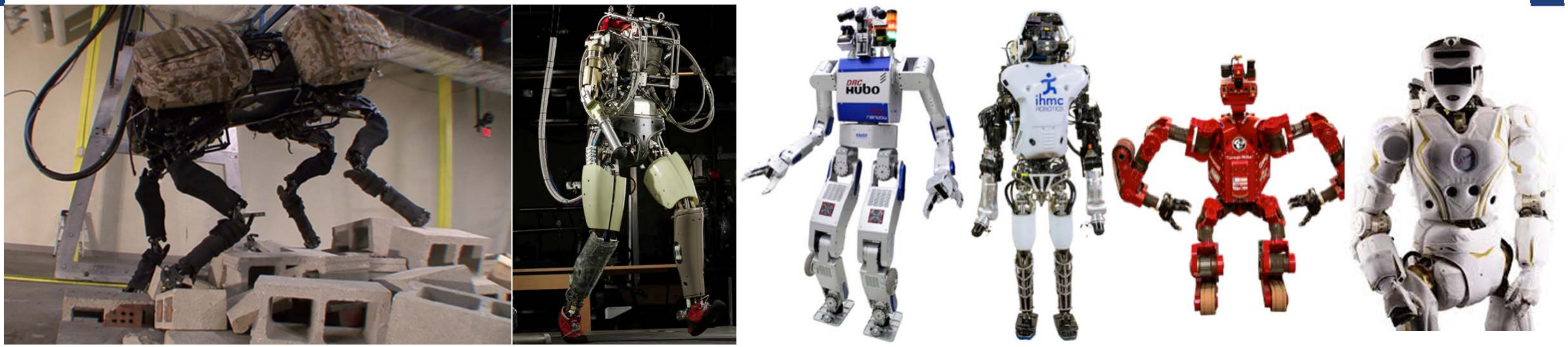


Lecture «Robot Dynamics»: Legged Robots

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)

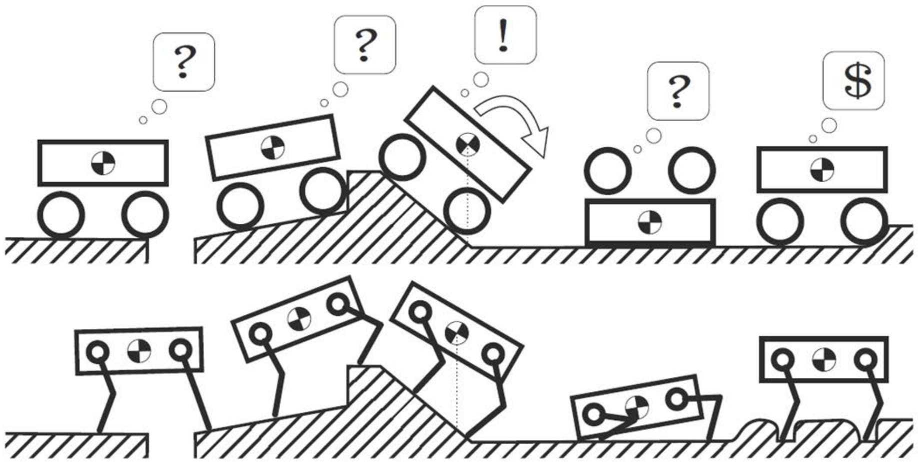
office hour: LEE H303 Friday 12.15 – 13.00

Marco Hutter, Roland Siegwart, and Thomas Stastny

	Topic		Title
20.09.2016	Intro and Outline	L1	Course Introduction; Recapitulation Position, Linear Velocity, Transformation
27.09.2016	Kinematics 1	L2	Rotation Representation; Introduction to Multi-body Kinematics
28.09.2016	Exercise 1a	E1a	Kinematics Modeling the ABB arm
04.10.2016	Kinematics 2	L3	Kinematics of Systems of Bodies; Jacobians
05.10.2016	Exercise 1b	L3	Differential Kinematics and Jacobians of the ABB Arm
11.10.2016	Kinematics 3	L4	Kinematic Control Methods: Inverse Differential Kinematics, Inverse Kinematics; Rotation Error; Multi-task Control
12.10.2016	Exercise 1c	E1b	Kinematic Control of the ABB Arm
18.10.2016	Dynamics L1	L5	Multi-body Dynamics
19.10.2016	Exercise 2a	E2a	Dynamic Modeling of the ABB Arm
25.10.2016	Dynamics L2	L6	Dynamic Model Based Control Methods
26.10.2016	Exercise 2b	E2b	Dynamic Control Methods Applied to the ABB arm
01.11.2016	Legged Robots	L7	Case Study and Application of Control Methods
08.11.2016	Rotorcraft 1	L8	Dynamic Modeling of Rotorcraft I
15.11.2016	Rotorcraft 2	L9	Dynamic Modeling of Rotorcraft II & Control
16.11.2016	Exercise 3	E3	Modeling and Control of Multicopter
22.11.2016	Case Studies 2	L10	Rotor Craft Case Study
29.11.2016	Fixed-wing 1	L11	Flight Dynamics; Basics of Aerodynamics; Modeling of Fixed-wing Aircraft
30.11.2016	Exercise 4	E4	Aircraft Aerodynamics / Flight performance / Model derivation
06.12.2016	Fixed-wing 2	L12	Stability, Control and Derivation of a Dynamic Model
07.12.2016	Exercise 5	E5	Fixed-wing Control and Simulation
13.12.2016	Case Studies 3	L13	Fixed-wing Case Study
20.12.2016	Summery and Outlook	L14	Summery; Wrap-up; Exam

Why legged robots?

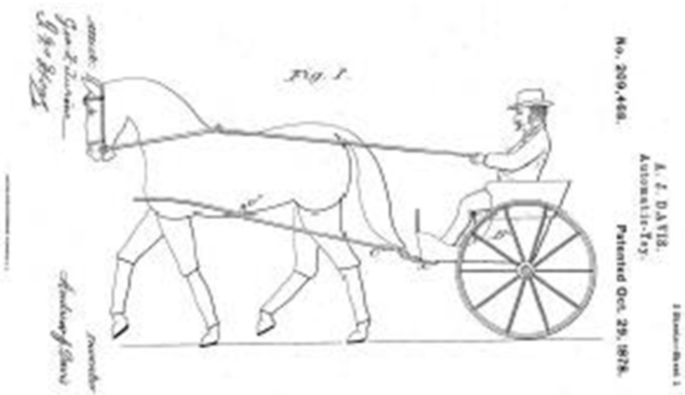
- Legged systems can overcome many obstacles

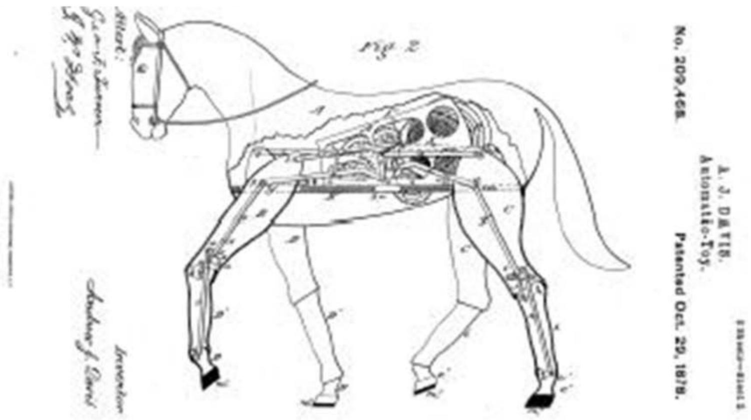


- But it is quite hard to achieve this since
  - many DOFs must be controlled in a coordinated way
  - the robot must interact with (uncertain) terrain

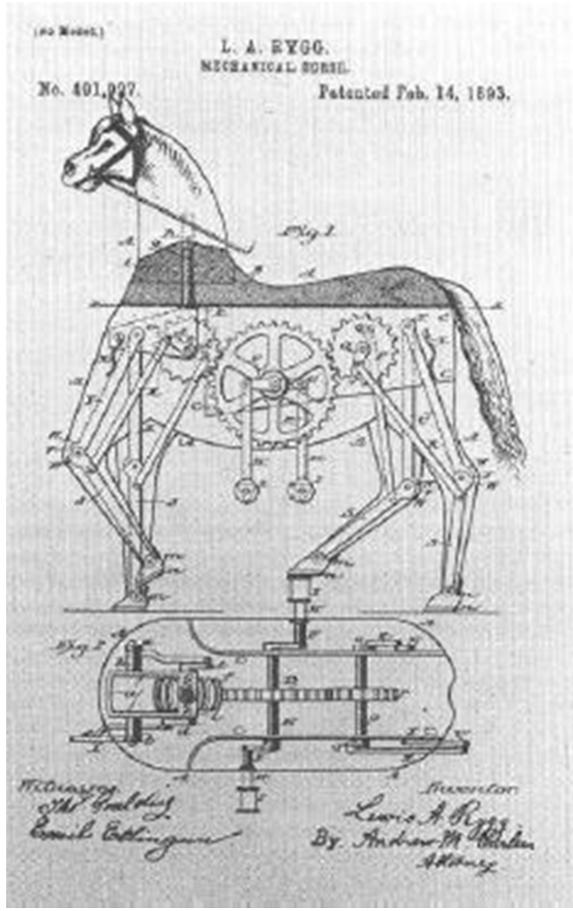
History of Legged Robotics

Walking Mechanism – First patents





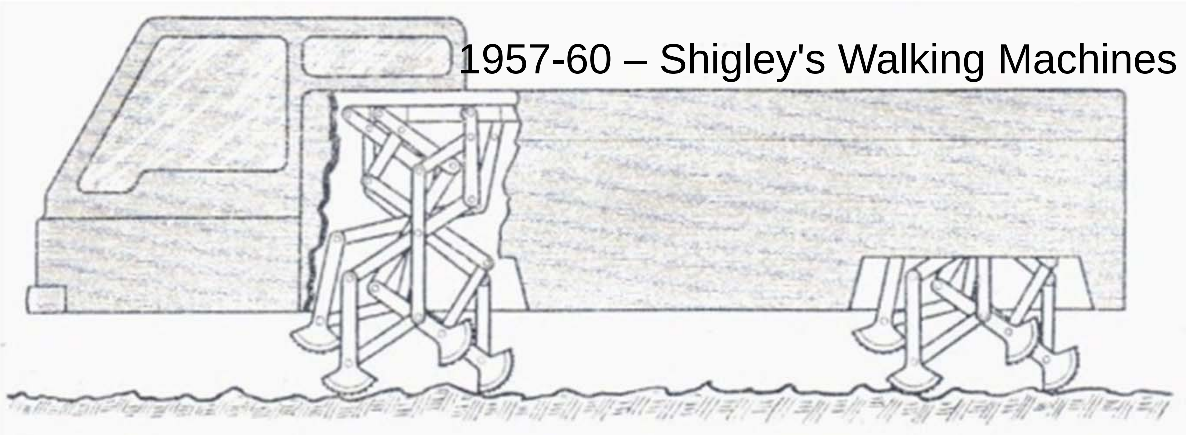
- Davis, 1878



Rygg, 1893

Walking Mechanisms

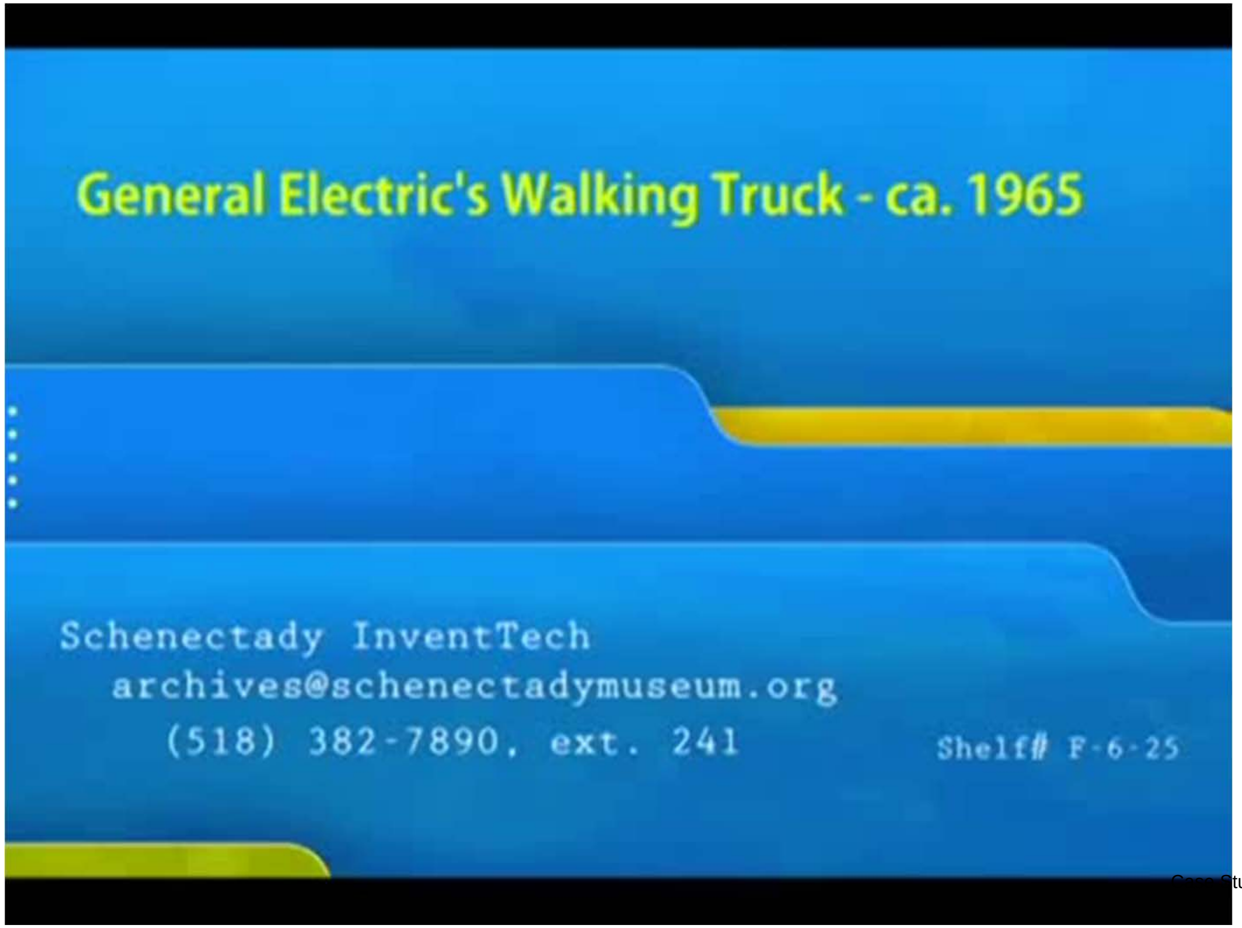
1957-60 – Shigley's Walking Machines



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



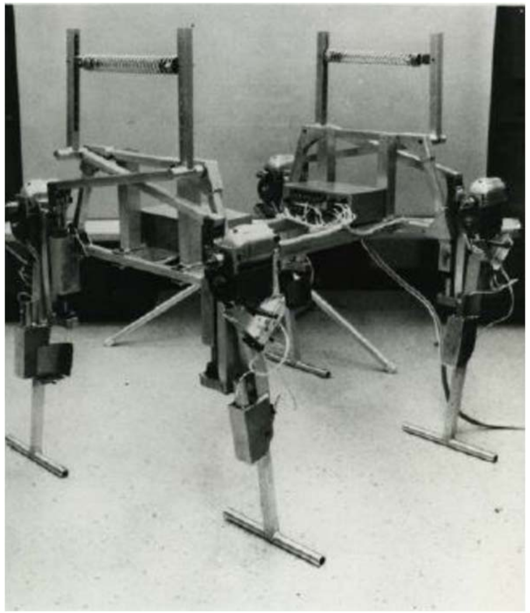


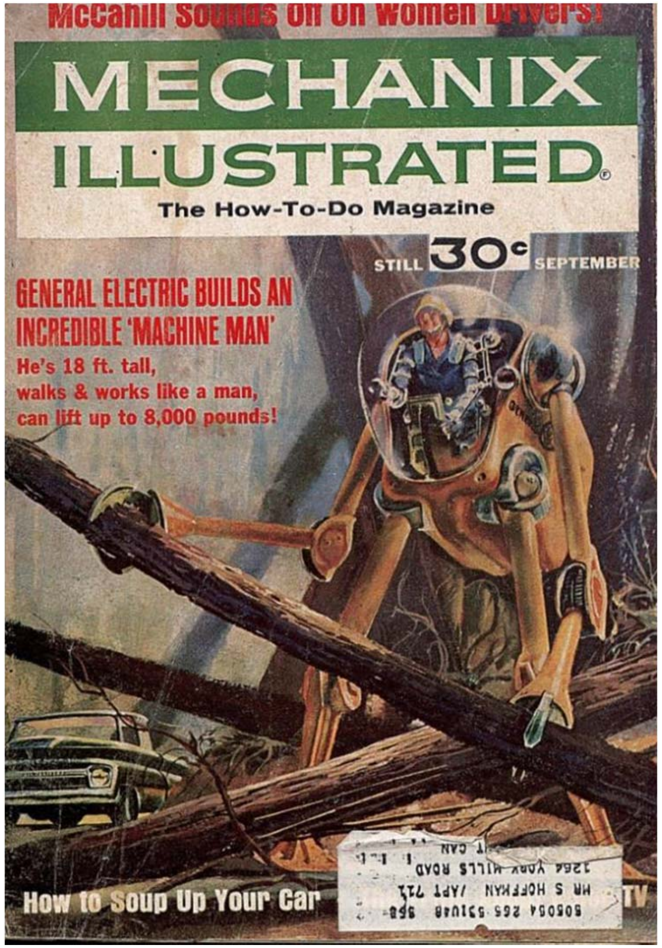


History of Legged Robotics

Phony Pony, GE Hardiman and many more…

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





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

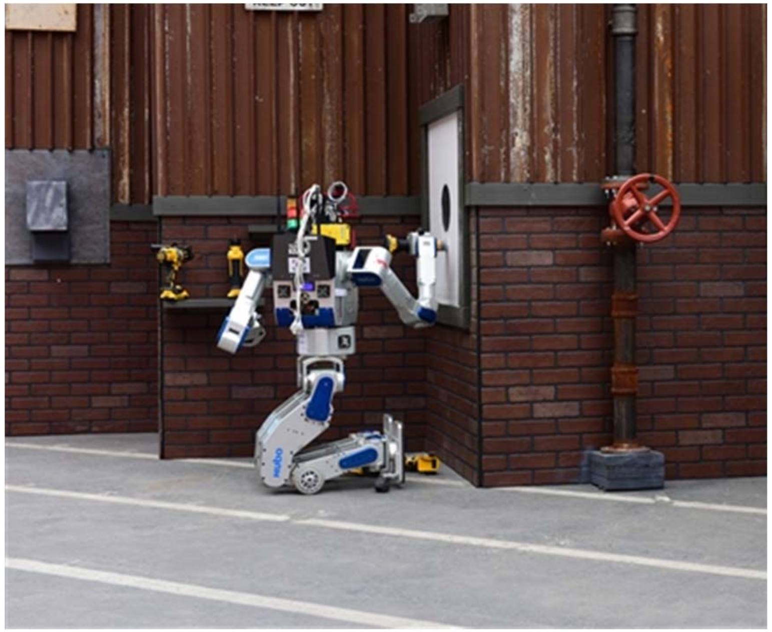
ETH zürich

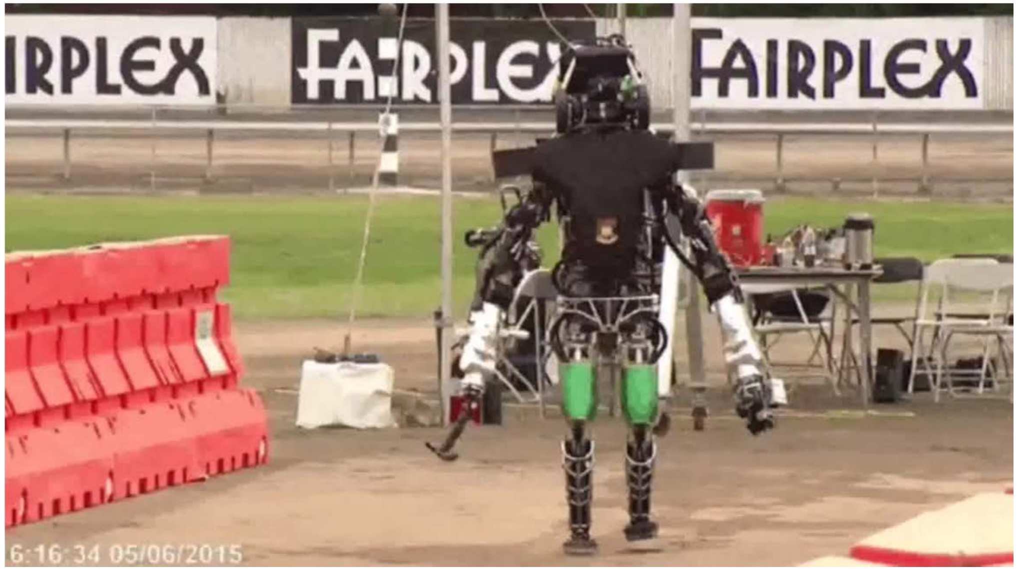
Legged Robotics

Where are we really and what are the challenges?

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

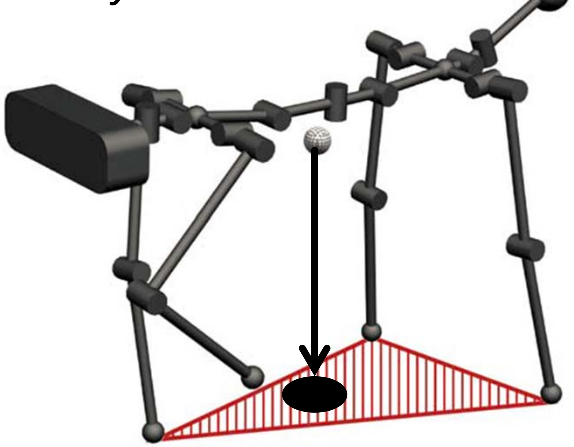
- Walking is still difficult





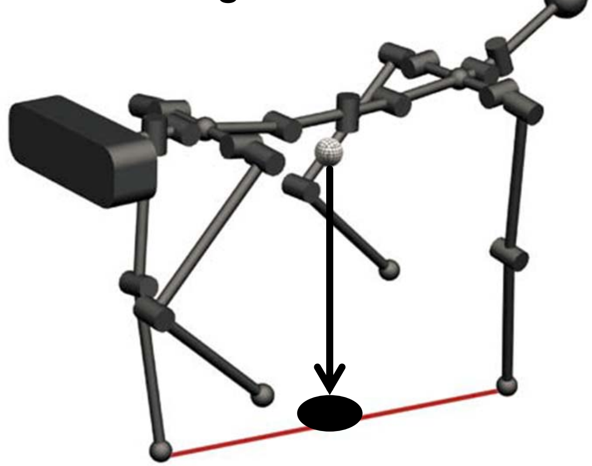
Static vs. Dynamic Stability

- Statically stable



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

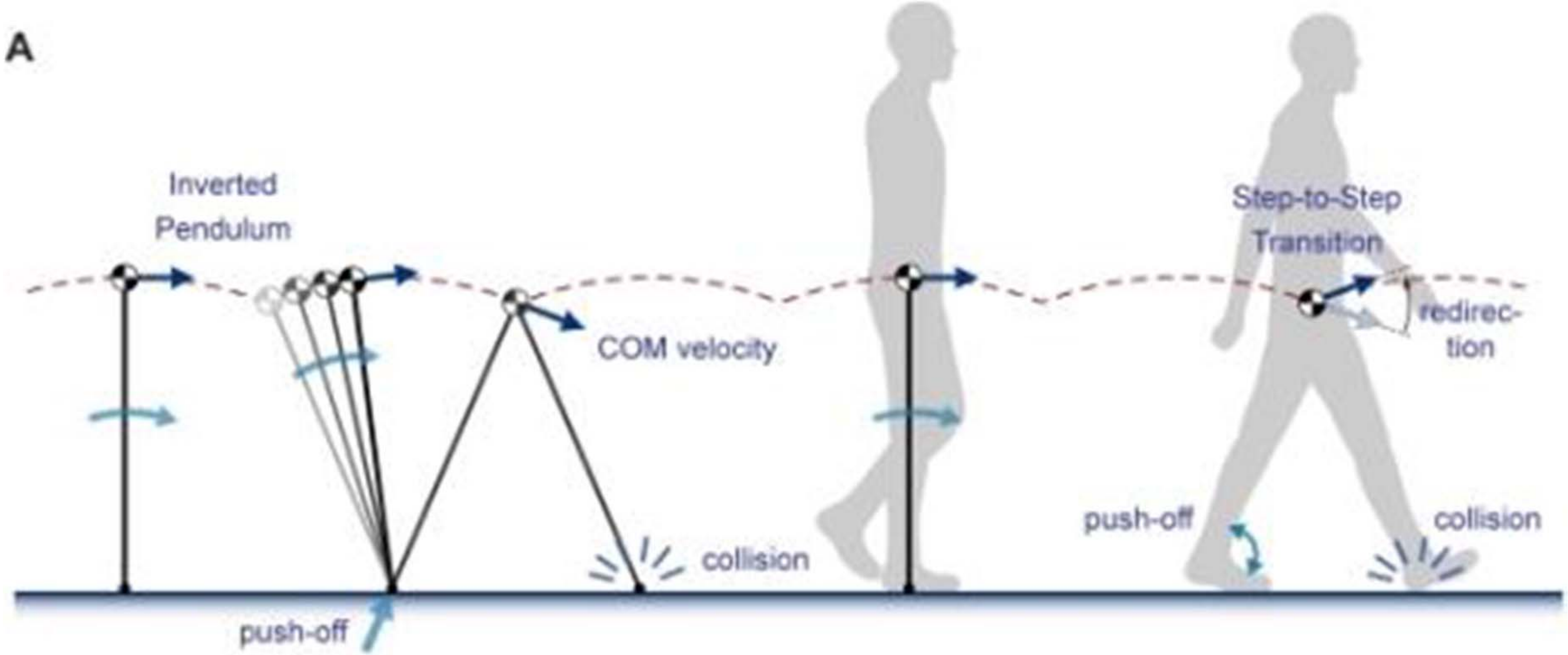
- Dynamic walking



  - 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

Static walking principles
Inverted Pendulum

- Static walking can be represented by inverted pendulum

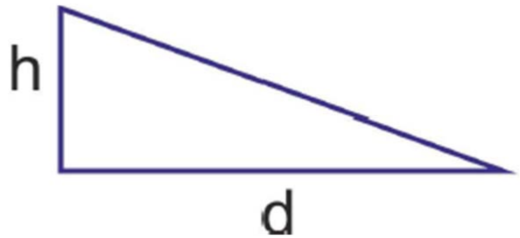


Static walking principles
Inverted Pendulum

- Static walking can be represented by inverted pendulum
- Exploit this in so-called passive dynamic walkers

Energetically very efficient

$$COT = \frac{E_{used}}{m \cdot g \cdot d} = \frac{m \cdot g \cdot h}{m \cdot g \cdot d} = \frac{h}{d}$$



Static walking principles
Inverted Pendulum

- Static walking can be represented by inverted pendulum
- Exploit this in so-called passive dynamic walkers
- Add small actuation to walk on flat ground

Cornell Ranger

Total distance:	65.24 km
Total time:	30:49:02
Power:	16.0 W
COT:	0.28

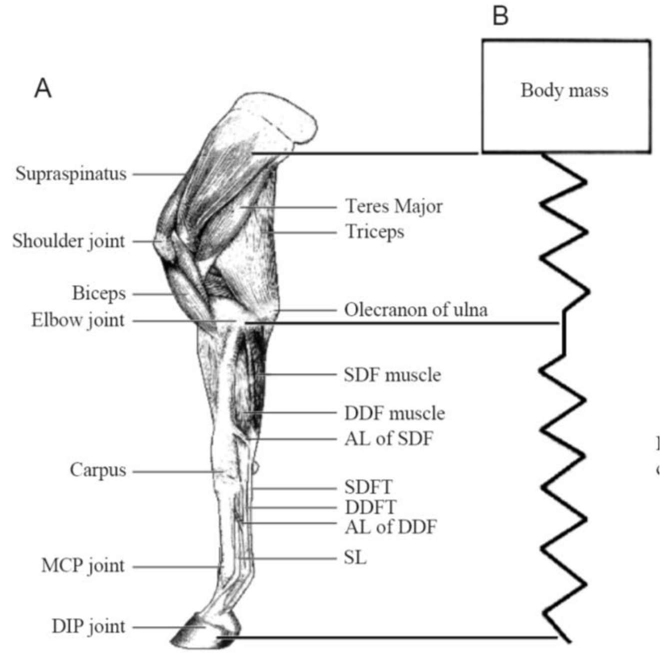
Dynamic locomotion
Leg Structure

Dynamic locomotion

Leg Structure

- Leg during running is NOT and inverted pendulum
- Spring loaded inverted pendulum (SLIP)
  - ☑ are robust against collisions
  - ☑ can better handle uncertainties
  - ☑ can temporarily store energy
  - ☑ reduce peak power

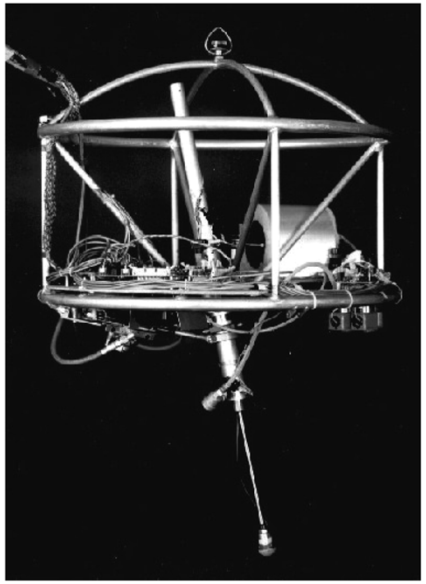
  [Alexander 1988,1990,2002,2003]

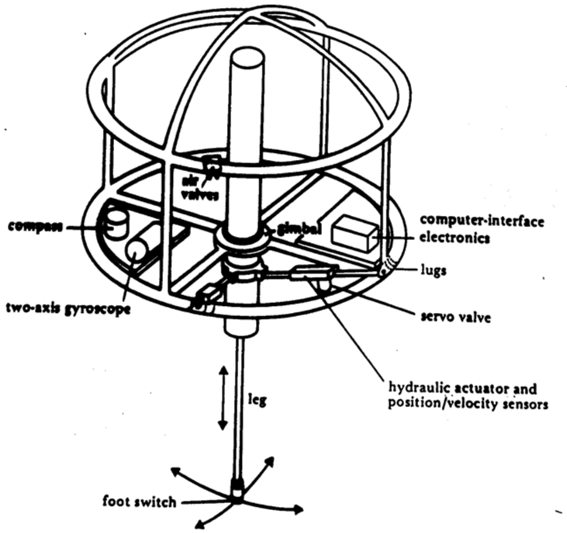


McGuigan & Wilson, 2003 – *J. Exp. Bio.*

Dynamic Locomotion
SLIP principles in robotics

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





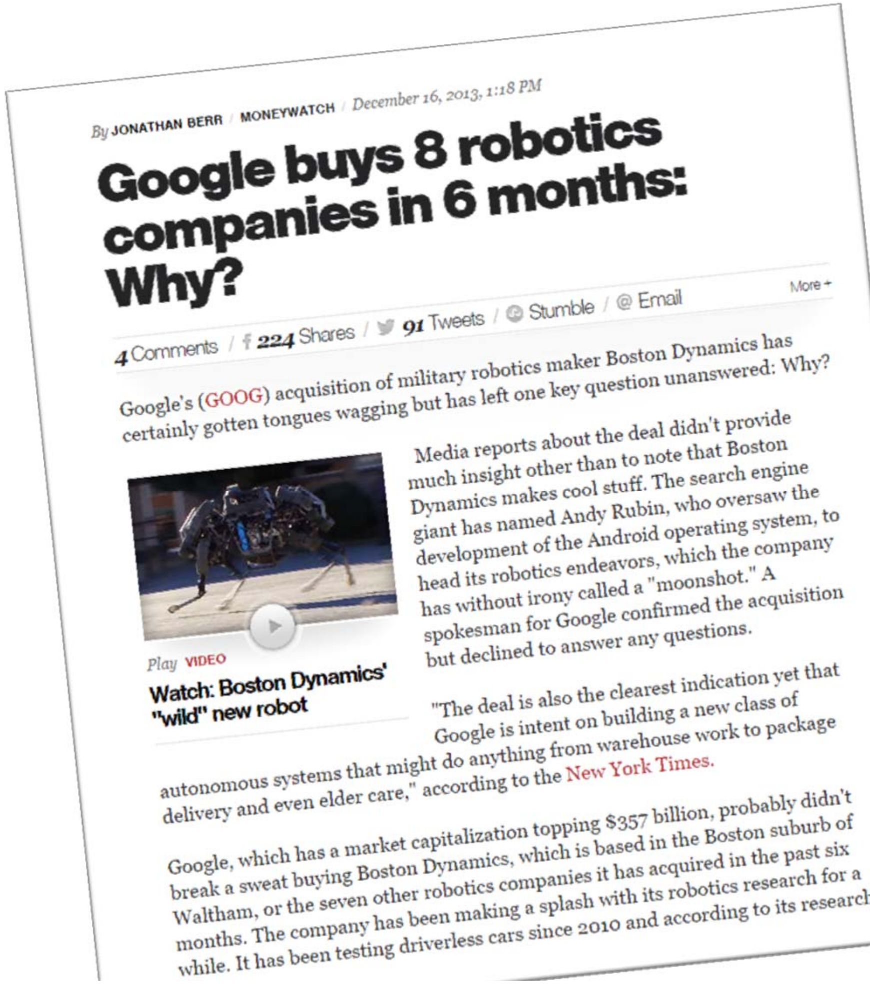
From Raibert Hopper to Humanoids and Quadrupeds

MIT and CMU Leg Lab (1980ies)

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

From Raibert Hopper to Humanoids and Quadrupeds
Boston Dynamics

- Founded 1992
- Big Dog V1 (2005), Big Dog V2 (2008)



By JONATHAN BERR / MONEYWATCH / December 16, 2013, 1:18 PM

Google buys 8 robotics companies in 6 months: Why?

4 Comments / 224 Shares / 91 Tweets / Stumble / Email · More +

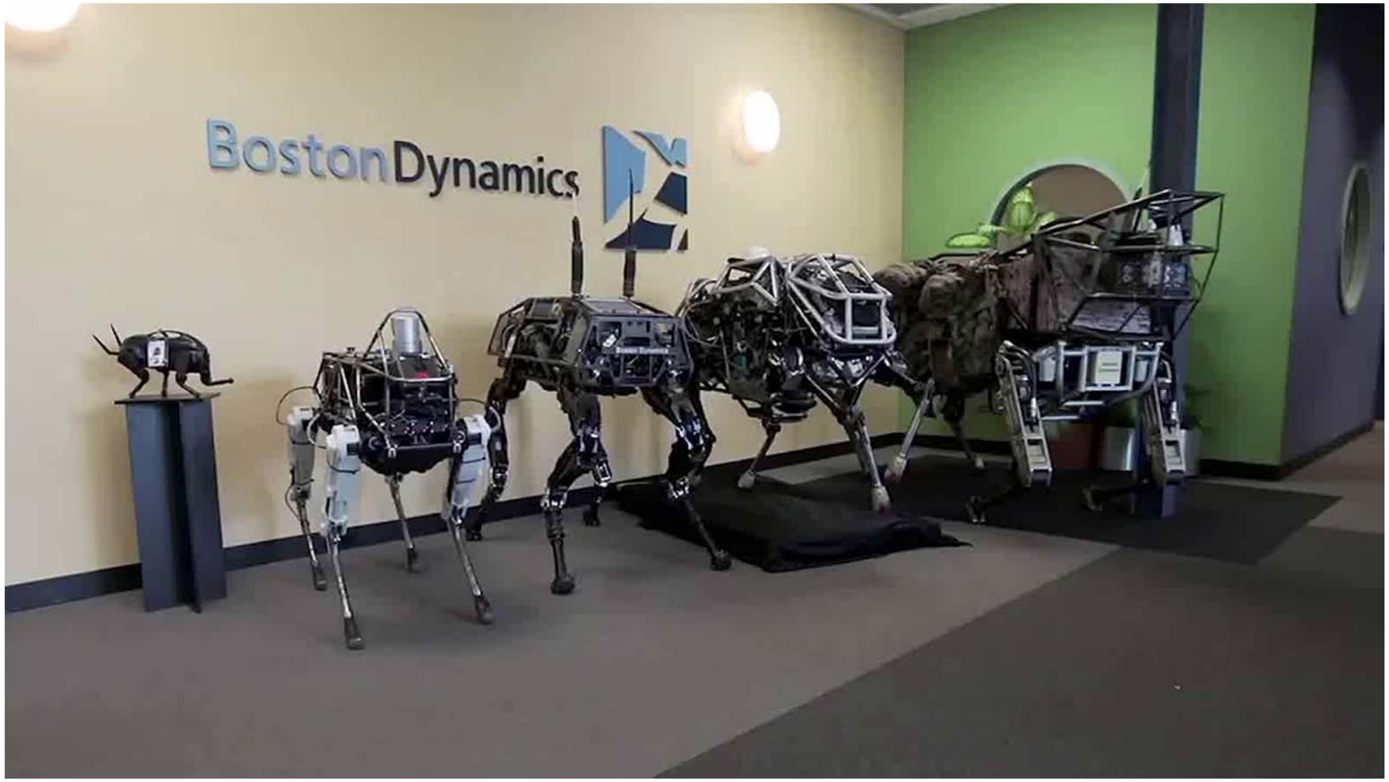
Google's (GOOG) acquisition of military robotics maker Boston Dynamics has certainly gotten tongues wagging but has left one key question unanswered: Why?

Media reports about the deal didn't provide much insight other than to note that Boston Dynamics makes cool stuff. The search engine giant has named Andy Rubin, who oversaw the development of the Android operating system, to head its robotics endeavors, which the company has without irony called a "moonshot." A spokesman for Google confirmed the acquisition but declined to answer any questions.

Play VIDEO
Watch: Boston Dynamics' "wild" new robot

"The deal is also the clearest indication yet that Google is intent on building a new class of autonomous systems that might do anything from warehouse work to package delivery and even elder care," according to the New York Times.

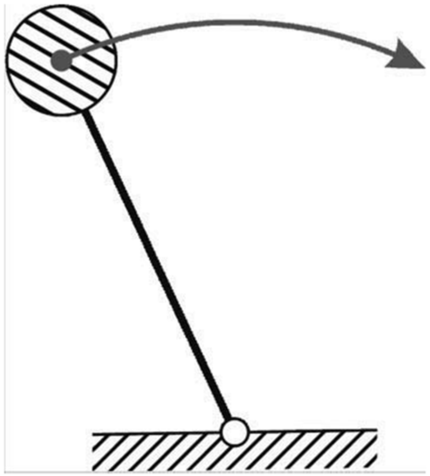
Google, which has a market capitalization topping $357 billion, probably didn't break a sweat buying Boston Dynamics, which is based in the Boston suburb of Waltham, or the seven other robotics companies it has acquired in the past six months. The company has been making a splash with its robotics research for a while. It has been testing driverless cars since 2010 and according to its research

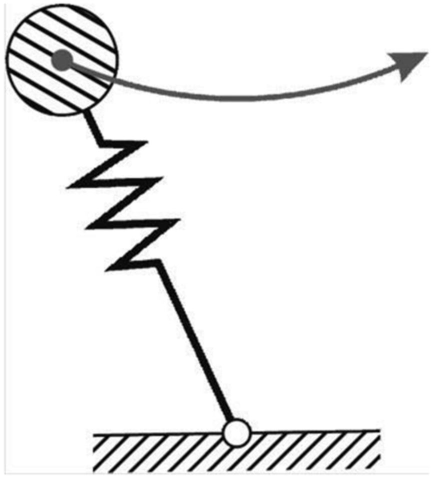

Boston Dynamics


Boston Dynamics
Boston Dynamics

Understanding Locomotion
Summary

- Static locomotion (IP) ⇔ Dynamic Locomotion (SLIP)

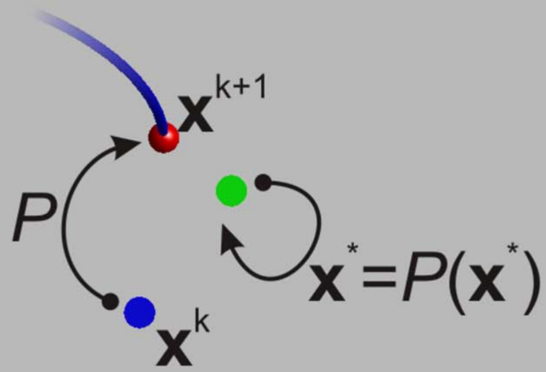


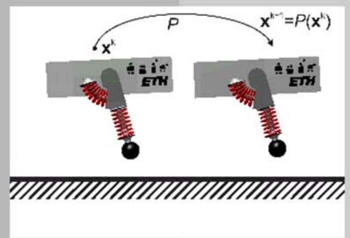


- How to determine stability?
- How to control (actively stabilize)?

Analyzing Stability through Limit Cycles

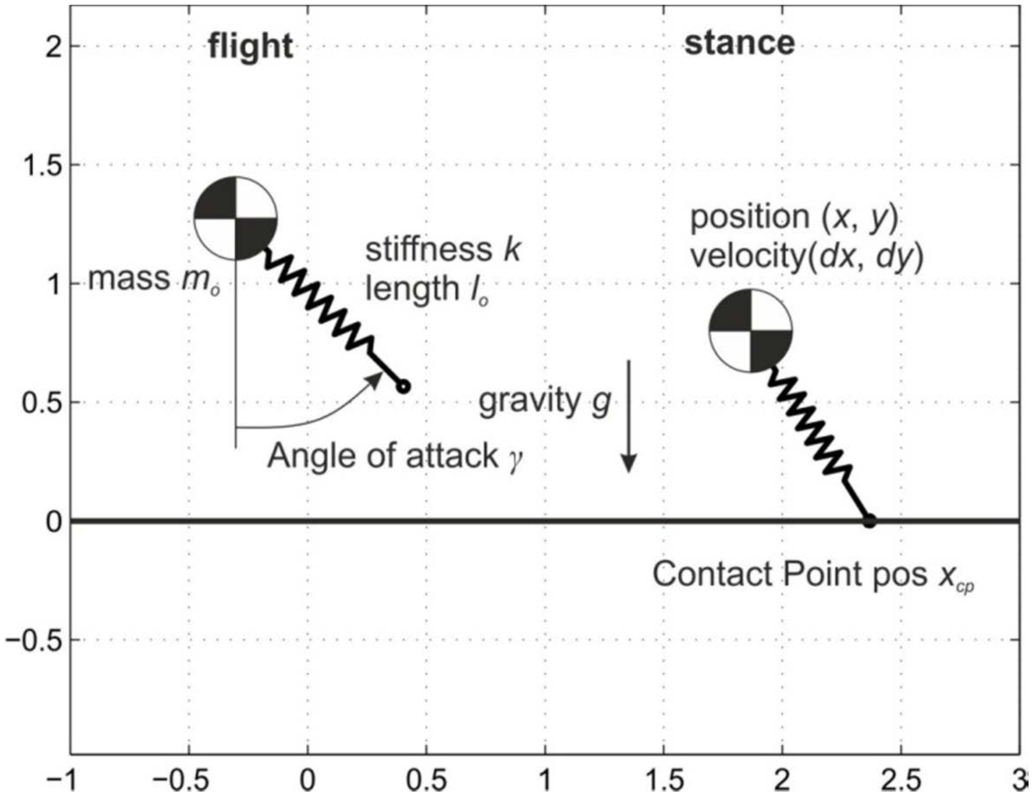
- Poincaré Map $\mathbf{x}_{k+1} = P\left(\mathbf{x}_k\right)$
- Fix-Point $\mathbf{x}^* = P\left(\mathbf{x}^*\right)$
- Linearization of mapping $\Delta\mathbf{x}_{k+1} = \frac{\partial P}{\partial \mathbf{x}}\Delta\mathbf{x}_k = \mathbf{\Phi}\Delta\mathbf{x}_k$
- The system is stable iff: $\lambda_i\left(\mathbf{\Phi}\right)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





[C. David Remy, 2011]

Dynamic Locomotion
Stability Analysis



- Point mass: $\mathbf{q} = \begin{bmatrix} x \\ y \end{bmatrix}$
- Equation of Motion:
  - flight

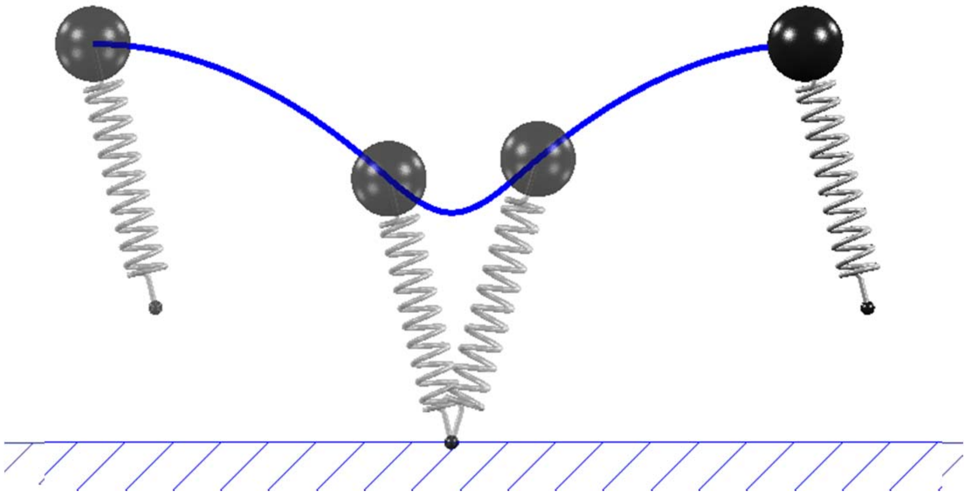
    $$\ddot{\mathbf{q}} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} 0 \\ -g \end{bmatrix}$$

  - stance

    $$\ddot{\mathbf{q}} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} \dfrac{-F^x_{spring}}{m_o} \\ \dfrac{F^y_{spring}}{m_o} - g \end{bmatrix}$$

$$\mathbf{F}_{spring} = f(\gamma, k, l)$$

Stability of Locomotion
Limit Cycle Analysis



- Point mass: $\mathbf{q} = \begin{bmatrix} x \\ y \end{bmatrix}$
- Equation of Motion:
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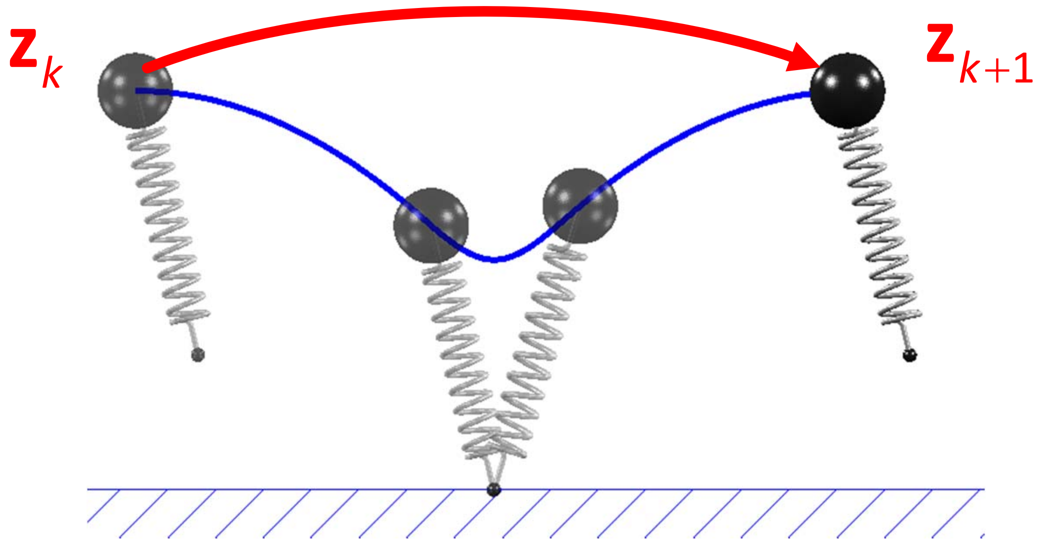
$$\ddot{\mathbf{q}} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} 0 \\ -g \end{bmatrix}$$

  - stance

$$\ddot{\mathbf{q}} = \begin{bmatrix} \ddot{x} \\ \ddot{y} \end{bmatrix} = \begin{bmatrix} \dfrac{-F_{spring}^{x}}{m_o} \\ \dfrac{F_{spring}^{y}}{m_o} - g \end{bmatrix}$$

$$\mathbf{F}_{spring} = f(\gamma, k, l)$$

Stability of Locomotion
Limit Cycle Analysis



- Point mass: $\mathbf{q} = \begin{bmatrix} x \\ y \end{bmatrix}$
- System state

$$\mathbf{z} = \begin{bmatrix} x \\ y \\ \dot{x} \\ \dot{y} \end{bmatrix} \xrightarrow{\text{analysis at apex}} \mathbf{z} = \begin{bmatrix} y \\ \dot{x} \end{bmatrix}$$

- How does the state propagate from one apex to the next?

Stability of Locomotion
Limit Cycle Analysis

- Given the Poincaré mapping from one apex to the next

$$\mathbf{z}_{k+1} = P(\mathbf{z}_k)$$

  - P includes differential equations that cannot be analytically solved!

- Analyze periodic stability of a fixed point $\mathbf{z}^* = P(\mathbf{z}^*)$

- How can we do this? Linearization…

$$\mathbf{z}_{k+1} = \mathbf{z}^* + \Delta\mathbf{z}_{k+1} = P(\mathbf{z}^* + \Delta\mathbf{z}_k) = \underbrace{P(\mathbf{z}^*)}_{\mathbf{z}^*} + \left.\frac{\partial P}{\partial \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}^*} \cdot \Delta\mathbf{z}_k + \cancelto{\approx 0}{\left.\frac{\partial^2 P}{\partial \mathbf{x}^2}\right|_{\mathbf{x}=\mathbf{x}^*} \cdot \Delta\mathbf{z}_k^2} + \ldots$$

$$\Delta\mathbf{z}_{k+1} = \frac{\partial P}{\partial \mathbf{z}} \Delta\mathbf{z}_k = \mathbf{\Phi}\Delta\mathbf{z}_k$$

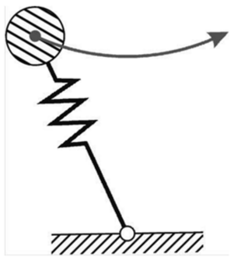
?

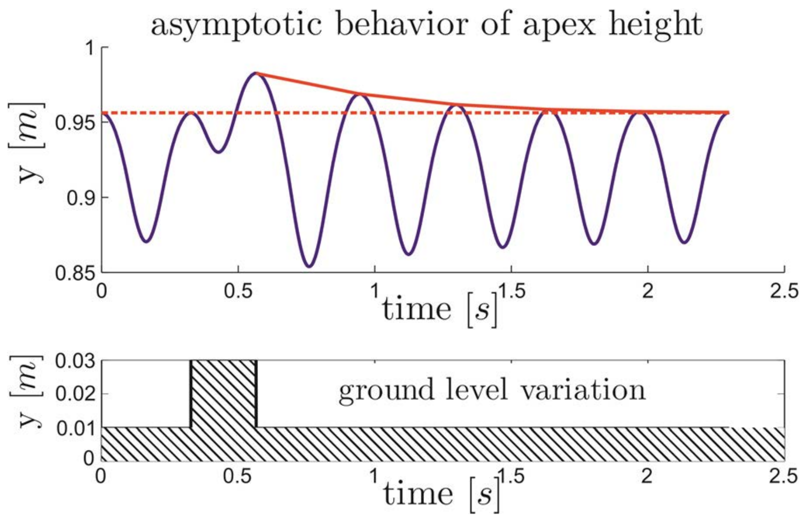
Stability of Locomotion
Numerical Limit Cycle Analysis

- Find the linearization of the Poincaré map around fix-point $$\begin{bmatrix} \Delta y_{k+1} \\ \Delta \dot{x}_{k+1} \end{bmatrix} = \left.\frac{\partial P}{\partial \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}^*} \cdot \begin{bmatrix} \Delta y_k \\ \Delta \dot{x}_k \end{bmatrix}$$
  - Choose $\Delta \mathbf{z}_k = \begin{bmatrix} \Delta y_k \\ \Delta \dot{x}_k \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} h$, with a small h
  - Simulate until the next apex, starting from $$\begin{bmatrix} y_{k+1} \\ \dot{x}_{k+1} \end{bmatrix} = P\left(\mathbf{z}^* + \begin{bmatrix} 1 \\ 0 \end{bmatrix} h \right)$$
  - Calculate $\left.\frac{\partial P}{\partial \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}^*} = \begin{bmatrix} \frac{y_{k+1} - y^*}{h} & * \\ \frac{\dot{x}_{k+1} - \dot{x}^*}{h} & * \end{bmatrix}$
  - Do the same thing for $\Delta \mathbf{z}_k = \begin{bmatrix} \Delta y_k \\ \Delta \dot{x}_k \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \end{bmatrix} h$

Stability of Locomotion
Numerical Limit Cycle Analysis

- The previous evaluation results in a 2x2 matrix $\left.\frac{\partial P}{\partial \mathbf{x}}\right|_{\mathbf{x}=\mathbf{x}^*}$
- Eigenvalue analysis:
  - System is energy conservative: $\lambda_1 = 1$
  - System can be
    - stable $|\lambda_2| < 1$
    - unstable: $|\lambda_2| > 1$

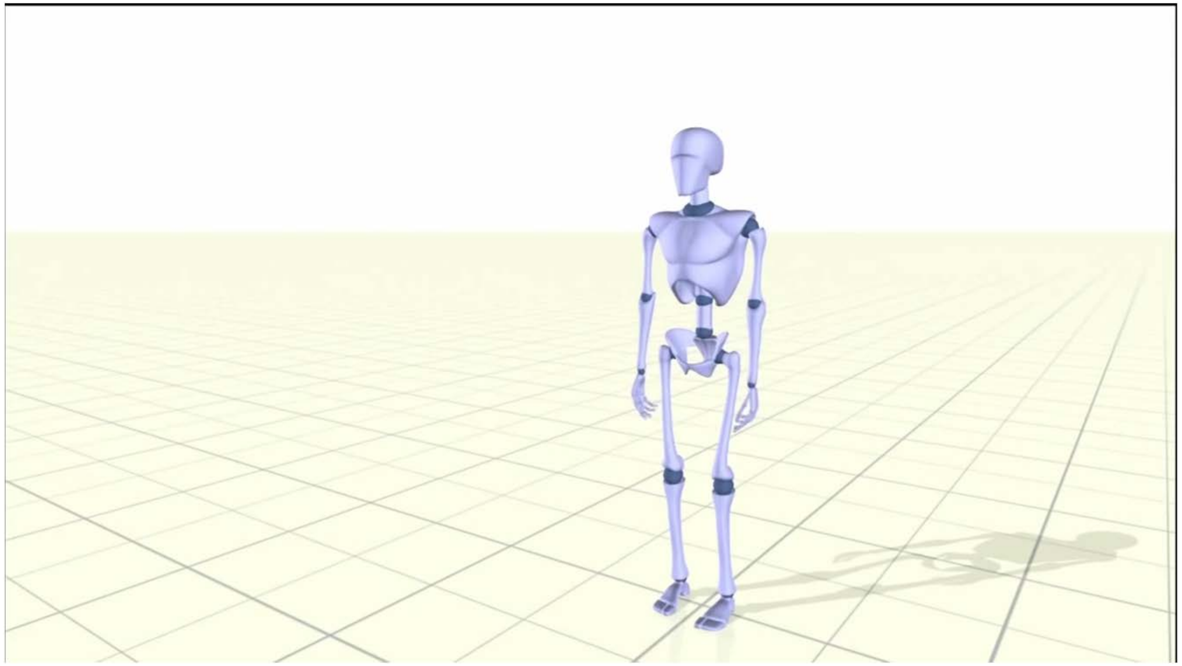




Stability and Control of Locomotion

Example of a biped

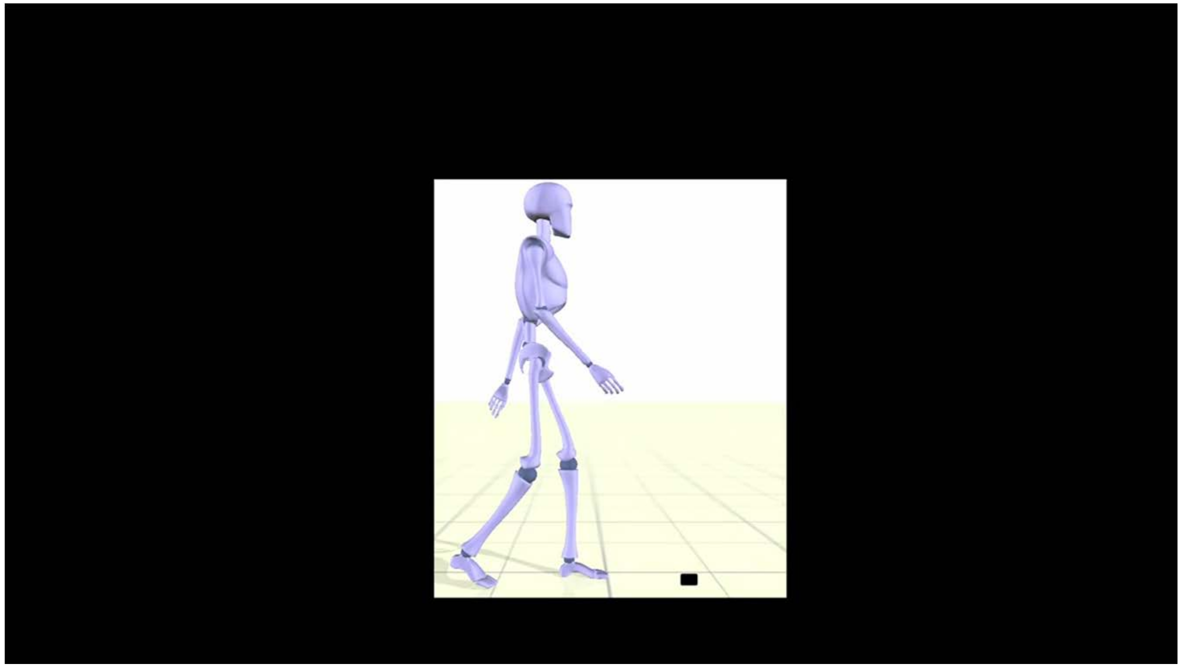
- External disturbances lead to instability



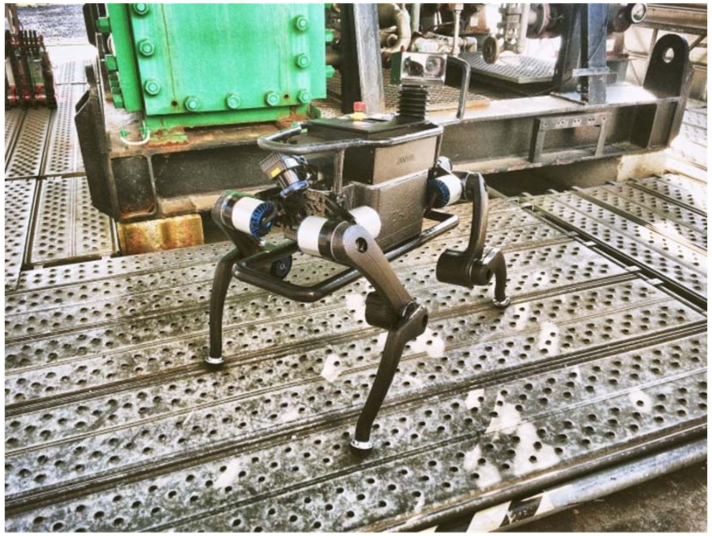
[Coros 2012]

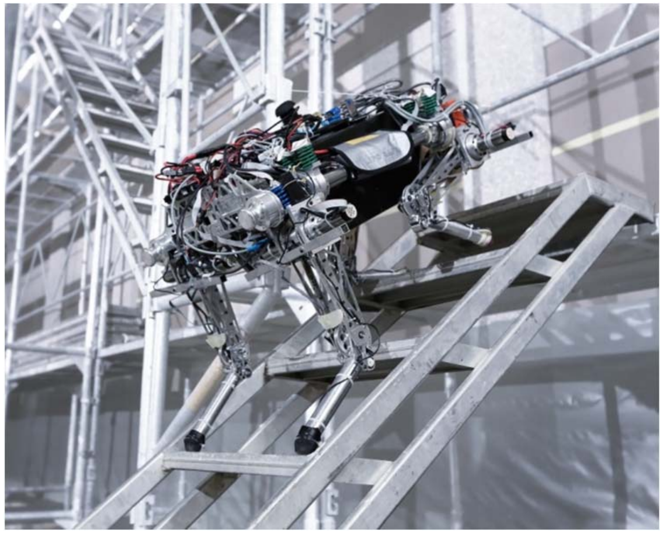
Stability and Control of Locomotion
Example of a biped

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



[Coros 2012]





Legged Robots for Challenging Environments

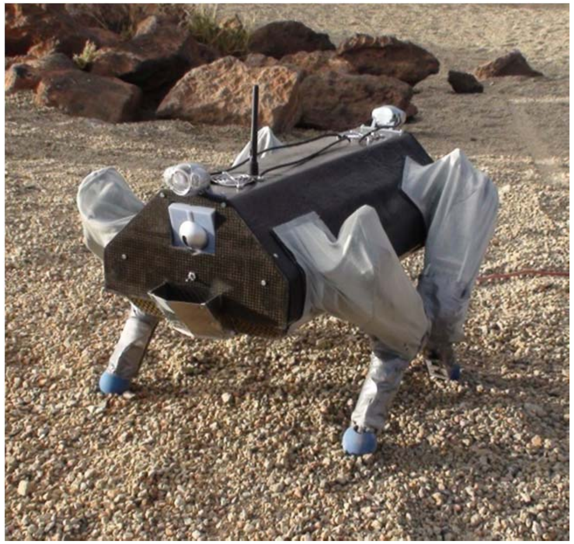
Marco Hutter
Robotic Systems Lab, ETH Zurich
28.10.2016

Legged Robots for Challenging Environments

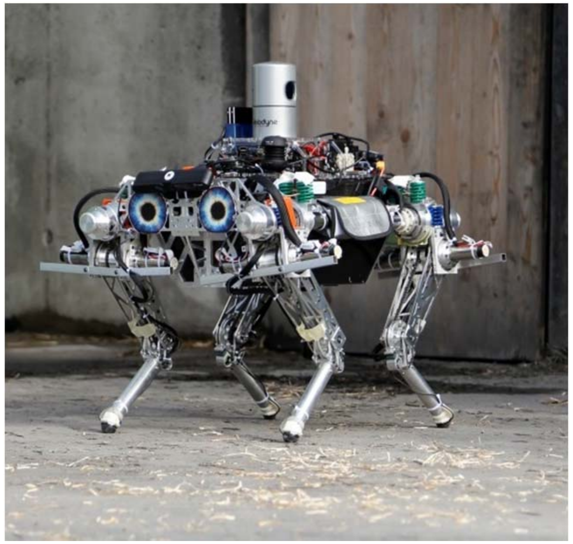
- Macerata, 2 days ago

Legged Robotics Research at ETH

2009 2012 2015



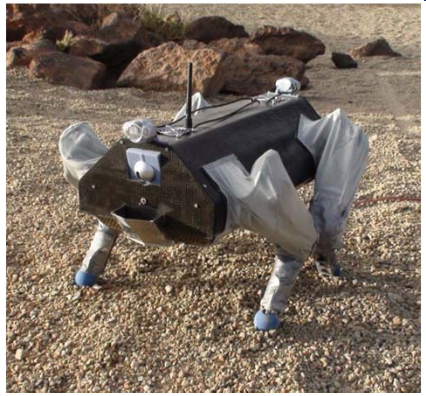
ALoF



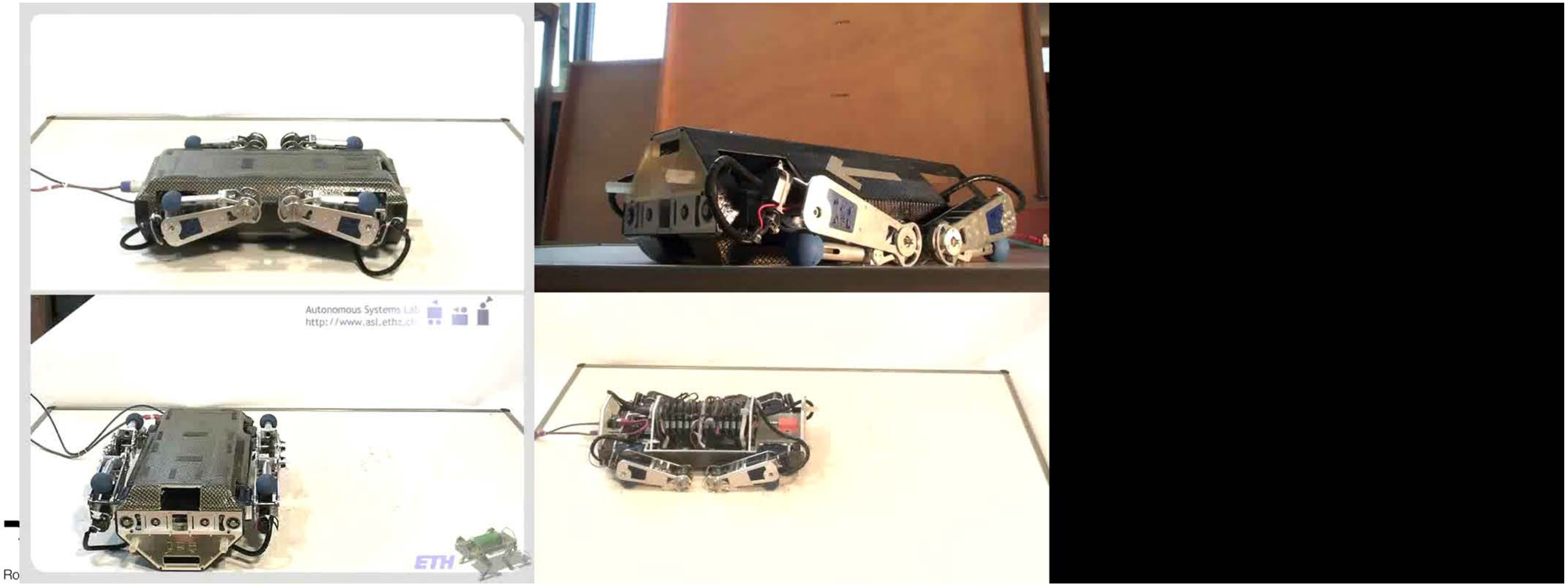
StarlETH

ANYmal

ALOF
a versatile quadruped robot



- High mobility
  - Clever design
  - Precise kinematic planning

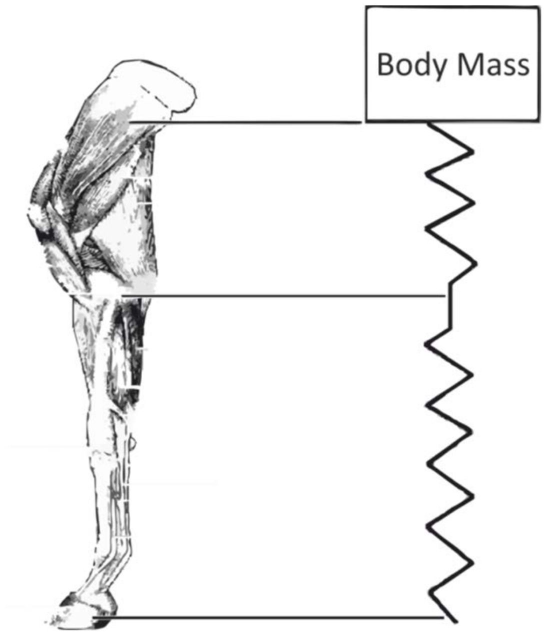


How to engineer a dog

Biomechanics of Animals
Compliance in muscles and tendons

- Muscle/tendon (mech. compliance)
  - Robustness
  - Energy storage
  - Power/speed amplification
  - Force control instead of position

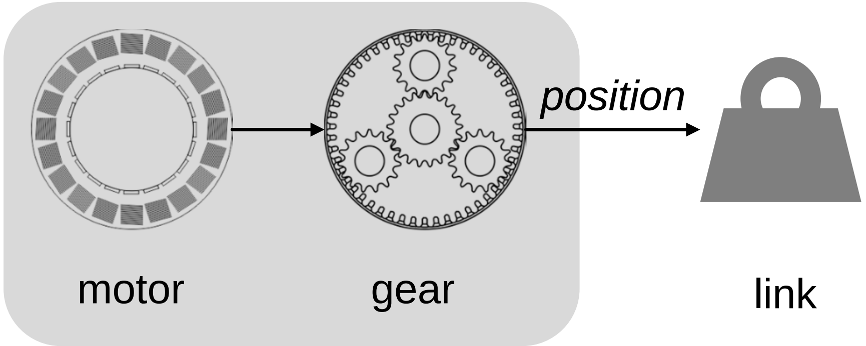
[Alexander 1988,1990,2002,2003]



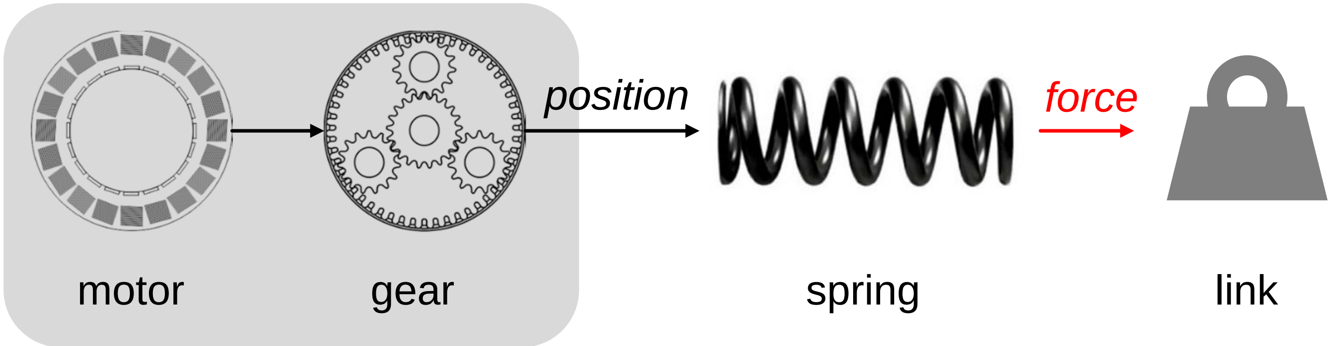
From Position to Force Controlled Systems

Compliance in robotic actuation

- Kinematic, position control

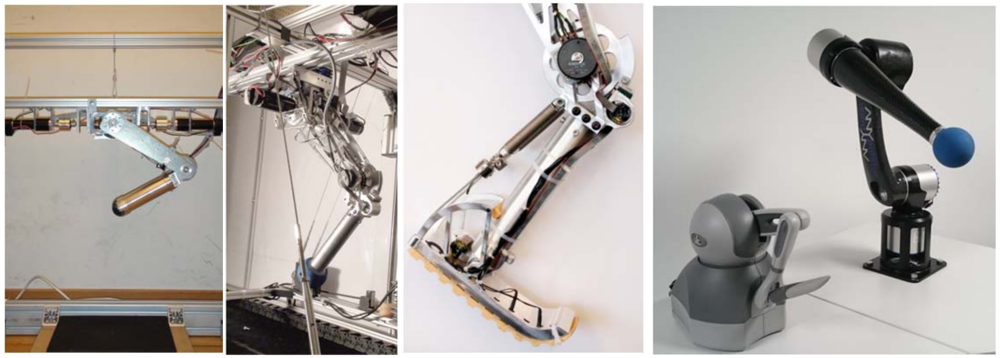


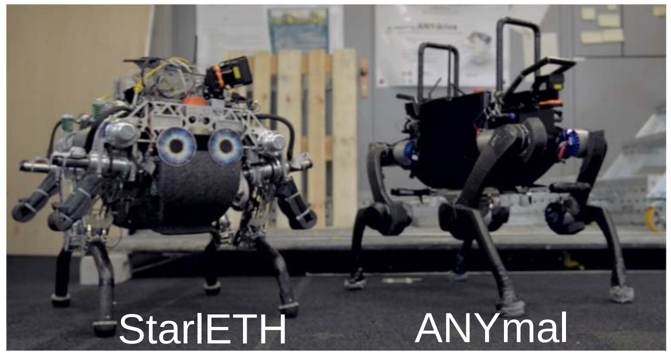
- Dynamic, force control



High-performance Series Elastic Actuators
Driving dynamic robots

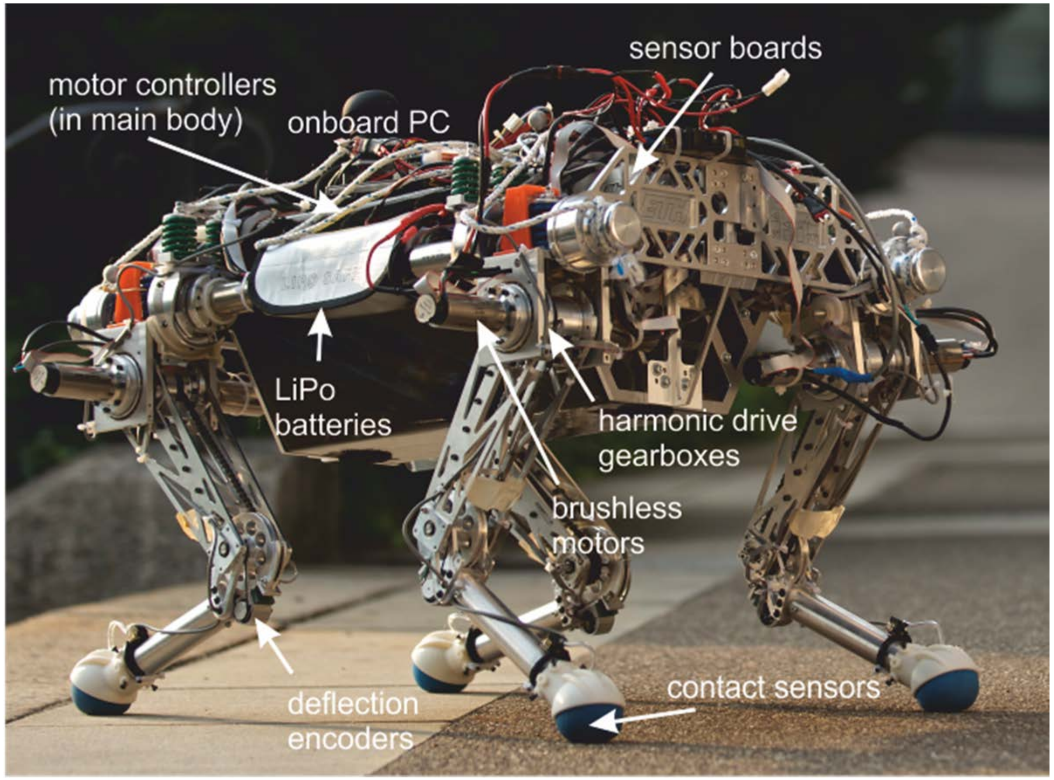
- How to
  - … **select** the optimal compliance?
  - … mechanically **integrate** this compliance?
  - … optimally **exploit** the compliance?
  - … **control** systems with integrated compliance?

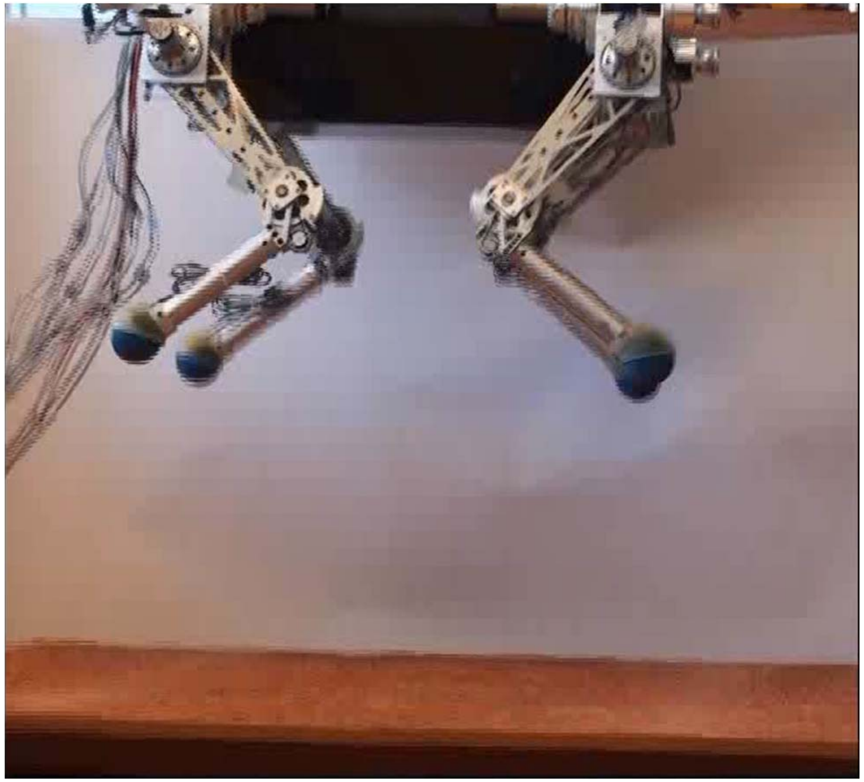




Robotic Systems Lab

StarlETH
A compliant quadrupedal robot

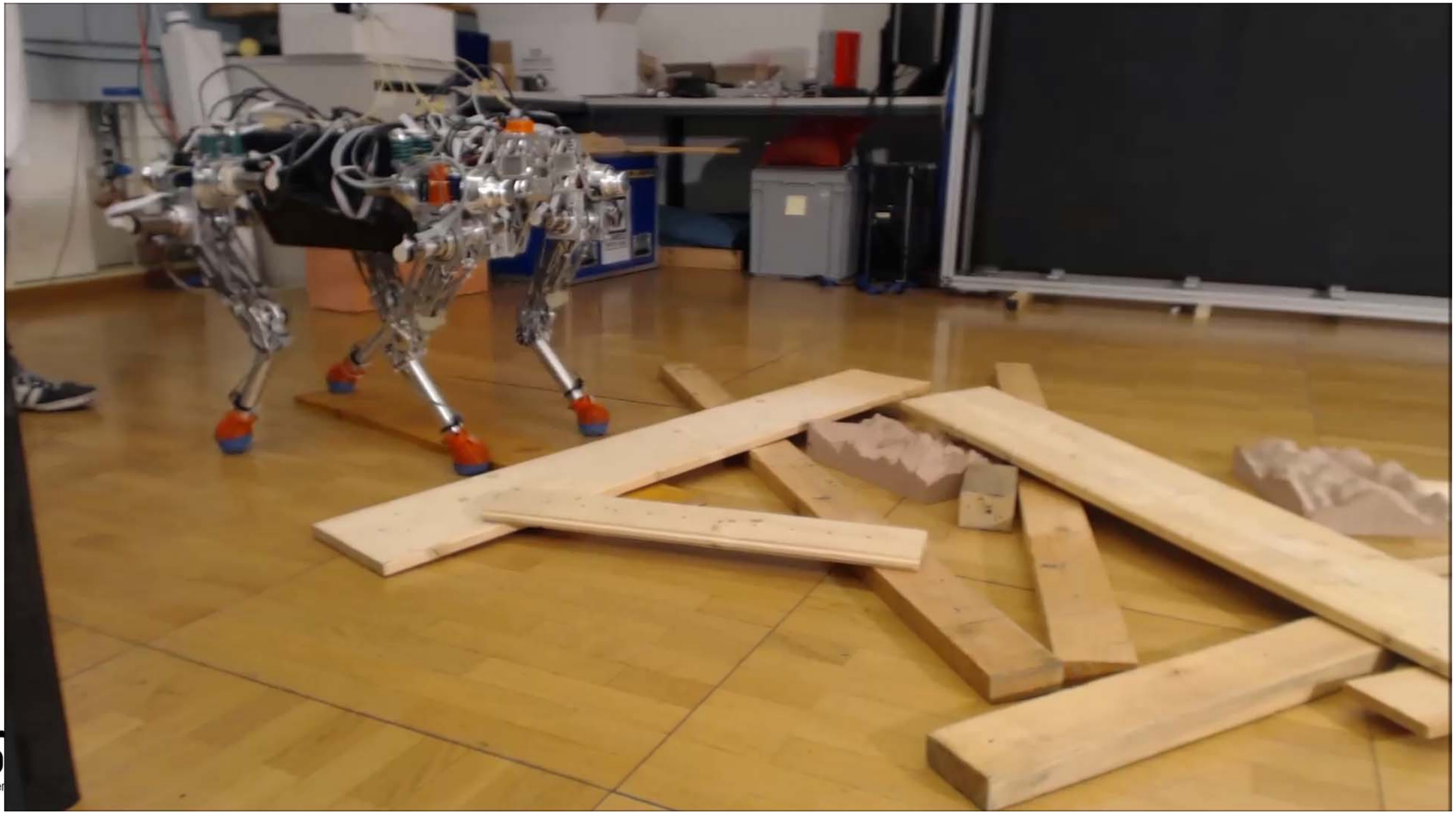




[Gehring et. al., ICRA 2013, RAM 2015]

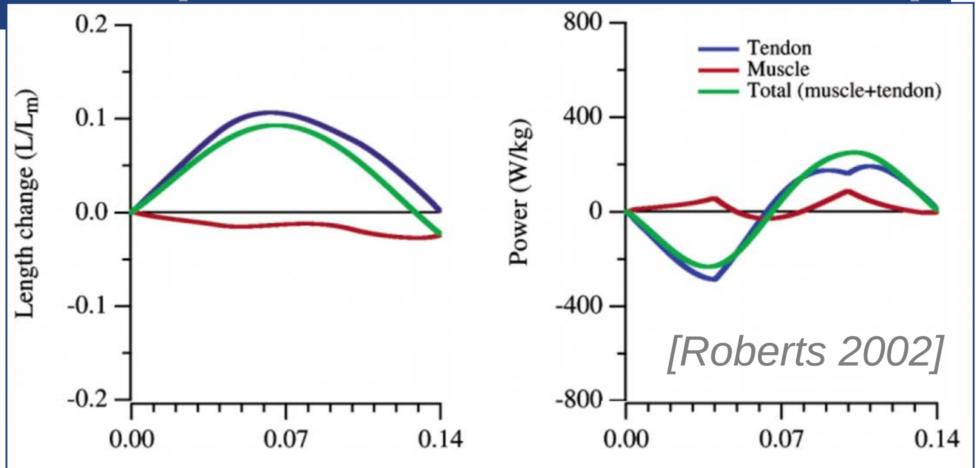
StarlETH – a Compliant Quadrupedal Robot

Towards autonomous running and climbing



[Hutter et. al., TMECH 2011, TRO 2014]

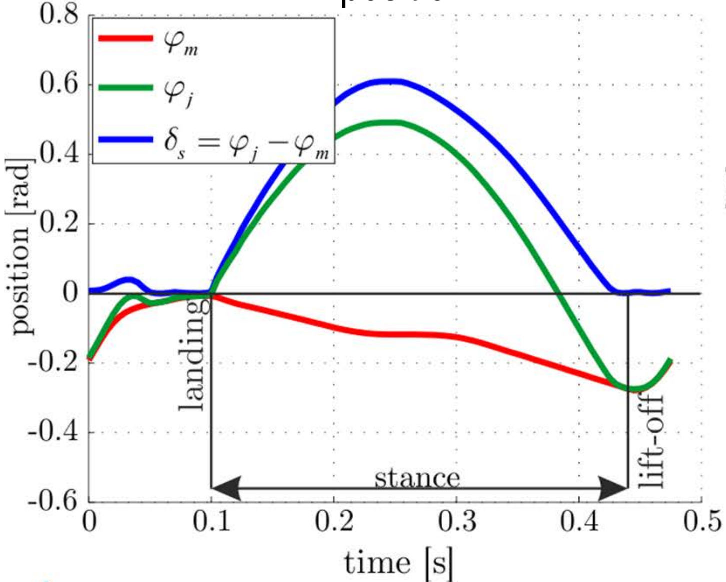
Exploitation of Passive Dynamics



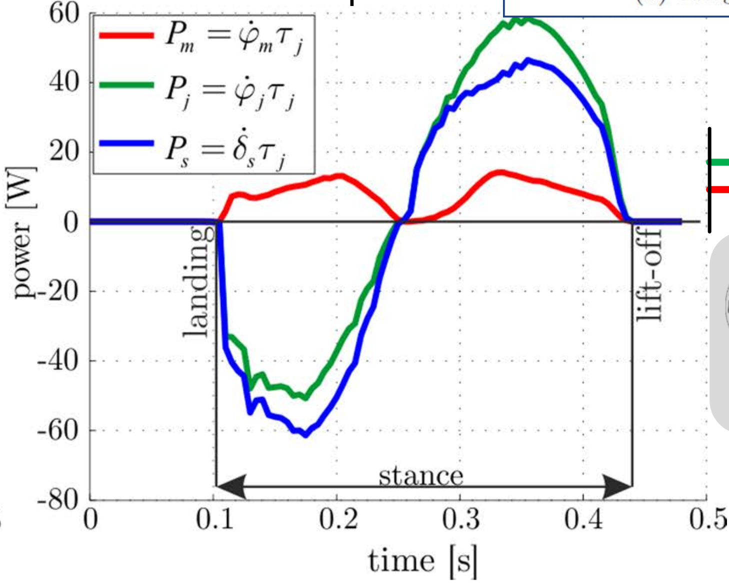
(a) Length change (b) Power development

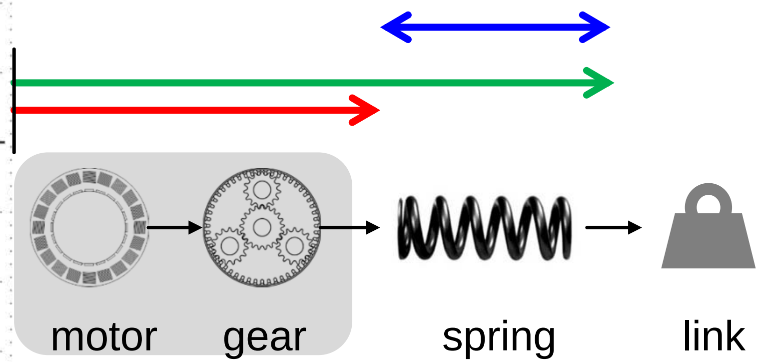
- 64% passive energy recovery
- Speed amplification 4.7, power amplification 4.1

position



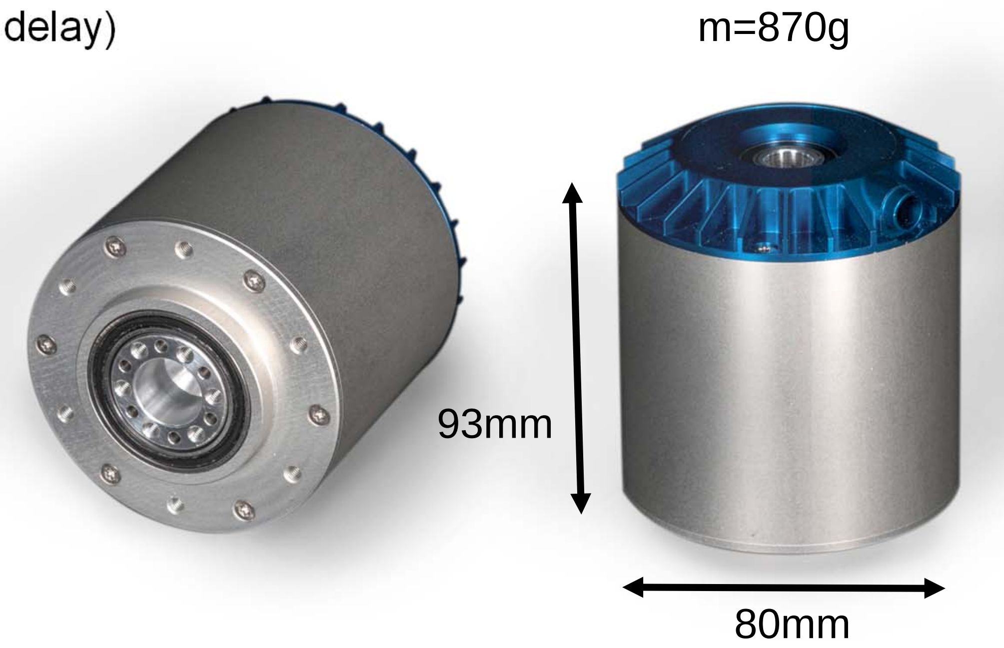
power



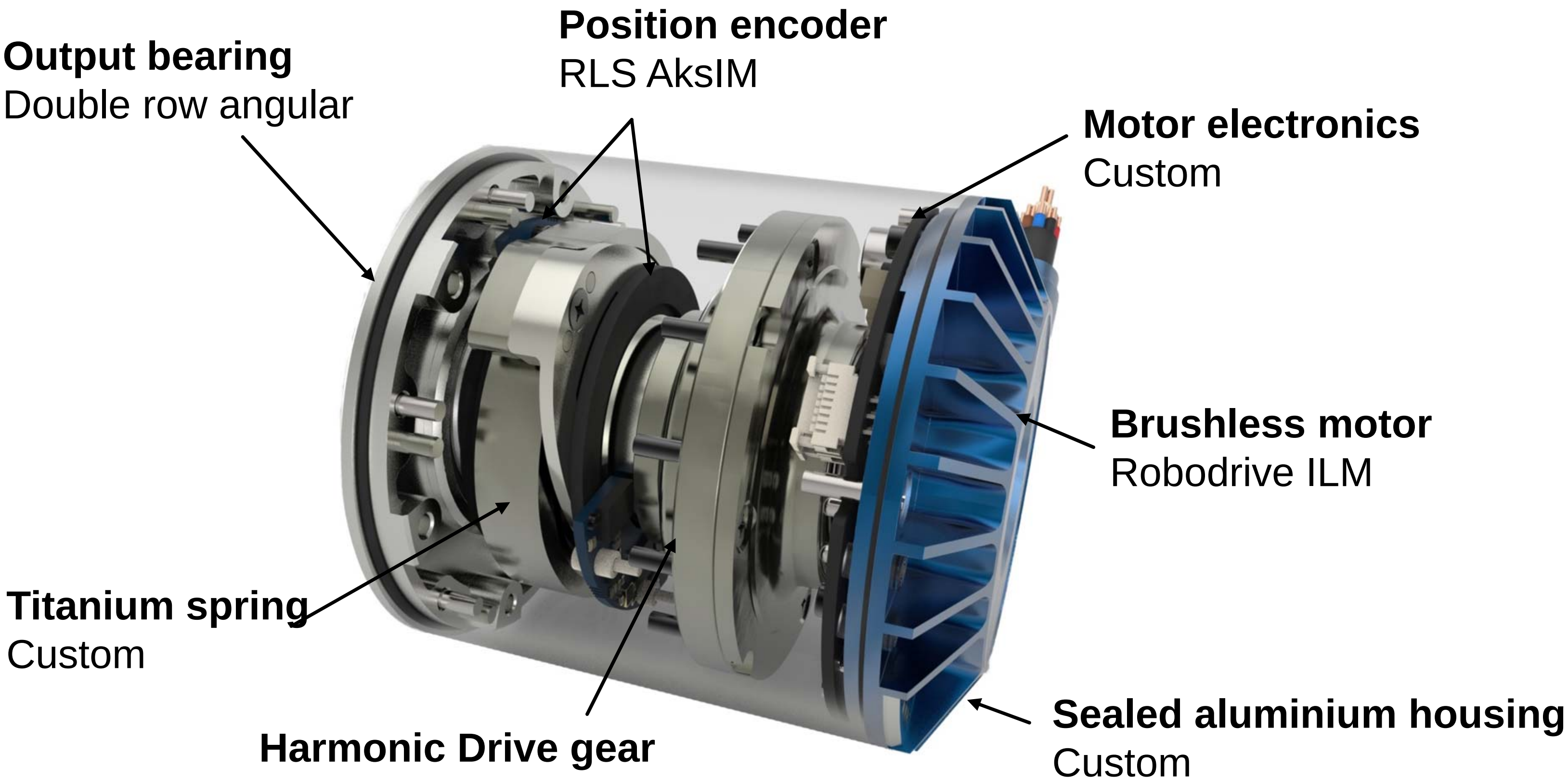


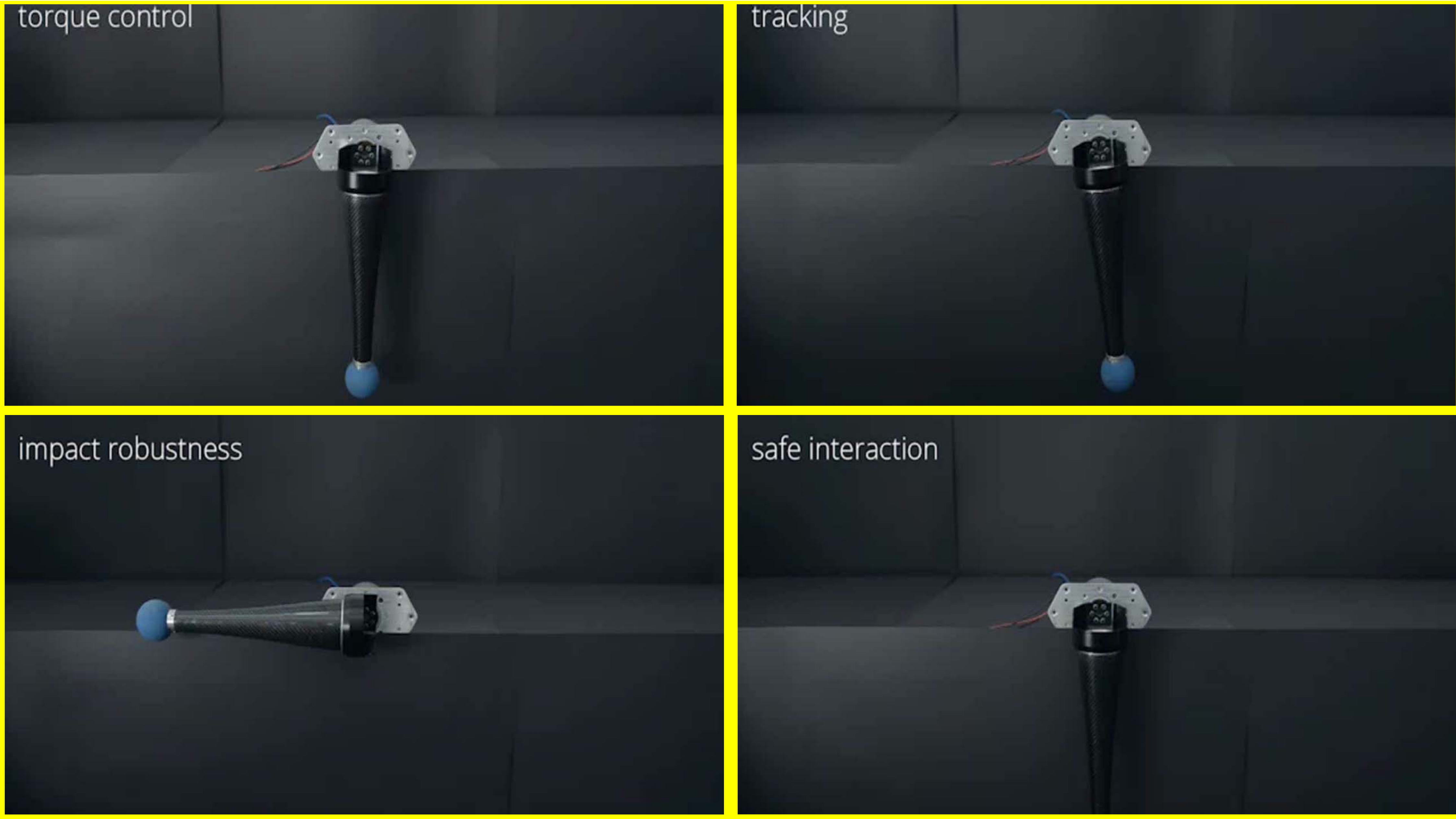
ANYdrive
A robust and force controllable robot joint unit

- Fully integrate SEAs
  - Custom motor control and sensing (no communication delay)
  - CAN (future EtherCAT) and power interface
  - Precise absolute output position and torque control
  - Hollow shaft for cabling
  - Large output load bearing
  - IP67



ANYdrive
Setup

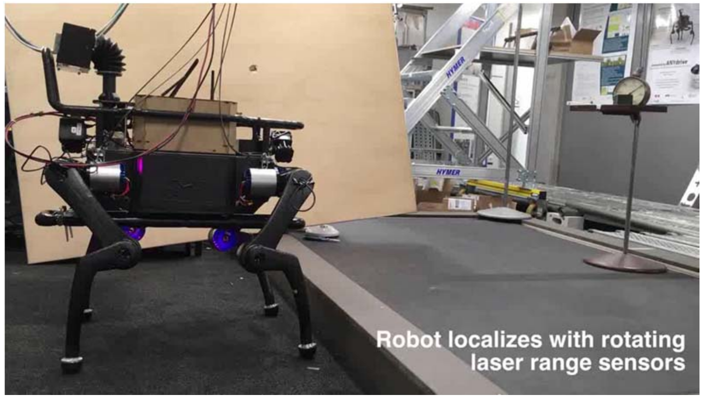


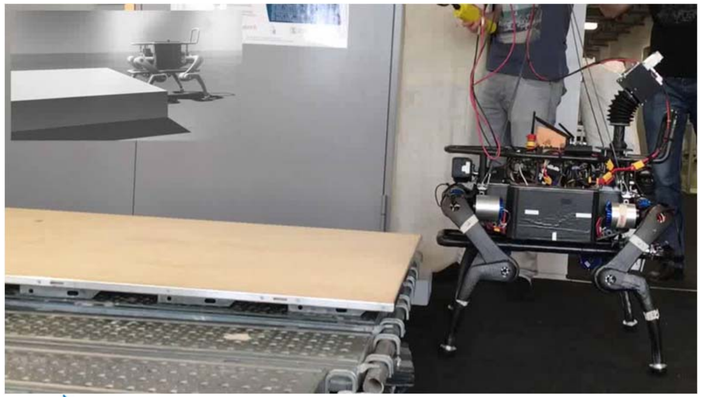

torque control
tracking
impact robustness
safe interaction

ANYmal – System overview

- High mobility
  - Extensive range of motion
  - Various maneuvers (climb)
- Powerful, dynamic & efficient
  - Different gaits (walk, trot, jump,…)

ANYmal
Combining dynamic motion skills with large mobility





ANYmal – System overview

Fully autonomous

- Onboard localization, mapping, planning, and control
- Modular sensor payload

Field-ready

- Water-proof
- 2–3 h endurance (280W avg power)
- 1-person operation (30kg)
- GUI for intuitive tele-operation
- Fall-safe

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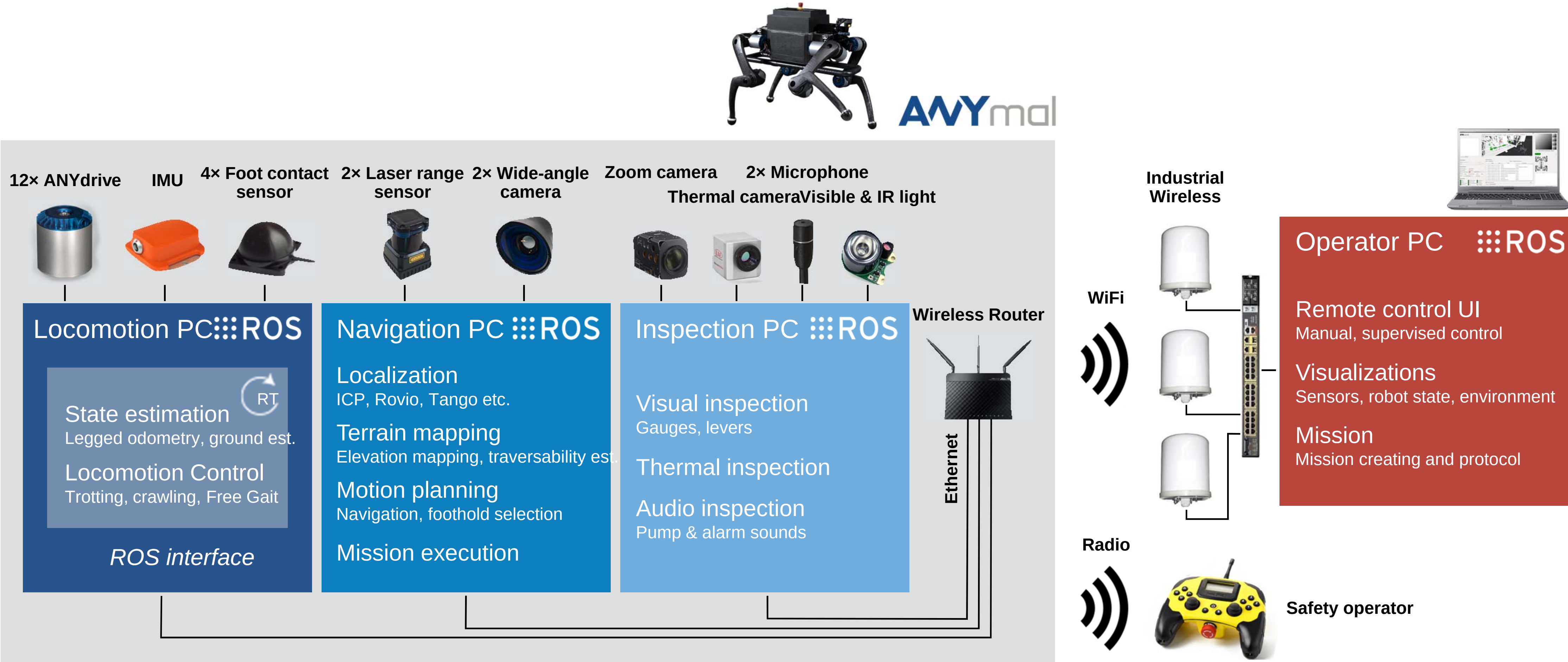
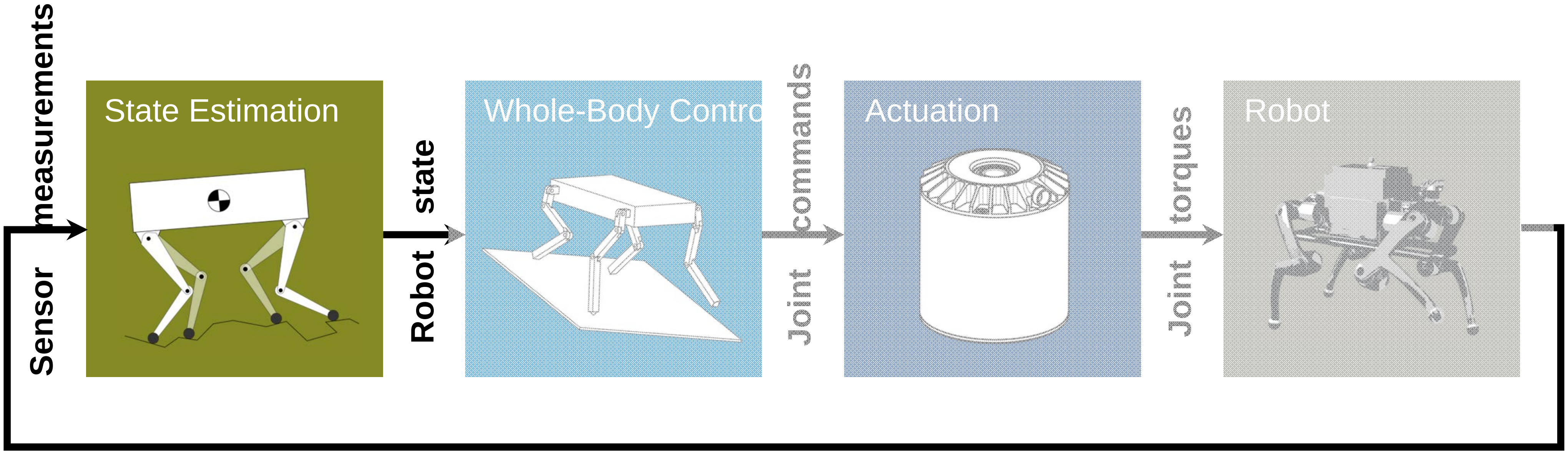
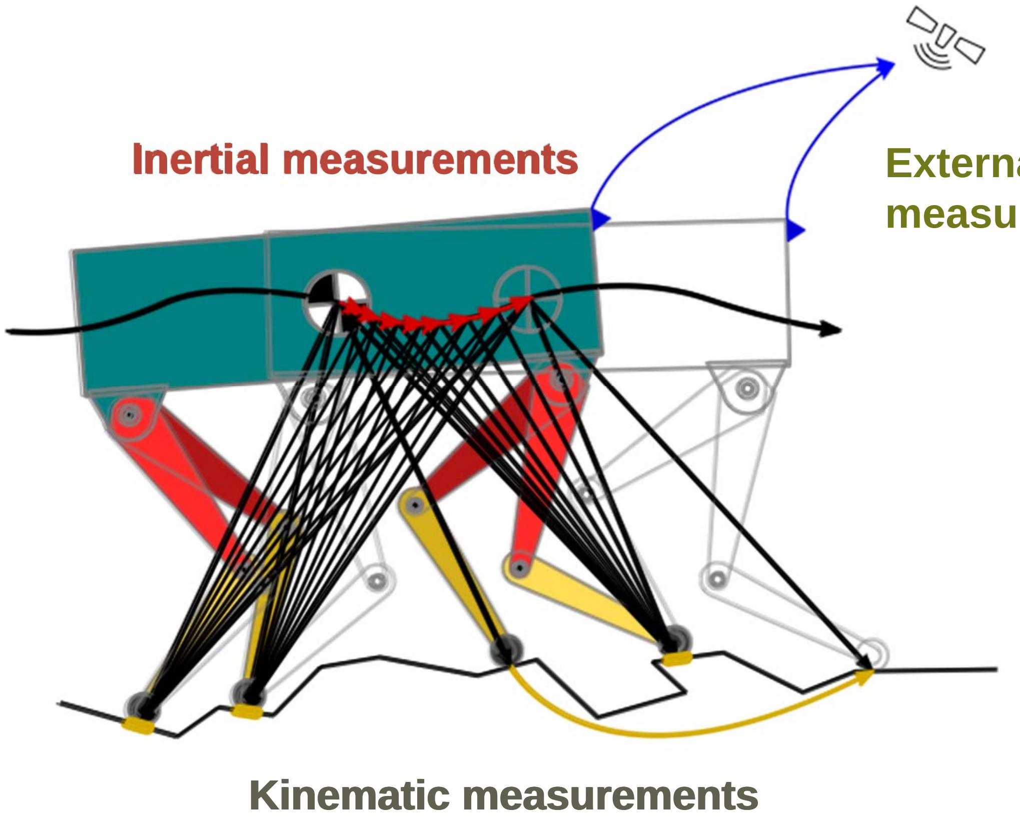
Software and Electronics Architecture



Locomotion


Sensor measurements
State Estimation
Robot state
Whole-Body Contro
Joint commands
Actuation
Joint torques
Robot

State Estimation

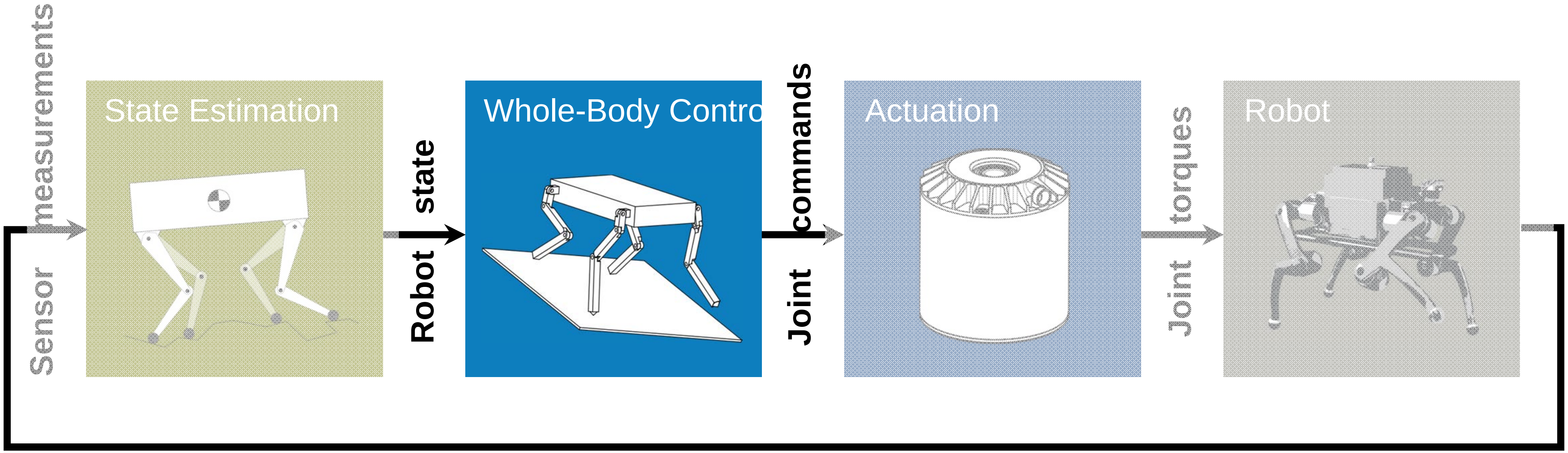


Extended Kalman Filter

- No assumption on terrain
- Kinematic measurements (encoders) for legs in contact
- Fused with inertial measurements (IMU)
- Error < 5% over distance
- Optionally combined with external pose (GPS, laser, vision, etc.)

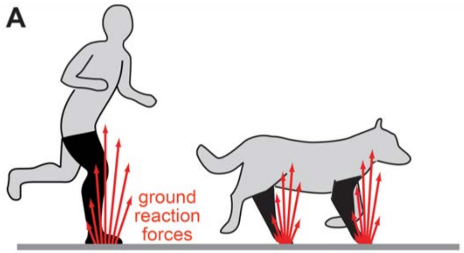
M. Bloesch, C. Gehring, P. Fankhauser, M. Hutter, M. A. Hoepflinger and R. Siegwart, “**State Estimation for Legged Robots on Unstable and Slippery Terrain**”, in International Conference on Intelligent Robots and Systems (IROS), 2013.

Locomotion

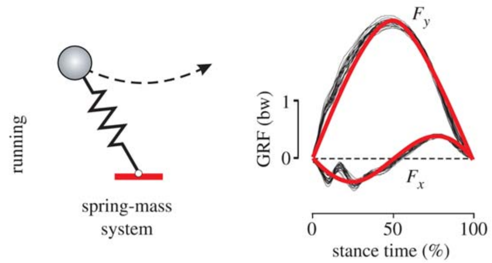

Sensor measurements
State Estimation
Robot state
Whole-Body Contro
Joint commands
Actuation
Joint torques
Robot

Foot Placement Control
Balance from stepping

- Biomechanical studies suggest SLIP models to describe complex running behaviors

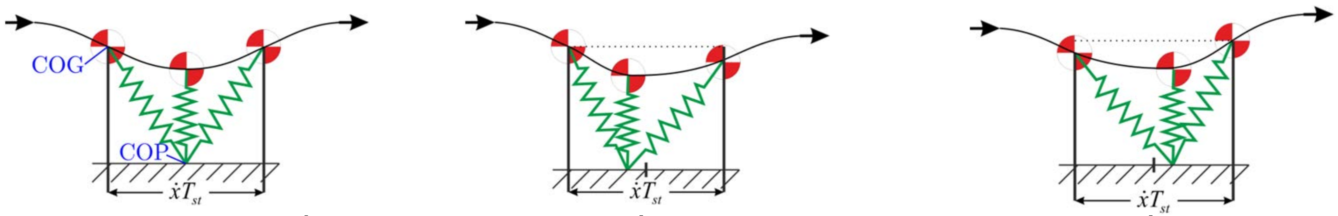


[Dickinson, Farley, Full 2000]



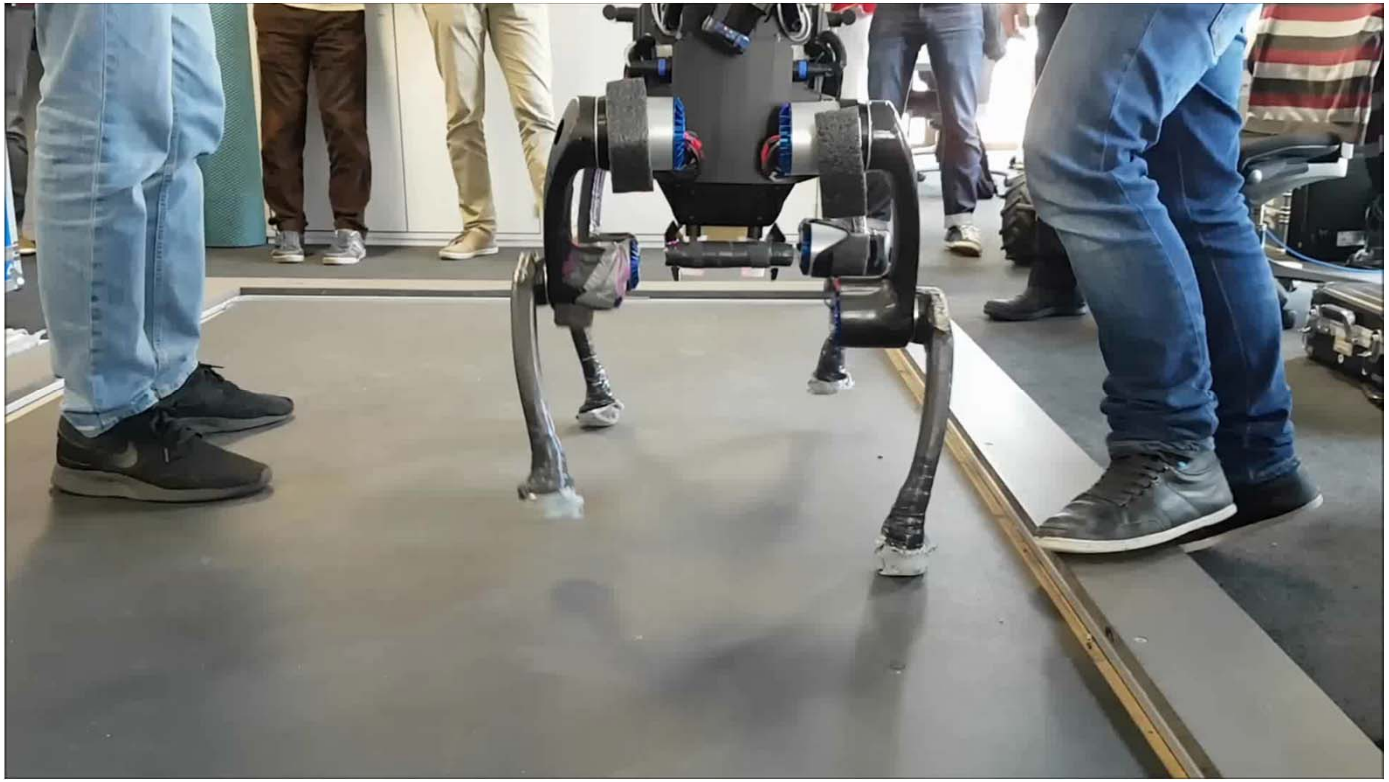
[Geyer 2006]

- Simple step-length rule to adjust the velocity $\mathbf{r}_F = \frac{1}{2}\dot{\mathbf{r}}_{HC,des}T_{st} + k_R^{FB}\left(\dot{\mathbf{r}}_{HC,des} - \dot{\mathbf{r}}_{HC}\right)\sqrt{h_{HC}}$ *[Raibert 1986]*



Constant speed Accelerate Decelerate

Foot Placement Control
Balance from stepping



Robotic Systems Lab

Kinematics and Dynamics in Control
Inverse kinematics for swing leg control

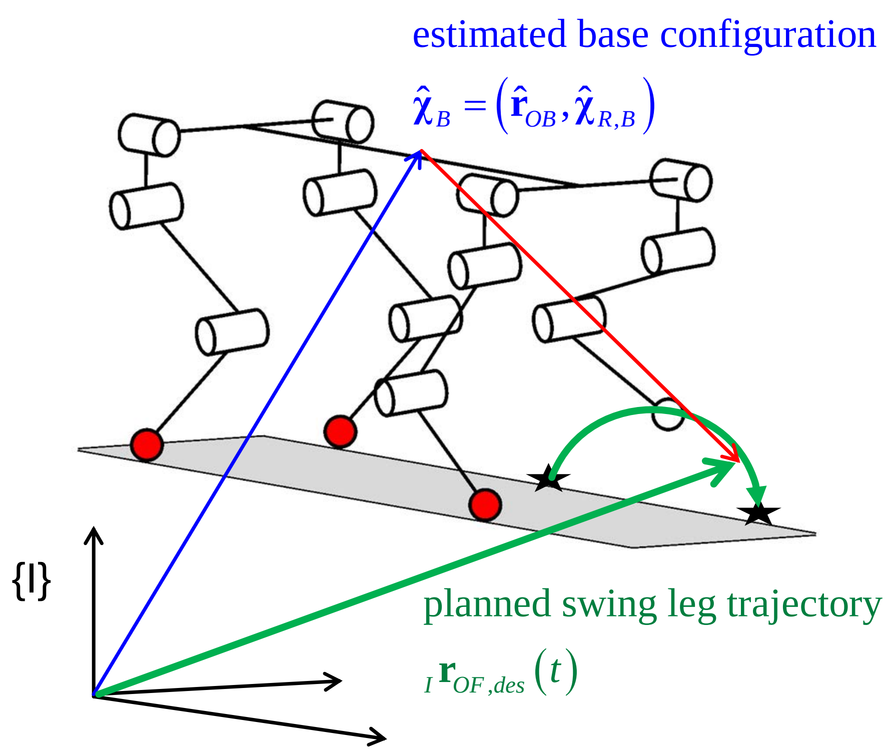
- Foot point in base frame

$$\mathbf{r}_{BF,des} = \mathbf{r}_{OF,des} - \hat{\mathbf{r}}_{OB}$$

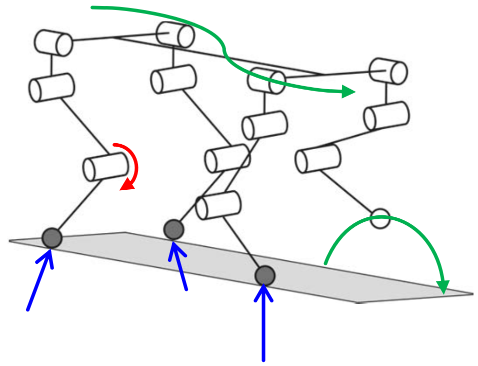
  - Expressed in world frame $\quad {}_I\mathbf{r}_{BF} = {}_I\mathbf{r}_{BF}\left(\mathbf{q}_r, \chi_B\right)$
  - Expressed in body frame $\quad {}_B\mathbf{r}_{BF} = {}_B\mathbf{r}_{BF}\left(\mathbf{q}_r\right)$

  - => inverse kinematics in body frame

$${}_B\mathbf{r}_{BF,des} = \mathbf{R}_{BI}\left(\hat{\chi}_{R,B}\right){}_I\mathbf{r}_{OF,des} - {}_B\hat{\mathbf{r}}_{OB} = {}_B\mathbf{r}_{BF,des}\left(\mathbf{q}_{r,\text{swing leg}}\right)$$



Whole-body Control of a Legged Robot



- Equations of motion

motion $\xleftarrow{\text{causes}}$ / $\xrightarrow{\text{inverse dynamics}}$ actuation

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g} + \mathbf{J}_s^T\mathbf{F}_s = \mathbf{S}^T\boldsymbol{\tau}$$

contact force

- Contact constraint

$$\mathbf{J}_s\ddot{\mathbf{q}} + \dot{\mathbf{J}}_s\dot{\mathbf{q}} = \mathbf{0}$$

- Desired motion optimization

$$\min \left\| \ddot{\mathbf{r}}_i(\mathbf{q}) - \ddot{\mathbf{r}}_{des} \right\|_2 \ \text{ or } \ddot{\mathbf{r}}_i < \ddot{\mathbf{r}}_{i,\max}$$

- Contact force optimization

$$\min \left\| \mathbf{W}_s\mathbf{F}_s - \mathbf{b}_F \right\|_2 \ \text{ or } \mathbf{F}_{s_i} < \mathbf{F}_{s,\max}$$

- Joint torque optimization

$$\min \left\| \mathbf{W}_\tau\boldsymbol{\tau} - \mathbf{b}_\tau \right\|_2 \ \text{ or } \boldsymbol{\tau} < \boldsymbol{\tau}_{\max}$$

Whole-body control = large scale simultaneous optimization of $\ddot{\mathbf{q}}$, $\mathbf{F}_s$, $\boldsymbol{\tau}$

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Kinematics and Dynamics in Control
(simple) whole body control

- Adjust joint torques to
  - track the swing leg $\quad \ddot{\mathbf{r}}_{OF} = \mathbf{J}_F \ddot{\mathbf{q}} + \dot{\mathbf{J}}_F \dot{\mathbf{q}} = \ddot{\mathbf{r}}_{OF,des}(t)$
  - to move the base $\quad \dot{\mathbf{w}}_B = \mathbf{J}_B \ddot{\mathbf{q}} + \dot{\mathbf{J}}_B \dot{\mathbf{q}} = \dot{\mathbf{w}}_{B,des}(t)$
  - ensure contact constraint $\quad \ddot{\mathbf{r}}_c = \mathbf{J}_c \ddot{\mathbf{q}} + \dot{\mathbf{J}}_c \dot{\mathbf{q}} = \mathbf{0}$

  $\Rightarrow$ fully defines the motion of the system

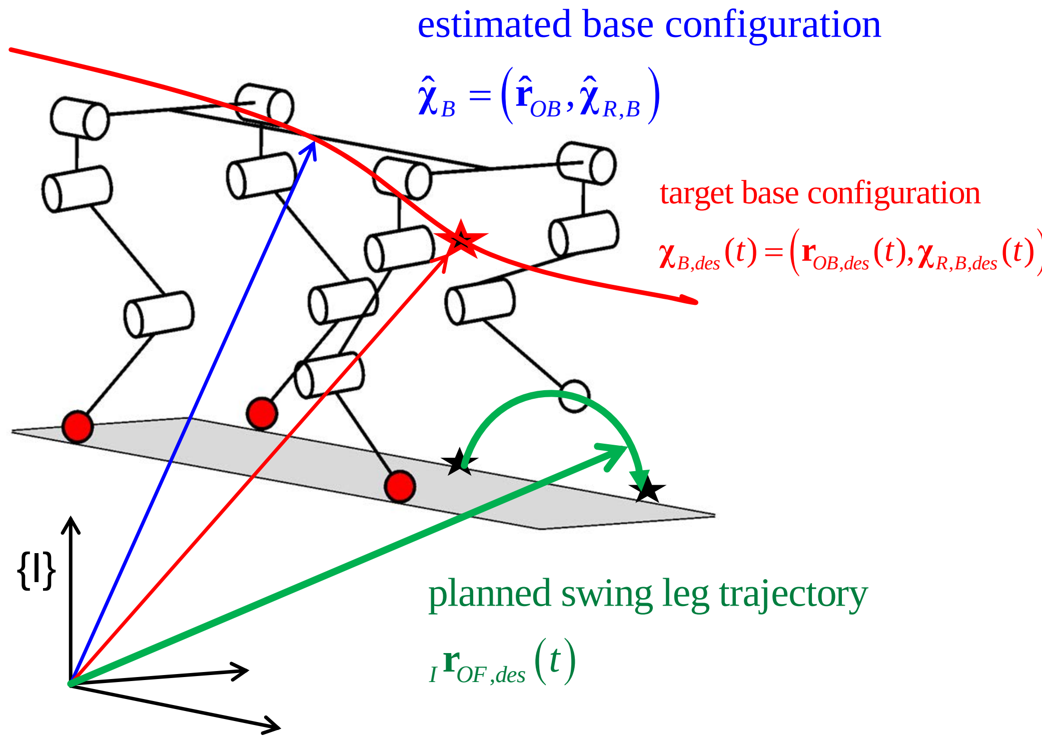
  12 actuated + 6 unactuated = 18 DOF

  6 motion + 9 constraints + 3 swing leg = 18

If more tasks, use pseudo-inverse

$$\ddot{\mathbf{q}}_{des} = \begin{bmatrix} \mathbf{J}_F \\ \mathbf{J}_B \\ \mathbf{J}_c \end{bmatrix}^{-1} \left(\begin{pmatrix} \ddot{\mathbf{r}}_{OF}(t) \\ \dot{\mathbf{w}}_B(t) \\ 0 \end{pmatrix} - \begin{bmatrix} \dot{\mathbf{J}}_F \\ \dot{\mathbf{J}}_B \\ \dot{\mathbf{J}}_c \end{bmatrix} \dot{\mathbf{q}} \right)$$

- Inverse dynamics control $\quad \boldsymbol{\tau} = \left(\hat{\mathbf{N}}_c^T \mathbf{S}^T \right)^+ \hat{\mathbf{N}}_c^T \left(\hat{\mathbf{M}} \ddot{\mathbf{q}}_{des} + \hat{\mathbf{b}} + \hat{\mathbf{g}} \right)$



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Locomotion as 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.

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

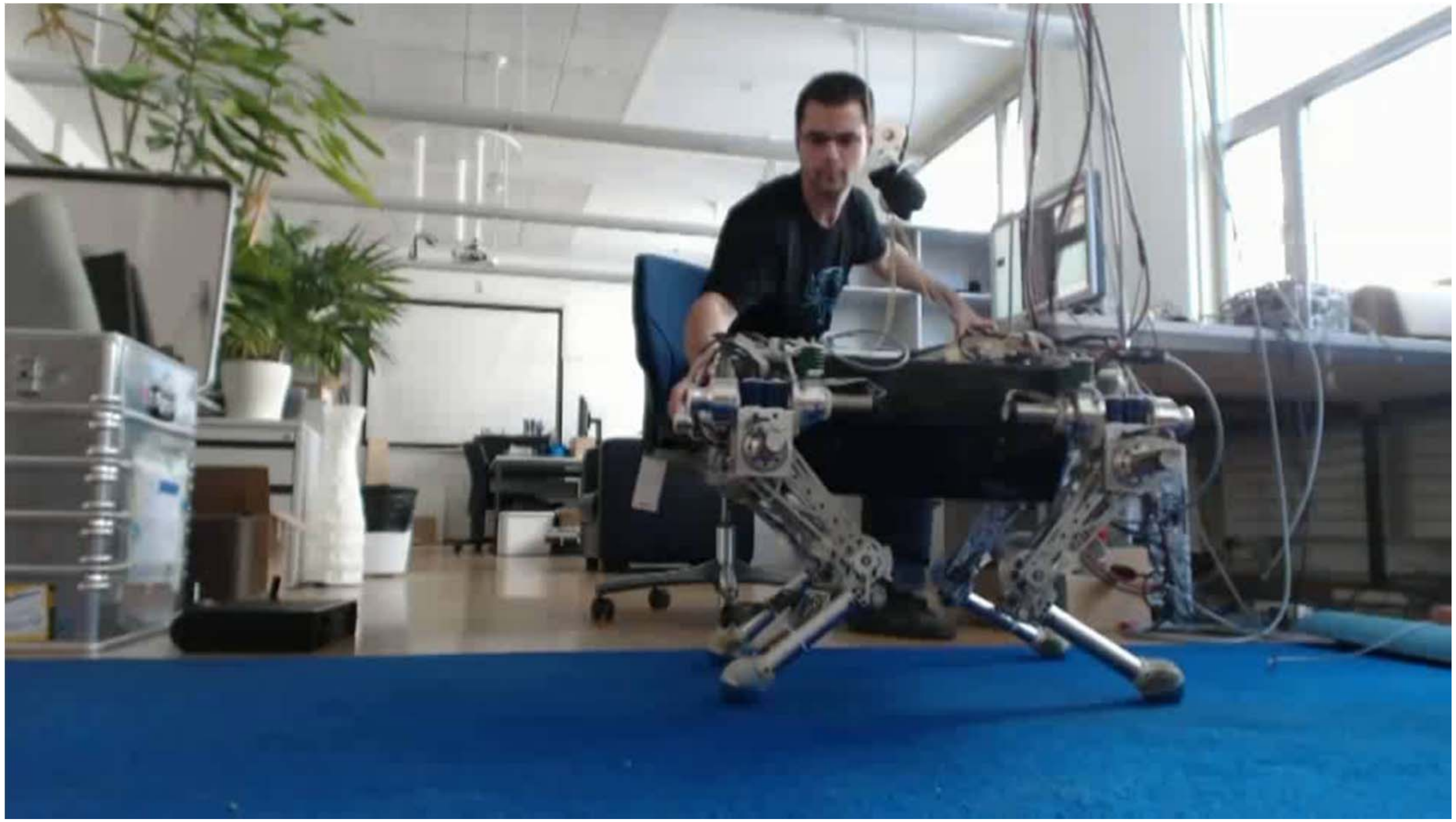
$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{b} + \mathbf{g} + \mathbf{J}_c\mathbf{F}_c = \mathbf{S}^T\boldsymbol{\tau}$$ <= equation of motion holds

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

Static Walking with Compliant Behavior



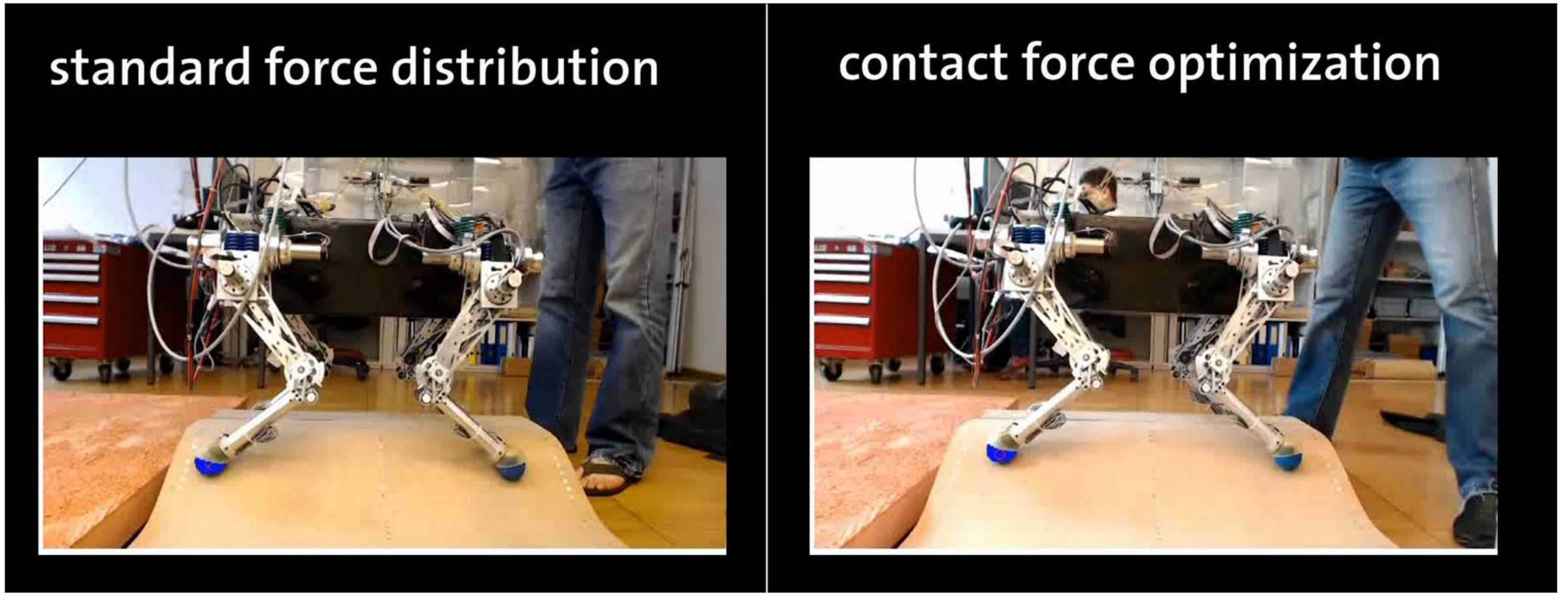
Static Walking – Force/Torque Optimization

- Different force and torque optimization strategies:
  - Reduced energy consumption by torque minimization $\mathbf{W}_\tau = \mathbf{I}$
  - Reduction of risk of slippage by contact force alignment $\mathbf{W}_F = diag(t_i)$

			Torque minimization	Tangential force minimization
				20%
Energy consumption	$E_\tau = \int \boldsymbol{\tau}^T \boldsymbol{\tau} \mathrm{d}t$	$[N^2 m^2 s]$	4701	5544
Risk of slippage	$\overline{\mu} = \text{mean}\left(\frac{F_{tan}(t)}{F_{norm}(t)}\right)$	[-]	0.2	0.04
Average tracking error	$\overline{\Delta r} = \text{mean}\,\|r(t) - r_{des}(t)\|$	[mm]	7.7	3.3

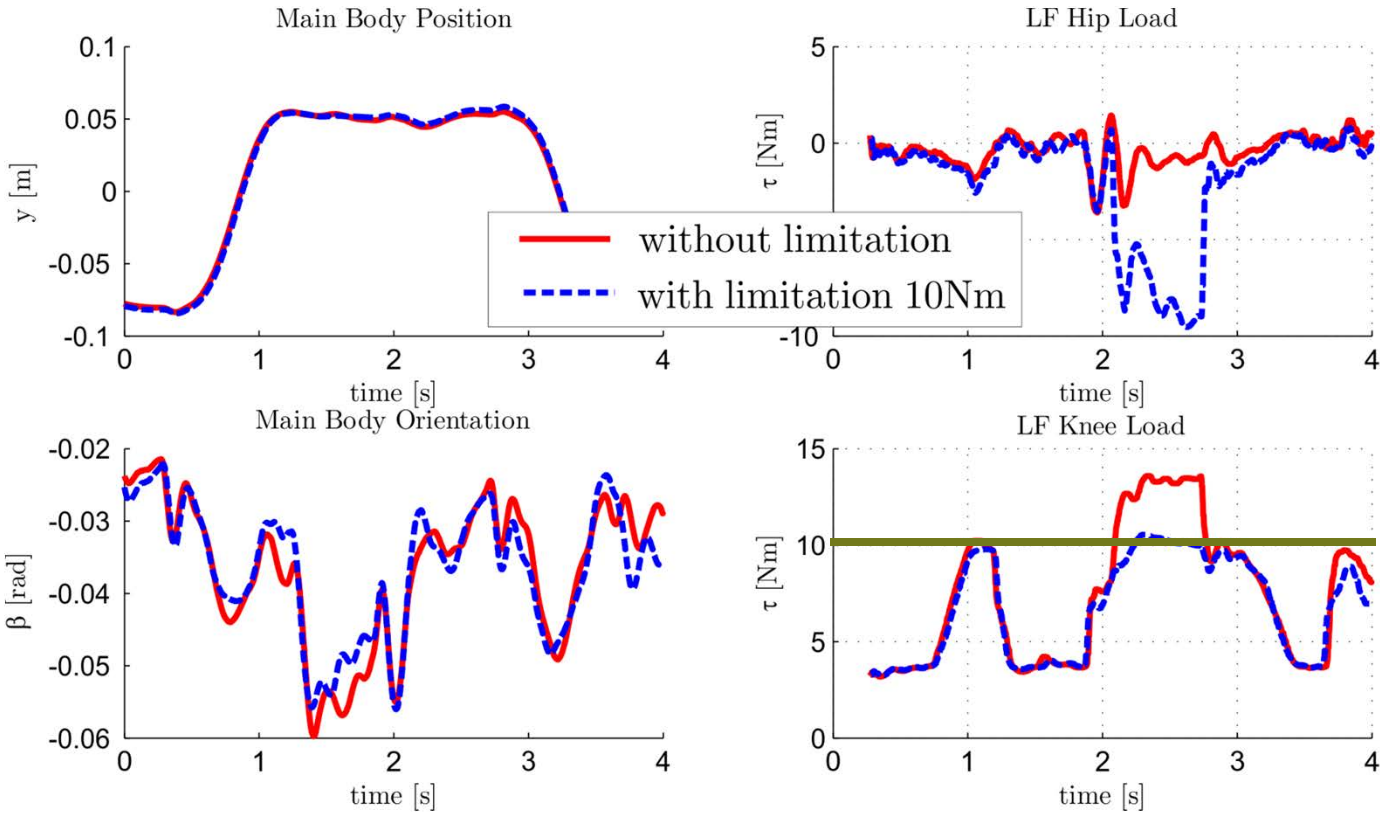
Static Walking – Force/Torque Optimization

- Different force and torque optimization strategies:
  - Reduced energy consumption by torque minimization $\mathbf{W}_\tau = \mathbf{I}$
  - Reduction of risk of slippage by contact force alignment $\mathbf{W}_F = diag(t_i)$



Joint Torque Limitations

- Inequality tasks

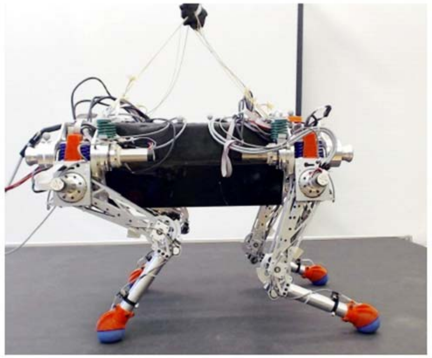


Joint Position Limitation

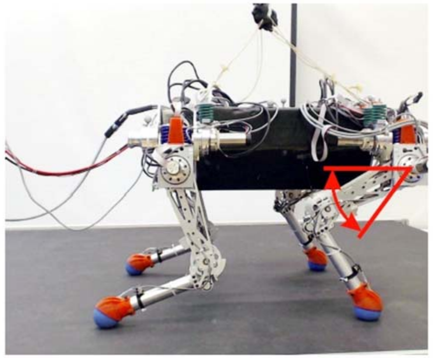
$$\boxed{\mathbf{A}_i\mathbf{x} \leq \mathbf{b}_i}$$

- Base shifting
- Joint Limitation = Inequality constraint

P_1^q : contact constraints
P_2^q : angle limitation
P_3^q : xy body position
P_4^q : body orientation
P_5^q : ground clearance



(a) Start configuration



(b) No joint limitation

Task Prioritization (Bellicoso, Humanoids 2016)

Priority	Task
1	Equations of Motion
2	No contact motion
3	Torque limits
4	Friction cone and $\boldsymbol{\lambda}$ modulation
5	Desired torso x, y position
6	Swing foot motion tracking
7	Limb kinematic limits
8	Main body yaw
9	Main body height
10	Main body roll and pitch
11	Contact force minimization

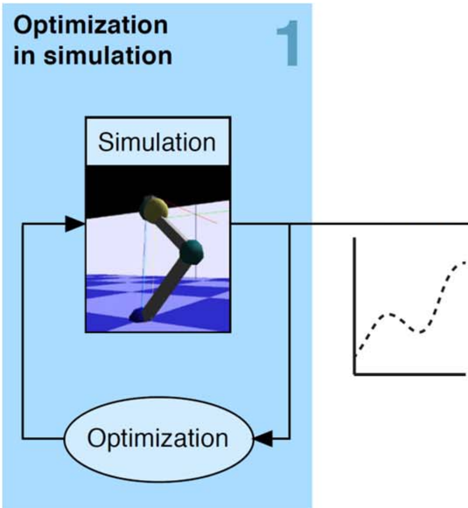
Motion Synthesis from Optimization

- Parameterization of behavior
  - Motion primitives
  - Gait pattern
  - Control gains
  - …

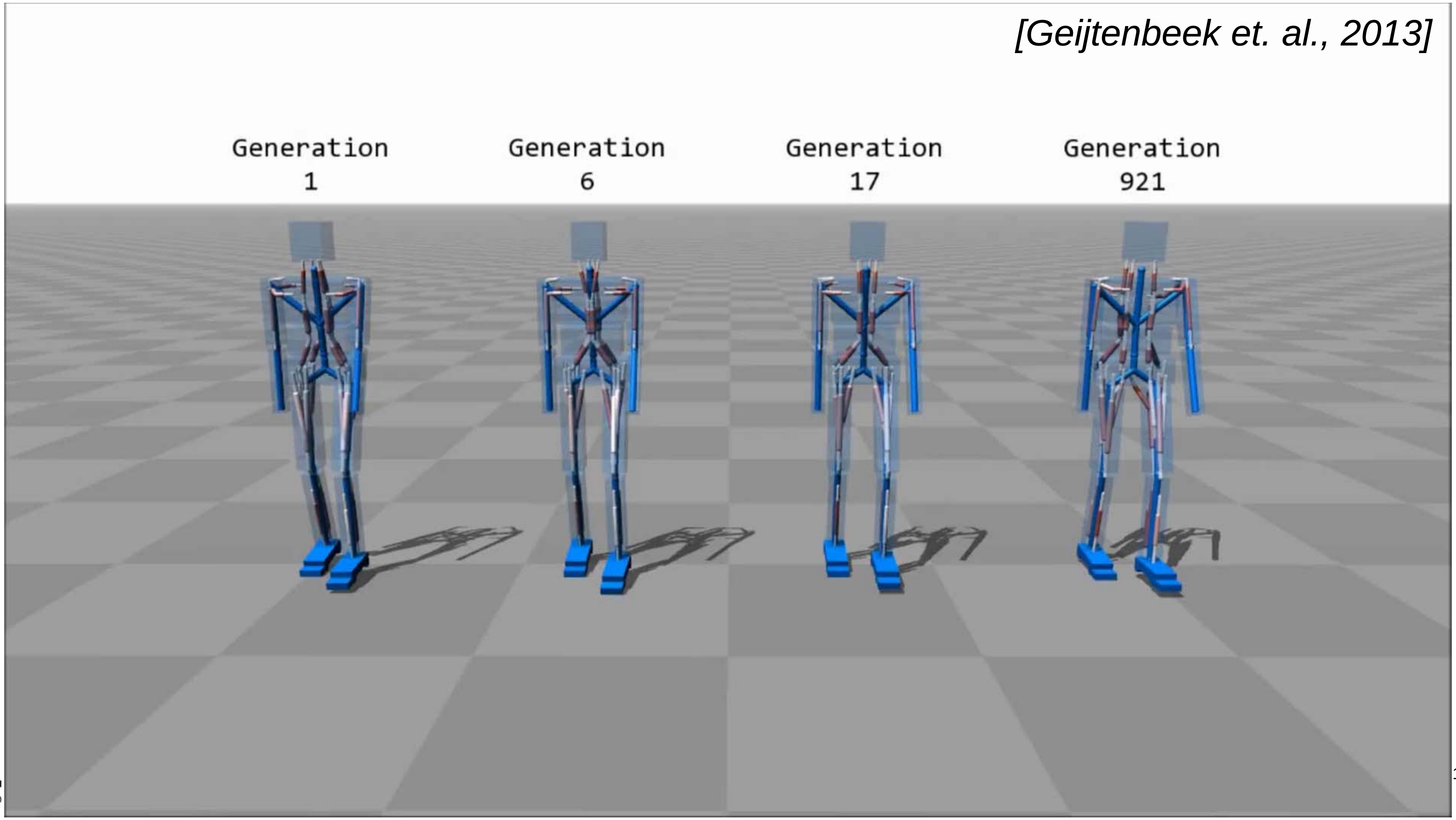
θ → optimizer: CMA-ES, ROCK*, PI2, … →

Target behavior = cost function

$$\theta^* = \arg\min_{\theta} \sum w_i \cdot \underbrace{C_i(\theta, \mathbf{q}, \dot{\mathbf{q}}, \boldsymbol{\tau})}$$

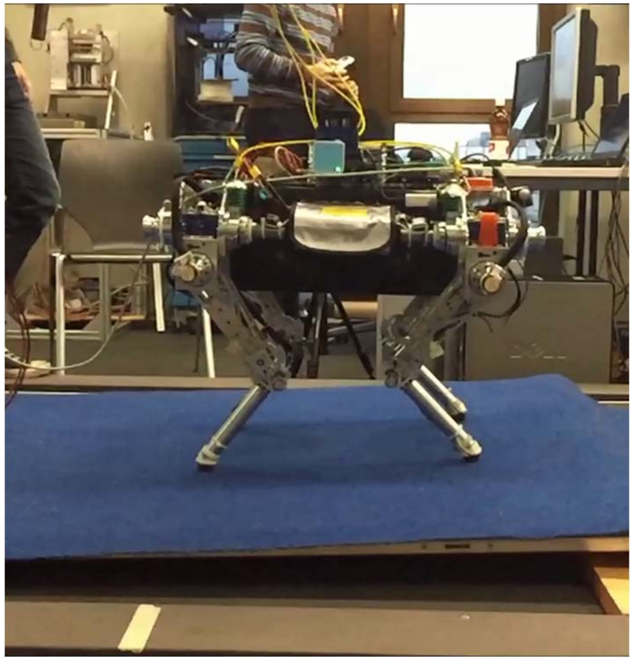


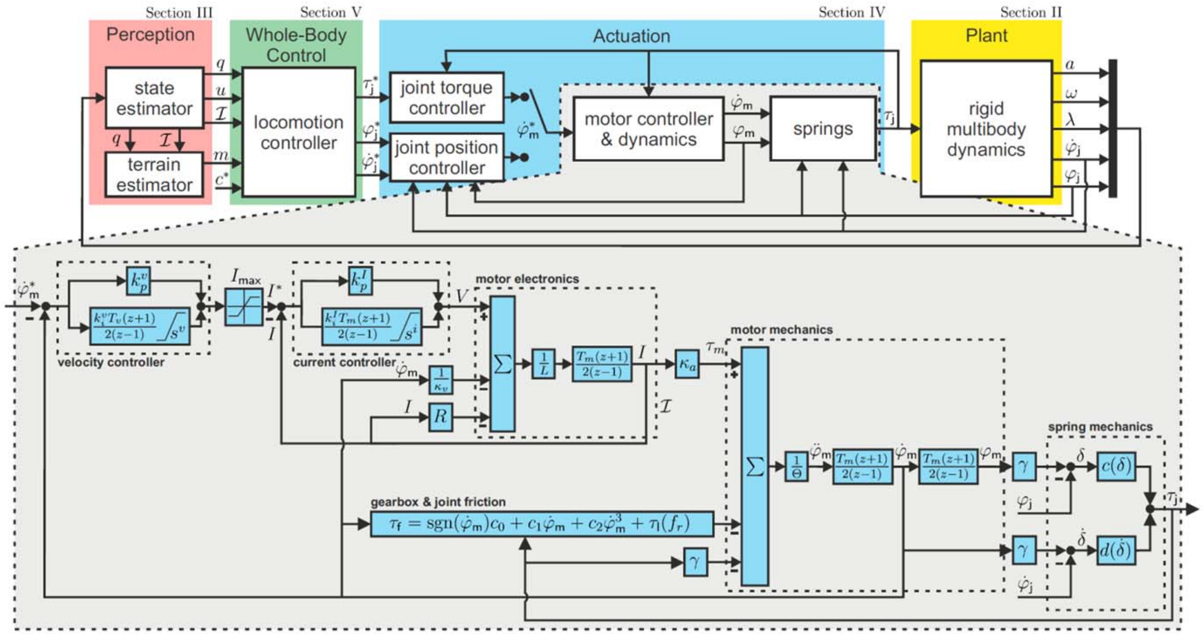
Motion Synthesis from Optimization



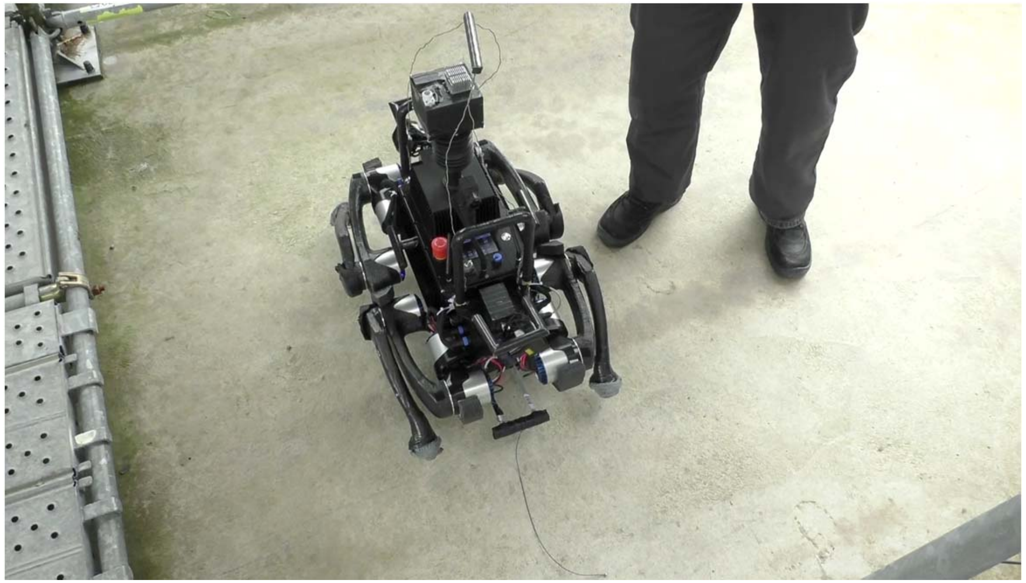
Emerging Behaviors
High jumping manoeuver

- Model ENTIRE system (including actuator dynamics and mechanical elasticity) allows reaching maximum performance





ANYmal – Application in real-world scenarios



- ARGOS challenge
  - Autonomous inspection of oil and gas sites
- NCCR rescue robotics
  - S&R application together with UAVs

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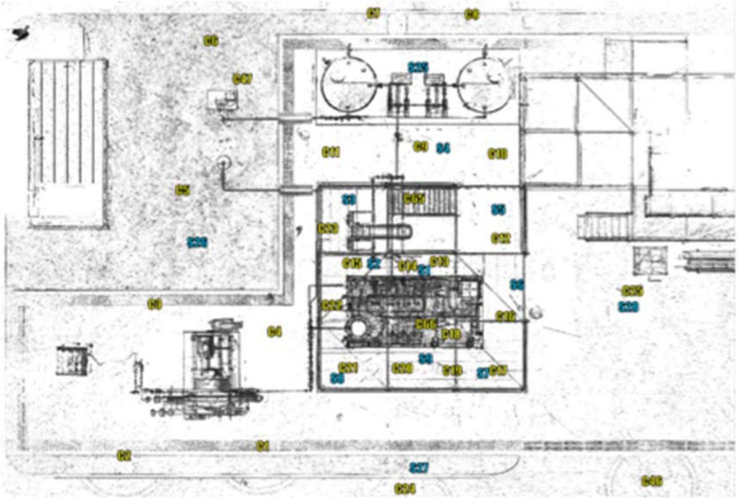
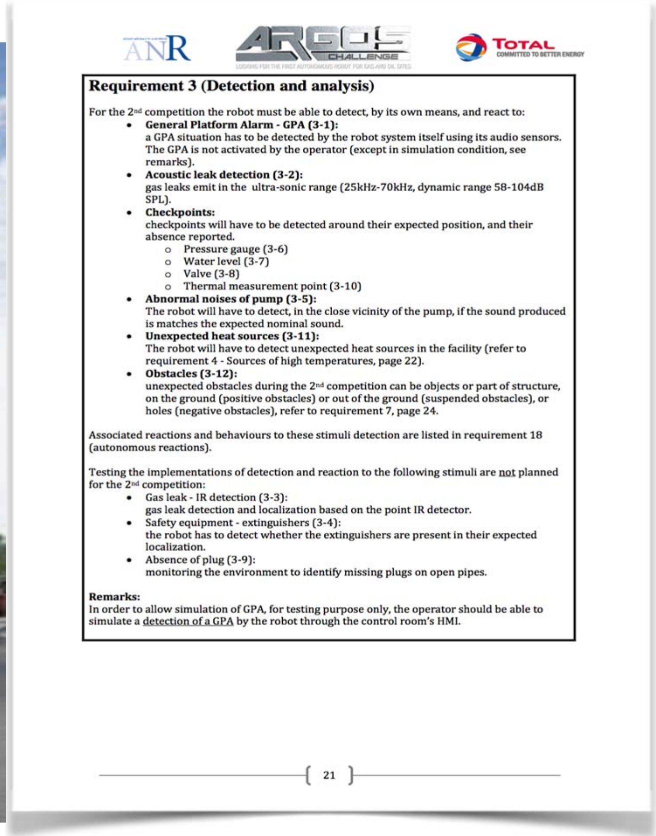
ARGOS Challenge
Autonomous Inspection of Oil and Gas Sites





ANR ARGOS CHALLENGE TOTAL

Requirement 3 (Detection and analysis)

For the 2nd competition the robot must be able to detect, by its own means, and react to:

- **General Platform Alarm - GPA (3-1):**
  a GPA situation has to be detected by the robot system itself using its audio sensors. The GPA is not activated by the operator (except in simulation condition, see remarks).
- **Acoustic leak detection (3-2):**
  gas leaks emit in the ultra-sonic range (25kHz-70kHz, dynamic range 58-104dB SPL).
- **Checkpoints:**
  checkpoints will have to be detected around their expected position, and their absence reported.
  - Pressure gauge (3-6)
  - Water level (3-7)
  - Valve (3-8)
  - Thermal measurement point (3-10)
- **Abnormal noises of pump (3-5):**
  The robot will have to detect, in the close vicinity of the pump, if the sound produced is matches the expected nominal sound.
- **Unexpected heat sources (3-11):**
  The robot will have to detect unexpected heat sources in the facility (refer to requirement 4 - Sources of high temperatures, page 22).
- **Obstacles (3-12):**
  unexpected obstacles during the 2nd competition can be objects or part of structure, on the ground (positive obstacles) or out of the ground (suspended obstacles), or holes (negative obstacles), refer to requirement 7, page 24.

Associated reactions and behaviours to these stimuli detection are listed in requirement 18 (autonomous reactions).

Testing the implementations of detection and reaction to the following stimuli are not planned for the 2nd competition:

- Gas leak - IR detection (3-3):
  gas leak detection and localization based on the point IR detector.
- Safety equipment - extinguishers (3-4):
  the robot has to detect whether the extinguishers are present in their expected localization.
- Absence of plug (3-9):
  monitoring the environment to identify missing plugs on open pipes.

Remarks:
In order to allow simulation of GPA, for testing purpose only, the operator should be able to simulate a detection of a GPA by the robot through the control room's HMI.

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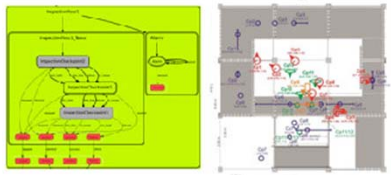
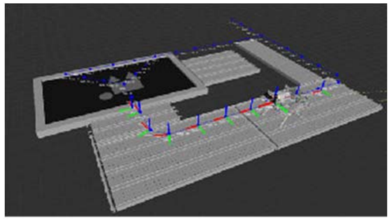
ARGOS Challenge
Autonomous Inspection of Oil and Gas Sites

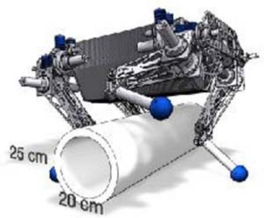


Mission planning
Mission layout, decision making, user interface …

Inspection
Gauges, water levels, levers, heat sources, alarm sounds …



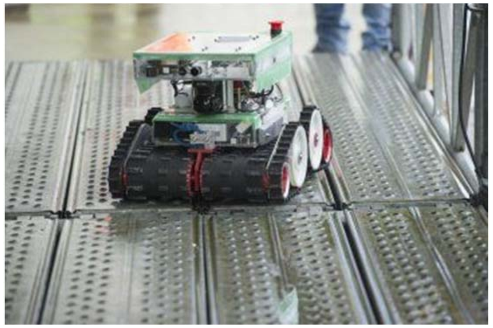
Navigation
Path planning, localization, obstacle avoidance …



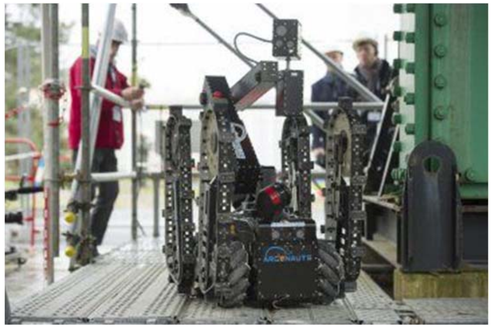
Climbing
Steps, Pipes, Stairs …

ARGOS Challenge

5 International Teams (Industry + Academia)

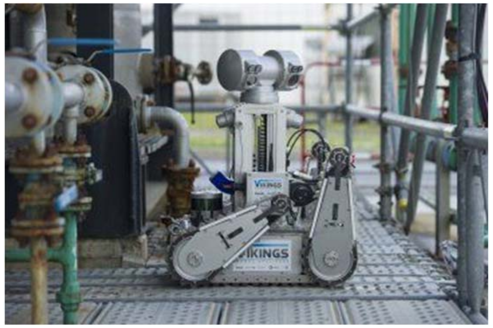


AIR-K
Japan

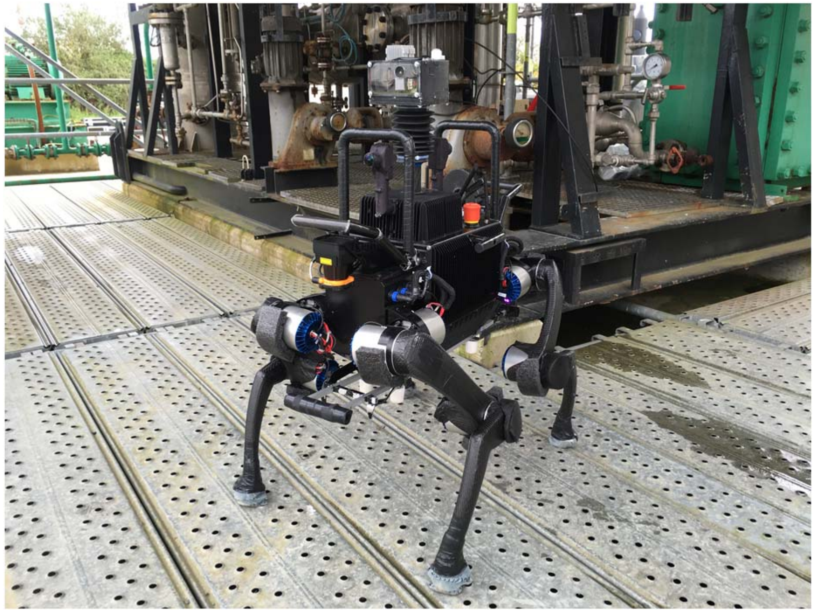


ARGONAUTS
Austria & Germany

FOXIRIS
Spain & Portugal

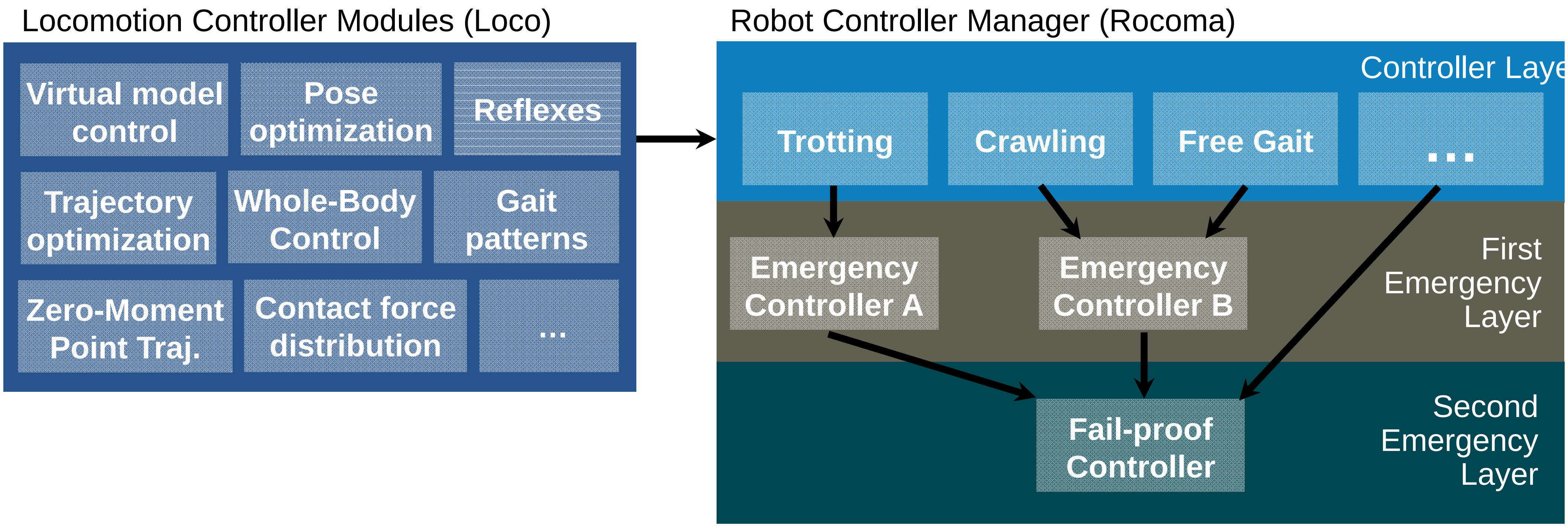


VIKINGS
France



LIO
Switzerland

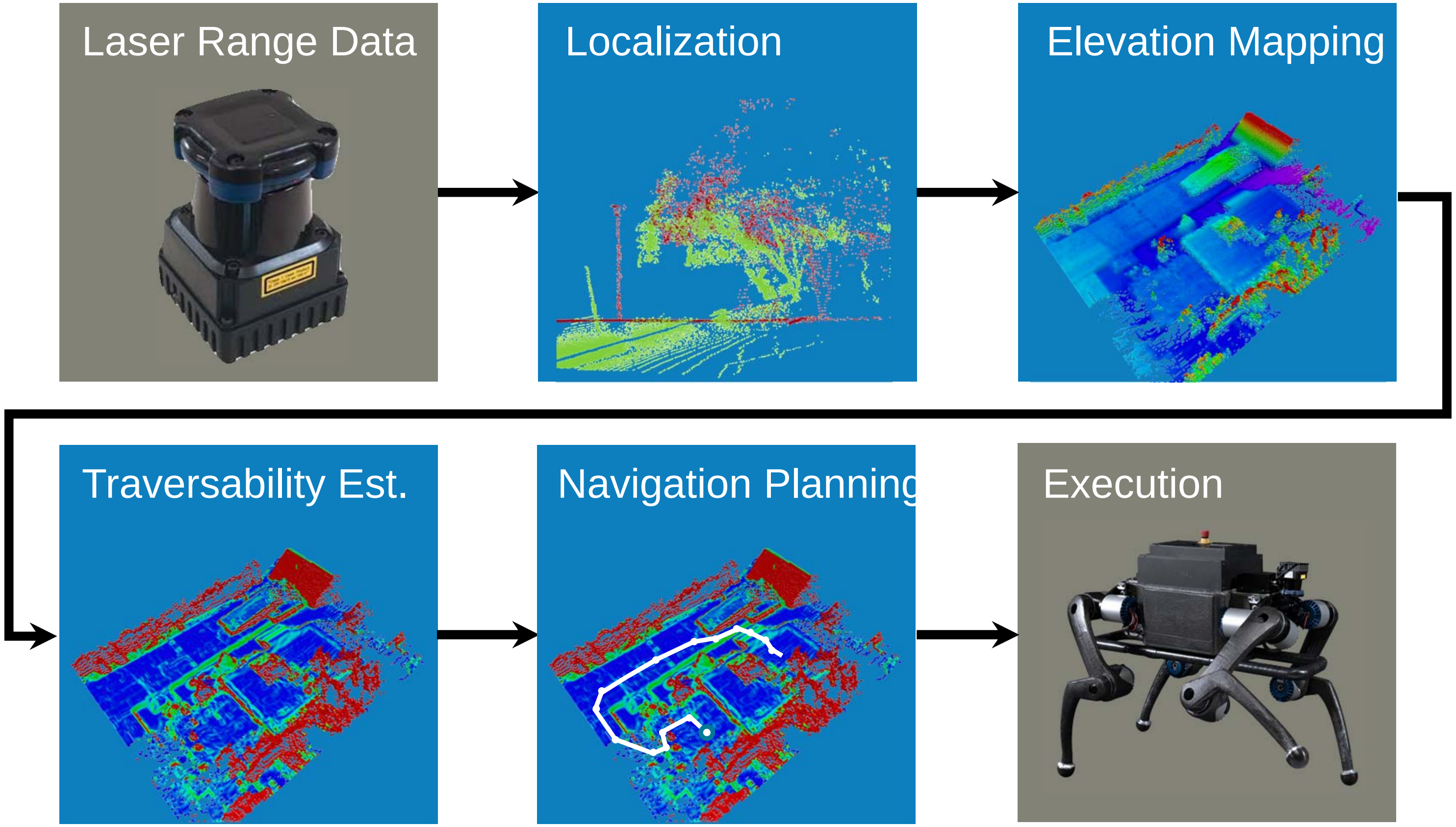
Locomotion Control



C. Gehring, S. Coros, M. Hutter, D. Bellicoso, H. Heijnen, R. Diethelm, M. Bloesch, P. Fankhauser, J. Hwangbo, M. A. Hoepflinger, and R. Siegwart, "**Practice Makes Perfect: An Optimization-Based Approach to Controlling Agile Motions for a Quadruped Robot.**", in IEEE Robotics & Automation Magazine, 2016.

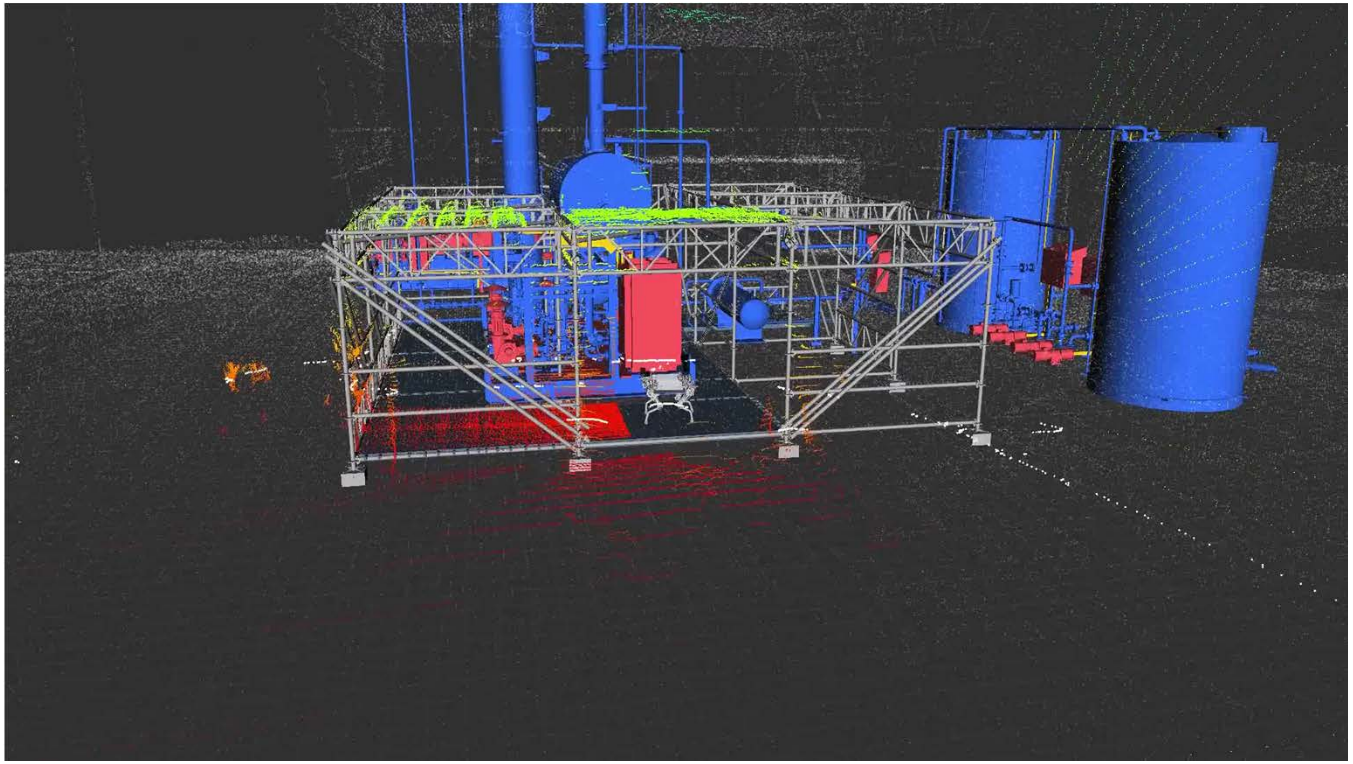
C. Dario Bellicoso, C. Gehring, J. Hwangbo, P. Fankhauser, M. Hutter, "**Emerging Terrain Adaptation from Hierarchical Whole Body Control**," in IEEE Internal Conference on Humanoid Robots (Humanoids), 2016.

Navigation


Laser Range Data
Localization
Elevation Mapping
Traversability Est.
Navigation Planning
Execution

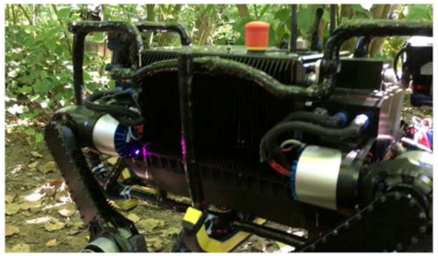
[Diethelm et. al., 2015]

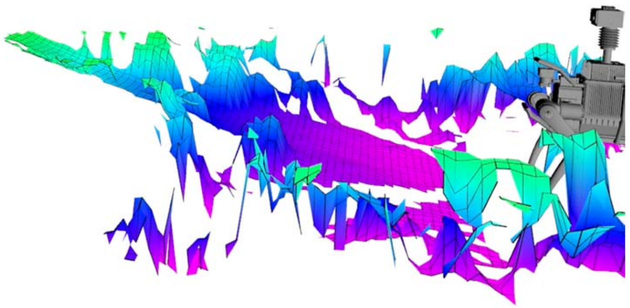
Navigation
ICP Localization



- Point cloud registration for localization in reference map
- Full rotation of LiDAR is aggregated for point cloud
- Use of existing maps or online mapping

Navigation
Elevation Mapping – Dense Terrain Mapping

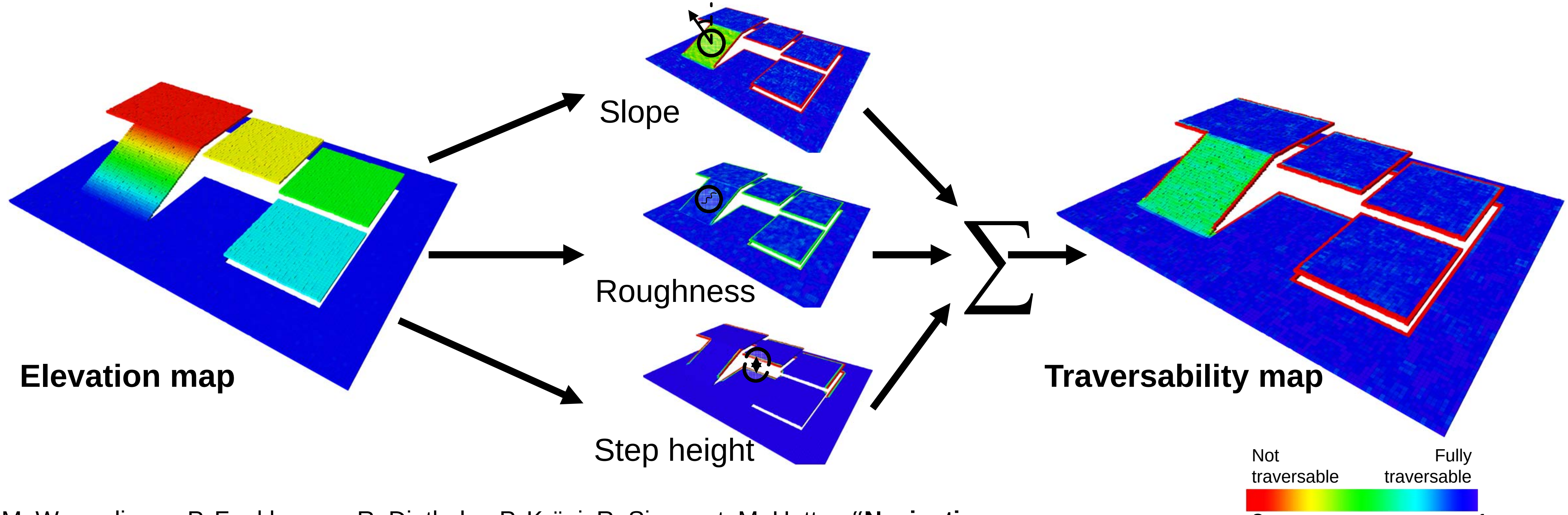




- Probabilistic fusion of range measurements and pose estimation
- Explicitly handles drift of state estimation (robot-centric)
- Input data from laser, Kinect, stereo cameras, Velodyne etc.

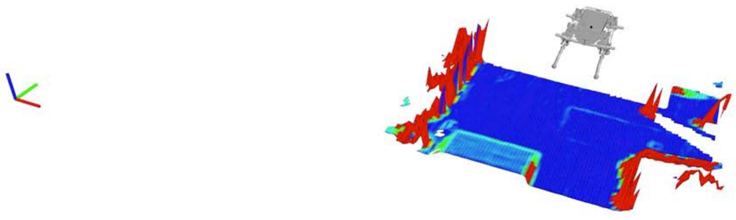
P. Fankhauser, M. Bloesch, C. Gehring, M. Hutter, R. Siegwart **"Robot-Centric Elevation Mapping with Uncertainty Estimates,"** in International Conference on Climbing and Walking Robots (CLAWAR), 2014.

Navigation
Traversability estimation



M. Wermelinger, P. Fankhauser, R. Diethelm, P. Krüsi, R. Siegwart, M. Hutter, **“Navigation Planning for Legged Robots in Challenging Terrain,”** in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016.

Navigation Planning



- Online navigation planning based on RRT* (OMPL)
- Works with and without initial map
- Continuous for changing environments

M. Wermelinger, P. Fankhauser, R. Diethelm, P. Krüsi, R. Siegwart, M. Hutter, **“Navigation Planning for Legged Robots in Challenging Terrain,”** in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2016.

Collaborative Navigation
Vision based localization

RSL Robotic Systems La

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Inspection

Visual inspection

Thermal Inspection

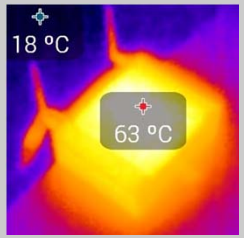
Auditive Inspection



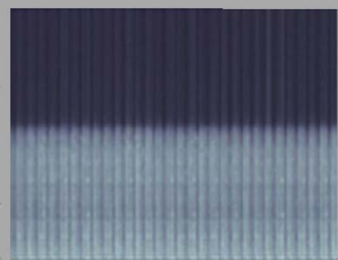



Pressure & Level gauges Valves Thermal points Pumps Gas leaks Platform alarm

Thermal-camera



Microphones (audible and ultra-sonic)

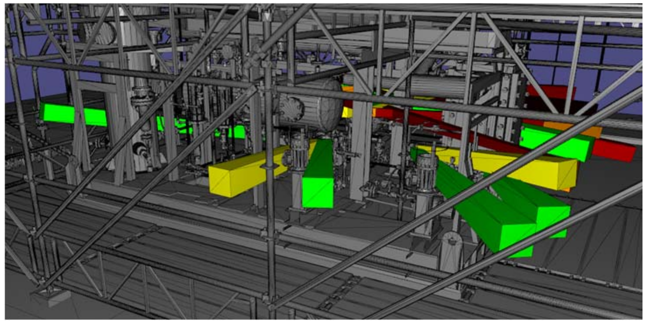


Robotic Systems Lab

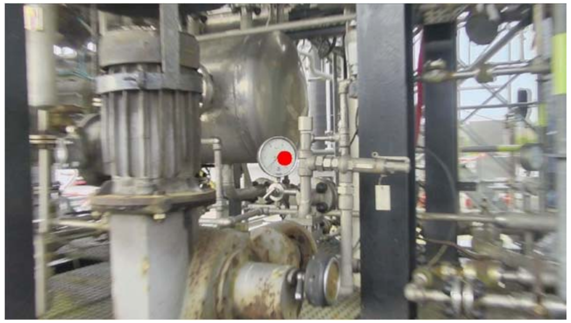
Inspection

Visual inspection of pressure gauges

Automatic view point generation



Visual servoing



Whole-body camera positioning

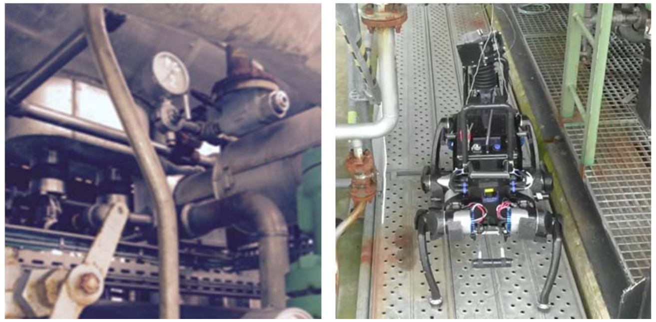
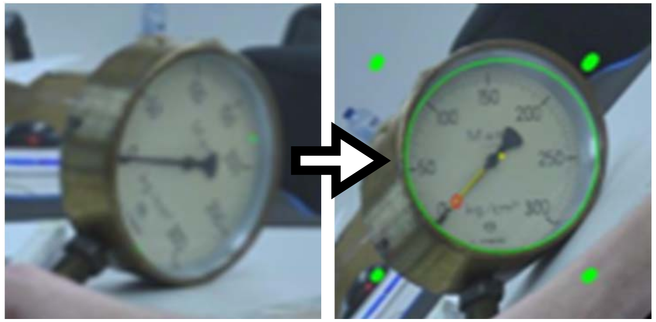
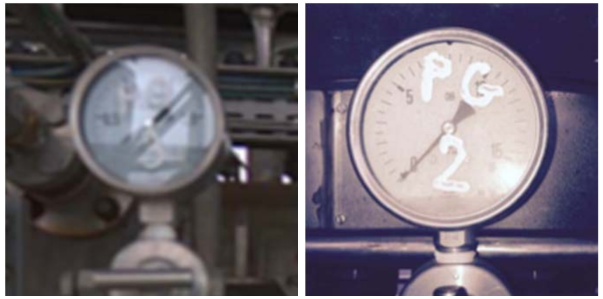


Image de-warping



Indicator reading

➔ Reading ok



➔ Reading unsuccessful, try alternative position or report as unknown

S. Bachmann, “**Visual Inspection of Manometers and Valve Levers**”, Master’s Thesis, ETH Zurich, 2015.