# The eXperimental Robot Project

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3. . . . to reality
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   - Sensors
   - Gears and Actuators
   - Motor Testbed
   - Other Projects

# XRP: Goals

The e**X**perimental **R**obot **P**roject

- Life-size humanoid robot
- Focus on legs (walking), arms and hands will come (much) later
- Fully free (open source, open hardware), transparent development process
- Goal: state-of-the-art software, hardware optimized for cost/manufacturability

# Why humanoids?

- Wheels ideal in dedicated environment (streets), otherwise fairly limited
- Human environments made for humans, wheels are really limiting (wheelchair!)
- Service robots
- Disaster recovery

- The real reason: they are cool. . .

# Other projects

- Progress on humanoids appears to be heating up
- Big company players (~~Boston Dynamics, Schaft~~ Google) extremely secretive
- University projects more, but still not fully, open
- Exisiting robots cost $\geq$ 100 k€ (our goal: few k€)
- Physics-based character animation is a hot topic at SIGGRAPH (but usually not on physical hardware)

# Simulation: Introduction

- Simulate robot using simplified physics models
- Goal: develop controllers
- Goal: evaluate actuation requirements
- Goal: inform design choices

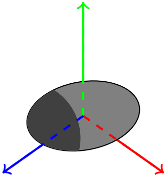
- Use dedicated dynamics toolkit plus external engine (Open Dynamics Engine: ODE, http://www.ode.org/) for verification

# Rigid Body Dynamics

How to simulate a robot?

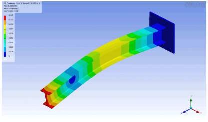
**Rigid body:**

- Non-deformable (no flexing, vibration, etc.)
- Details of mass distribution condensed into 10 parameters
- 6 degrees of freedom



Next step up in realism: **soft body**

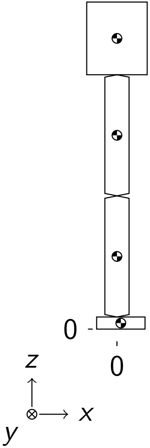
- Complete details of mass distribution/stiffness/etc. matter
- Infinitely many degrees of freedom
- Simulation by finite element method



Wikipedia

# Robot model

**Side view**




Pelvis/torso
Hip (HZ, HY, HX)

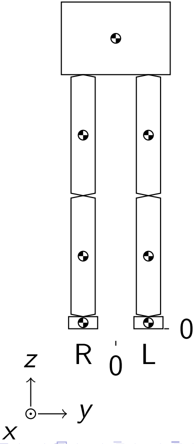
Thigh

Knee (KY)

Shank

Ankle (AY, AX)
Foot

**Front view**



# Why is walking a hard problem?

Industrial Robot vs. Biped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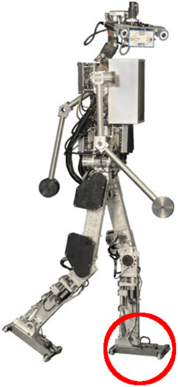
Industrial Robot vs. Biped

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# Industrial Robot vs. Biped

## Main difference

- Industrial Robot: Base bolted to ground
- Biped: stance leg only kept in place by friction

- Industrial Robot: one actuator per degree of freedom
- "Any" trajectory can be followed

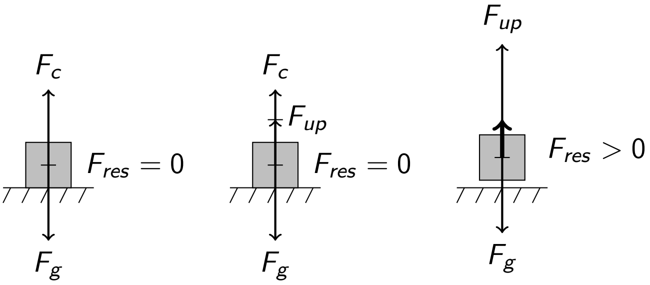
- Biped: reaction forces on stance foot not directly controllable
- Intrinsic dynamics matter
- No longer "any trajectory possible"

# Demo: trajectory tracking is not enough!

Demo time!

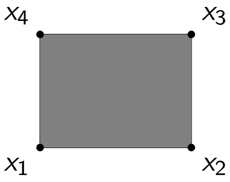
# Contact forces: normal component

- Contact is a complicated microscopic phenomenon
- Contacts are (usually) non-sticky!
- Normal component of contact force: $F_c^{(n)} \geq 0$.

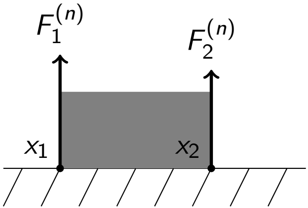


# Multiple contacts: the center of pressure

Consider multiple contact points $x_i$:



(top view)



(side view)

Define center of pressure as weighted average of contact points.

# Center of pressure (2)

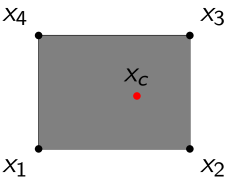
CoP is average of contact points, weighted by contribution to normal component of contact force.

$$x_c = \frac{\sum_i x_i F_i^{(n)}}{\sum_i F_i^{(n)}}$$

Rewrite as:

$$x_c = \sum_i \alpha_i x_i \ , \quad \alpha_i = \frac{F_i^{(n)}}{\sum_i F_i^{(n)}}$$

$F_i^{(n)} > 0$ implies $0 \leq \alpha_i \leq 1$.




$x_c$ must lie inside rectangle!

# Center of pressure (3)

CoP seems to depend to microscopic details of contact $\Rightarrow$ useless. However:

Sum all contact forces into total contact force and torque:

$$F = \sum_i F_i \ , \quad T = \sum_i x_i \times F_i$$

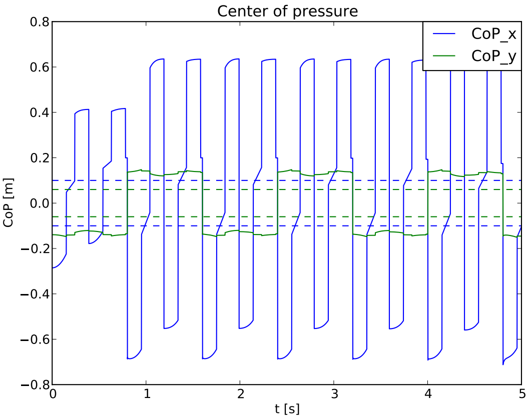
Let $n$ be the normal vector and coordinate origin in the contact plane. Then:

$$x_c = \frac{n \times T}{n \cdot F}$$

# Center of pressure (4)

- Stance foot stationary $\Rightarrow$ contact forces compensate reaction from robot body
- Necessary conditions for real contact:
  - $F^{(n)} \geq 0$
  - $x_c$ inside foot (convex hull for multiple feet)
- Sufficient for no-slip (Coulomb friction with $\mu \to \infty$)
- Usually sufficient in practice

# Naive walking revisited



# Control strategy

- Focus on contact forces

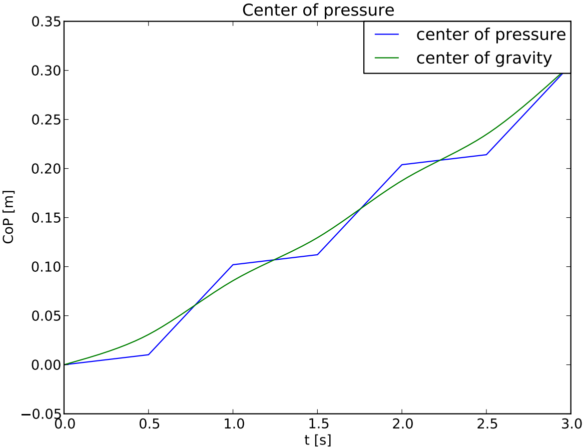
- Imagine: robot floating in space
- Linear and angular momentum conserved
- Conservation of linear momentum implies that center-of-mass trajectory cannot be influenced

- Robot on ground: Total linear and angular momentum can only be changed through contact forces
- Linear/angular momentum change $\Leftrightarrow$ Contact forces

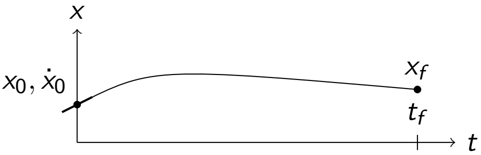
# Control strategy (2)

- Simplifying restriction: $L = \dot{L} = 0$ (total angular momentum zero)
- Contact forces fully determined from center of mass trajectory (joint angle trajectories do not matter!)
- Specify 6 contact forces via $\dot{L} = 0$ (3 eqn.), center of pressure (2 eqn.), $z_{\mathrm{com}}(t)$ (1 eqn.)
- Solve boundary value problem to find center of mass trajectory
- Idea from PhD thesis of T. Buschmann (TU Munich)

# Control strategy (3): Demo



# Control strategy (4)




- We have 3 boundary conditions $x_0$, $\dot{x}_0$, $x_f$ for a second order differential equation
- Add CoP trajectory modification to get remaining DoF
- Modification may violate CoP constraint
- Sometimes, you need to take a sidestep ...
- ... but usually, this approach works.

# Control strategy (5)

- Use inverse dynamics to control contact forces and track center of gravity trajectory

Two cases:

- One leg on the ground: control contact force plus swing leg acceleration
- Two legs on the ground: control *two* contact forces

Each gives 12 equations for 12 joint space degrees of freedom.

# Demo #1: Walking on flat ground

Demo time!

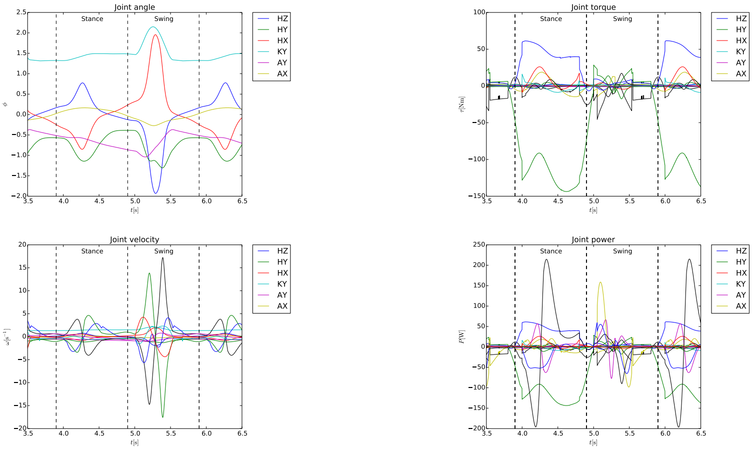
# Demo #2: Unmodelled uneven terrain

Demo time!

# Demo #3: Modelled uneven terrain

Demo time!

# Curves


Joint angle
Stance
Swing
HZ
HY
HX
KY
AY
AX
$\phi$
$t$[s]
Joint torque
$\tau$[Nm]
Joint velocity
$\omega$[s$^{-1}$]
Joint power
$P$[W]

# Control strategy: summary

Control strategy based on contact force management

- + Reasonable performance
- o Foot positions fixed in advance
  - + Can be used by higher-level controller, e.g. for climbing stairs
  - – Limits options for push recovery (cannot take sidesteps)
- – $L = 0$ causes excessive torso motion and forces unnatural walking style

# XRP dynamics toolkit

- General-purpose physics engine: forward dynamics only
- Treat physics as black box: inefficient

- Dynamics algorithms, specialized for our robot model
- Analytical inverse kinematics for 6-DoF legs
- Forward dynamics
- Inverse dynamics
- Contact force prediction/management

- Open source, alpha release soon

**Reference:** R. Featherstone: Rigid Body Dynamics Algorithms (Springer 2008)

# Long term prospect: optimization

- Hand-crafted controllers OK for simple walking
- Approach breaks down for complicated movements
- Design movements by large-scale numerical optimization
- Good way to use (still) increasing computational power
- Many interesting results in simulation (SIGGRAPH)
- Few results on physical robots: Why?

# Actuation requirements

Ballpark estimates:

- Peak joint torque: $\sim$ 100 Nm
- Peak velocity: $\sim$ 20 rad/s
- Peak power: $\sim$ 250W (per DoF)

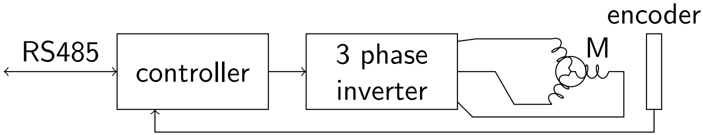
Mainstream option: BLDC motor

# Motor

- Cheap 30$ 2kW BLDC RC Motor
- Weight: $\sim$ 500g
- Slightly overpowered but has only 270KV
- $\rightarrow$ 849 rad/s @ max. voltage
- Torque: 3.15 Nm @ max. current (calculated)


$\Rightarrow$ Required gear reduction ratio: $\sim$ 1:50

# BLDC controller



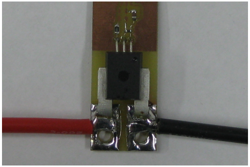

R/C BLDC controllers not intended for servo applications.

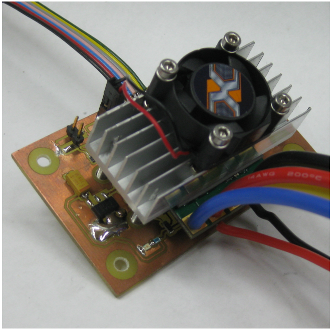
Own BLDC controller features:

- Encoder based
- Space vector modulation (3 phase AC phase-locked to motor rotation)
- Communication via RS485

# BLDC: power stage

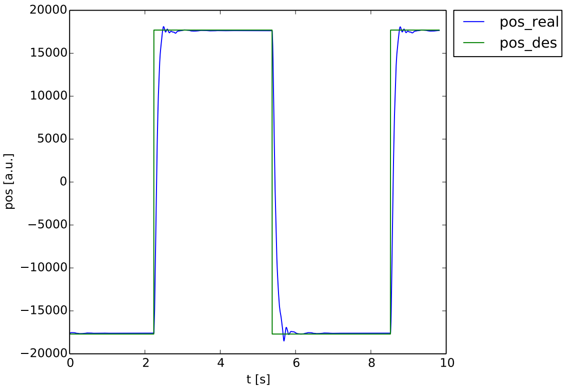
- Re-use power stage from 120A R/C BLDC controller
- Add 2 hall effect current sensors (ACS759)





# BLDC: results

position control (PID): step response



# Rotation Sensors

Austria Microsystems AS504x/AS5311

- Magnetic hall effect sensors
- AS504x: 12 bit (4096 steps/rev) absolute
- AS5311: 128 pole ring, 10/12 bit interpolation
- Combine both for 17 bit (0.003°) absolute sensor
- About 10$/sensor, 5$/magnet
- Quadrature output

Problems:

- Nonlinearity?
- Sampling

# Gear Requirements

Ballpark estimates:

- Peak joint torque in order of 100 Nm
- Motor torque $\sim$ 2 Nm
- Needed reduction $\sim$1:50

Options left:

- Gearing: Harmonic Drives, Planetary Gears
- Linear actuators: Ball screws, Planetary Roller Screws

# Comparsion

| | Planetary Gear | Harmonic Drive |
|---|---|---|
| Speed | - | + |
| Efficiency | 3% loss per stage | 87% |
| Backlash | - | ++ |
| Costs | + | - - |
| Weight | - | ++ |

# Motor Testbed

# Motor Testbed

- Static load: up to 100Nm
- 2 Ports for axial and linear actuators
- Destructive video material will be on our blog . . .

# TUlip

- Humanoid robot, realized at Eindhoven/Delft/Twente university
- 120cm, 15kg
- Uses *series elastic actuation* (resulting bandwidth: 5-10 Hz)
- Brushed motors (Maxon RE30, 60W)
- Planetary gears (Maxon GP32)
- Predecessor named *Flame*

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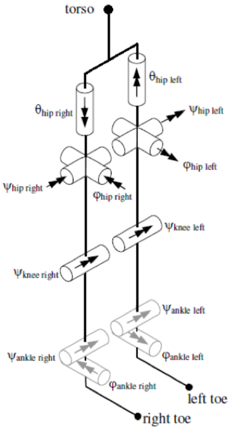
# TUlip: Kinematic concept

- 6 DoFs per leg: 3 hip, 1 knee, 2 ankle
- Hip Joint has 2 axis in 1 plane
- Third axis is in the torso
- Ankle roll axis is passive (spring)

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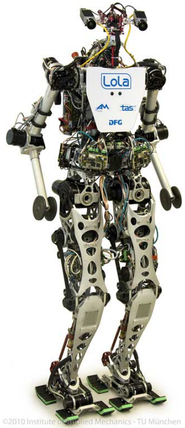
# Video #1: Flame Demo Video

Video time!

Source: www.youtube.com/watch?v=7JU_zQkVOiI

# Lola

- Humanoid robot, realized at TU Munich
- 180cm, 55kg
- 25 DoF total, 7 DoFs per leg
- Predecessor named *Johnny Walker*

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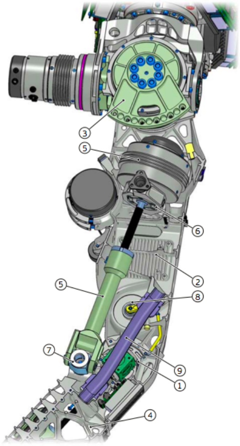
# Lola: Actuation concept

- Brushless motors (PMSM)
- Harmonic Drives (hip joint, toe joint)
- Planetary Roller Screws used as linear actuator (knee, ankles)

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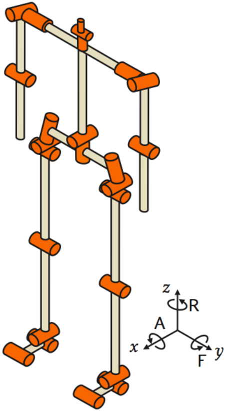
# Lola: Kinematic concept

- 7 DoFs per Leg
- Comparable to TUlip
- Additional toe joint
- All joints are active
- Hip $z$ axis is tilted against $xy$ plane

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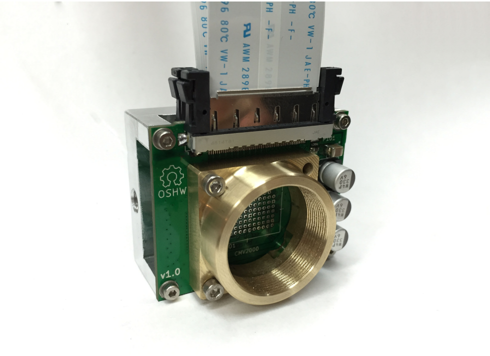
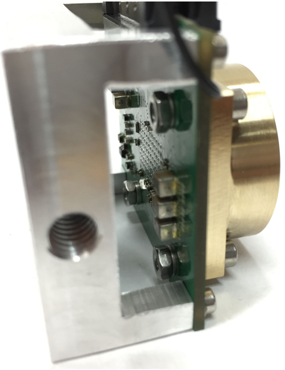
# Video #2: Lola Demo Video

Video time!

Source: www.youtube.com/watch?v=P4Y41Ago3cg

# Camera system



# Camera system

- Scientific camera based on Apertus project
- CMOSIS CMV2000 sensor
- Global Shutter
- 2k resolution, up to 340fps, up to 12bit
- All design files: http://github.com/xrpbot/cmv_2000_hardware

# Current status/Outlook

- Preparatory phase: simulation, study exisiting designs
- Workshop mostly set up: milling machine (Deckel FP2), small CNC lathe, electronics
- Biggest challenge: actuation concept
- Ready to start construction after gear question is solved

# Thank you!

http://xrpbot.org

...or meet us at C4 assembly (Chaos West)!