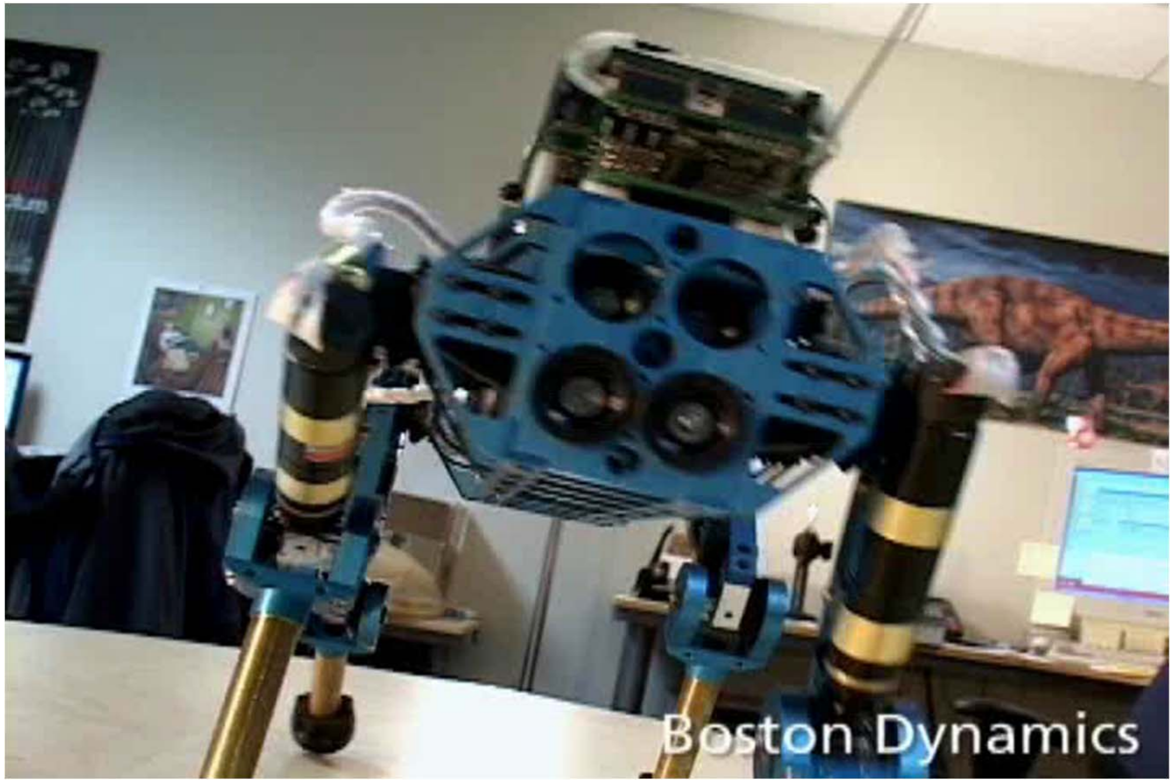
Control Concepts
an overview

- Kinematic control:
  - High-gain joint position trajectory tracking
- Impedance control with joint space inverse dynamics
  - Low-gain joint control with model compensation
- Task-space inverse dynamics control
  - Directly regulating in «task space»
- Virtual model control
  - dynamic control of a quasistatic system

Motion planning and high-gain kinematic trajectory following



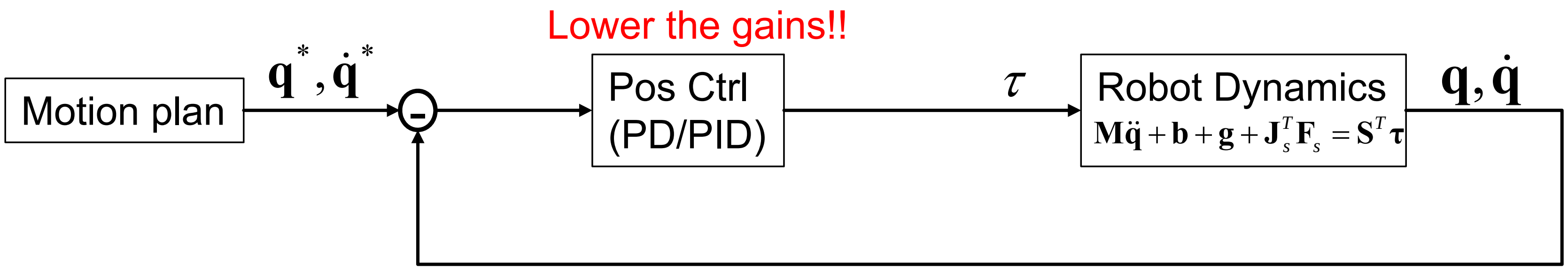
Motion planning and high-gain kinematic trajectory following



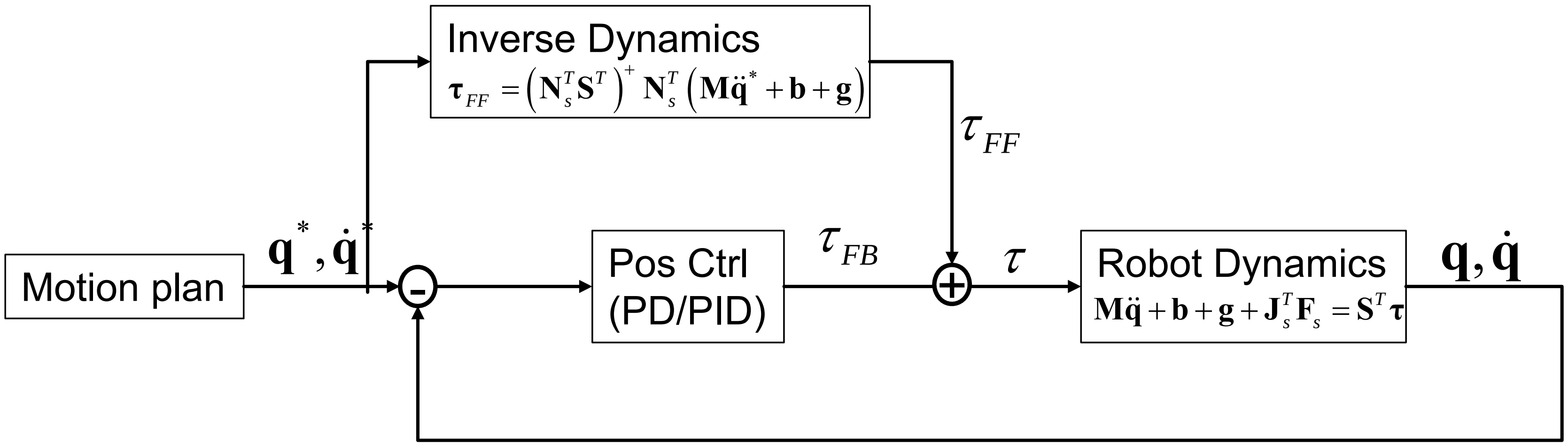
Motion planning and high-gain kinematic trajectory following

Unperceived/unplanned obstacles

Low-gain joint control with model compensation



Low-gain joint control with model compensation



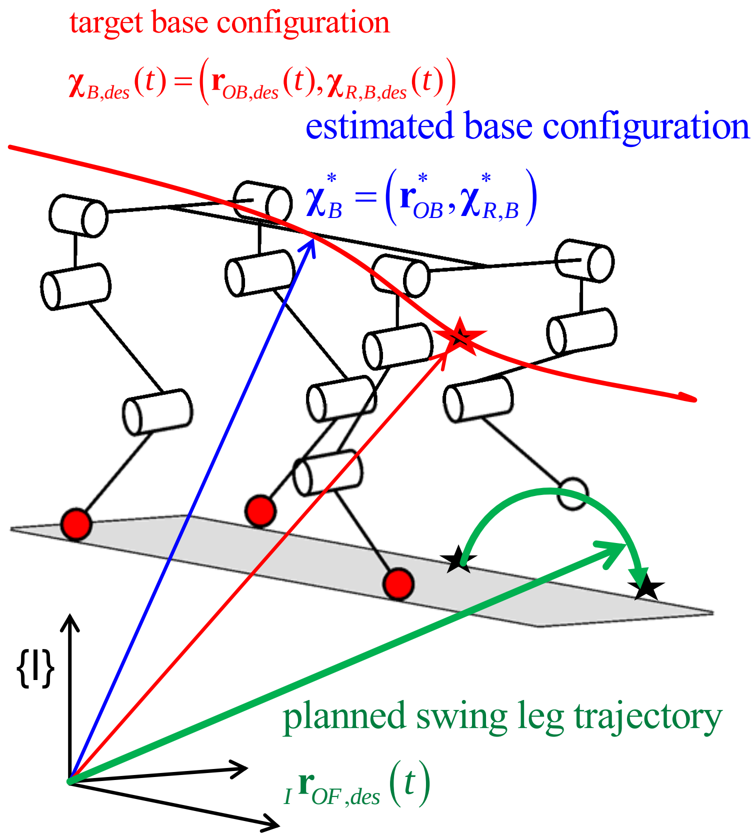
Low-gain kinematic trajectory following + Inv. Dynamics

Unperceived/unplanned obstacles

Inverse dynamics control
Joint acceleration from multiple objectives

- Adjust joint torques to
  - track the swing leg
  - to move the base
  - ensure contact constraint

$\Rightarrow$ fully defines the motion of the system
12 actuated + 6 unactuated = 18 DOF
6 motion + 9 constraints + 3 swing leg = 18



- Inverse dynamics control

Task-space inverse dynamics control

solving ID in task space

Locomotion as Multi-task Optimization Problem

- Write inverse dynamics as constraint (prioritized) optimization

  - Step 1: move base

    $$\min_{\ddot{\mathbf{q}}} \left\| \dot{\mathbf{w}}_{B,des}(t) - \mathbf{J}_B \ddot{\mathbf{q}} - \dot{\mathbf{J}}_B \dot{\mathbf{q}} \right\|$$

    s.t.

    $\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g} + \mathbf{J}_c^T \mathbf{F}_c = \mathbf{S}^T \boldsymbol{\tau}$ <= equation of motion holds

    $\mathbf{J}_B \ddot{\mathbf{q}} + \dot{\mathbf{J}}_B \dot{\mathbf{q}} = \mathbf{0}$ <= contact constraint holds

    $\mathbf{F}_{c,n_i} > F_{n,\min}$ <= minimal normal contact force

    $\mu \mathbf{F}_{c,n_i} > \left\| \mathbf{F}_{c,t_i} \right\|_2$ <= contact force in friction cone

  - Step 2: move swing leg

    $$\min_{\ddot{\mathbf{q}}} \left\| \ddot{\mathbf{r}}_{OF,des}(t) - \mathbf{J}_F \ddot{\mathbf{q}} - \dot{\mathbf{J}}_F \dot{\mathbf{q}} \right\|$$

    s.t.

    $c_1 = \ddot{\mathbf{x}}_{B,des}(t) - \mathbf{J}_B \ddot{\mathbf{q}} - \dot{\mathbf{J}}_B \dot{\mathbf{q}}$ <= higher priority task is not influenced

    $\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g} + \mathbf{J}_c \mathbf{F}_c = \mathbf{S}^T \boldsymbol{\tau}$ <= equation of motion holds

    $\mathbf{F}_{c,n_i} > F_{n,\min}$ <= minimal normal contact force

    $\mu \mathbf{F}_{c,n_i} > \left\| \mathbf{F}_{c,t_i} \right\|_2$ <= contact force in friction cone

  - Last step: minimize e.g torque $\min \left\| \boldsymbol{\tau} \right\|$ or tangential contact forces $\min \left\| \mathbf{F}_{s,t_i} \right\|$
    s.t. all other task are still fulfilled

Virtual Model Control (with gravity compensation)

Pratt et. al. 1997

- Create forces as if external spring-dampers would be attached

1. Find contact forces that produce the reaction to all external forces

$$\begin{pmatrix} \mathbf{F}_{c_1} \\ \vdots \\ \mathbf{F}_{c_{n_c}} \end{pmatrix} = \begin{bmatrix} \mathbb{I} & \cdots & \mathbb{I} \\ [\mathbf{r}_{c1}]_\times & \cdots & [\mathbf{r}_{c_{n_c}}]_\times \end{bmatrix}^+ \begin{bmatrix} \sum \mathbf{F}_{g_i} - \sum \mathbf{F}_{vi} \\ \sum \mathbf{r}_{g_i} \times \mathbf{F}_{g_i} - \sum \mathbf{r}_{vi} \times \mathbf{F}_{vi} \end{bmatrix}$$

2. Determine the desired joint torques

$$\boldsymbol{\tau} = -\sum_i \mathbf{J}_{bg_i}^T \mathbf{F}_{g_i} + \sum_i \mathbf{J}_{bv_i}^T \mathbf{F}_{v_i} + \sum_i \mathbf{J}_{bc_i}^T \mathbf{F}_{c_i}$$

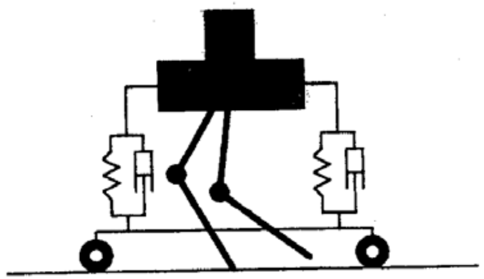


Figure 5: Spring Turkey with virtual granny walker mechanism.

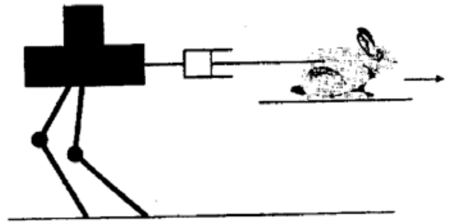


Figure 6: Spring Turkey with virtual dog track bunny mechanism.

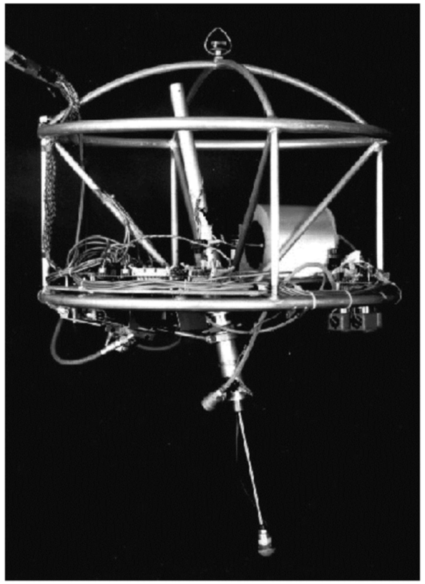
Virtual Model Control (with gravity compensation)

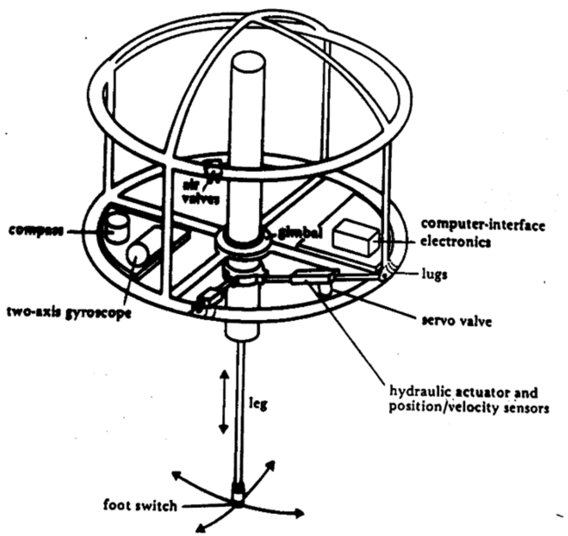
Stability

- How is stability defined?
  - Difference of static vs dynamic stability
  - Limit cycle analysis: look at running on a step-to-step basis

Dynamic Locomotion
SLIP principles in robotics

- Early Raibert hoppers (MIT leg lab) [1983]
  - Pneumatic piston
  - Hydraulic leg “angle” orientation





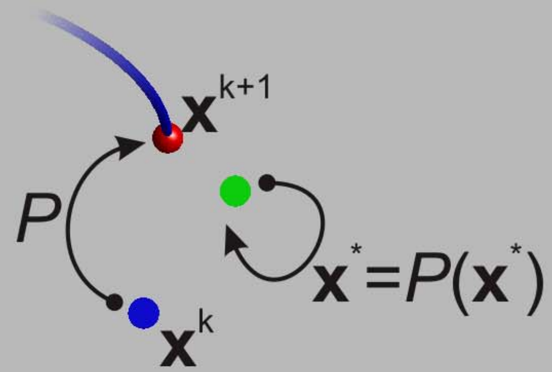
From Raibert Hopper to Humanoids and Quadrupeds

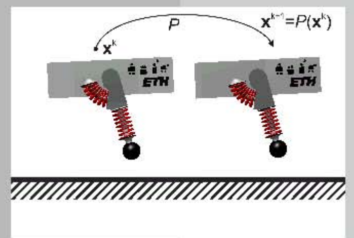
MIT and CMU Leg Lab (1980ies)

Marc Raibert, Gill Pratt, Jerry Pratt, Hugh Herr, Russ Tedrake, Jessica Hodgins, Martin Bühler,…

Analyzing Stability through Limit Cycles

- Poincaré Map $\mathbf{x}_{k+1} = P\left(\mathbf{x}_k\right)$
- Fix-Point $\mathbf{x}^* = P\left(\mathbf{x}^*\right)$
- Linearization of mapping $\Delta\mathbf{x}_{k+1} = \dfrac{\partial P}{\partial \mathbf{x}} \Delta\mathbf{x}_k = \mathbf{\Phi}\Delta\mathbf{x}_k$
- The system is stable iff: $\lambda_i\left(\mathbf{\Phi}\right) < 1$

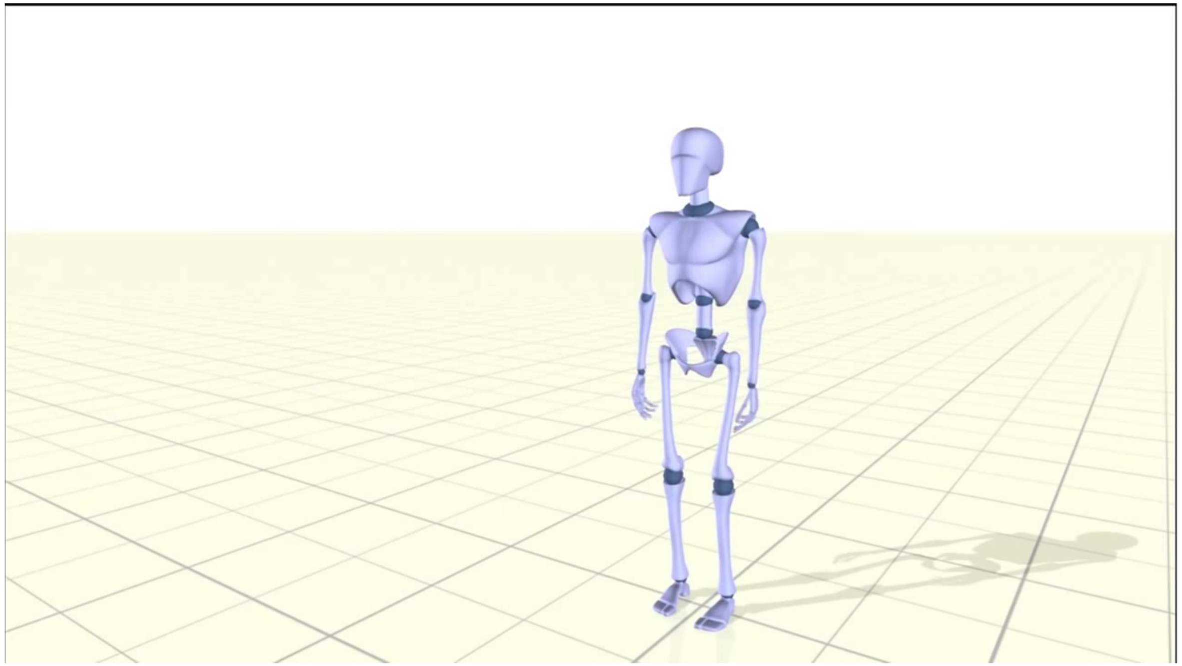




[C. David Remy, 2011]

Stability and Control of Locomotion
Example of a biped

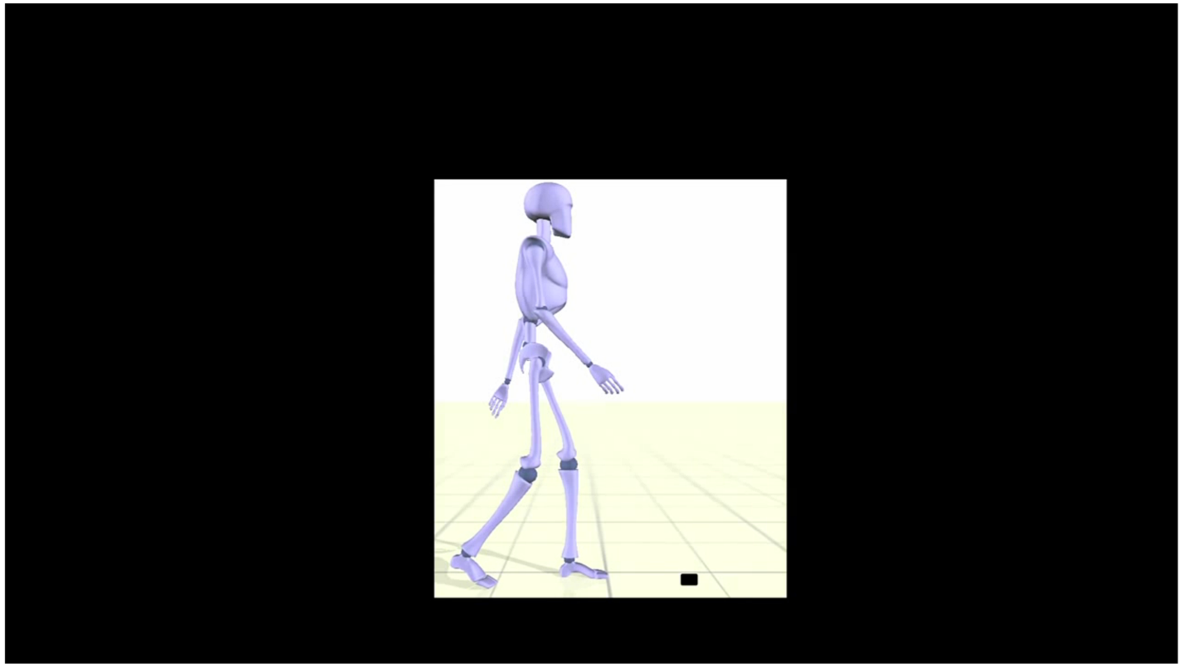
- External disturbances lead to instability



[Coros 2012]

Stability and Control of Locomotion
Example of a biped

- External disturbances lead to instability
- Foot step control for fall recovery



[Coros 2012]

Stability and Control of Locomotion

Example of a quadruped

- Dynamic gaits
  - Inverted pendulum

[Raibert 1986]

$$\mathbf{r}_F = \frac{1}{2}\dot{\mathbf{r}}_{HC,des}T_{st} + k_R^{FB}\left(\dot{\mathbf{r}}_{HC,des} - \dot{\mathbf{r}}_{HC}\right)\sqrt{h_{HC}}$$