# NimbRo Humanoid Robots Winning RoboCup AdultSize Soccer Competitions: Mechatronics, Perception, Control, and Learning

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Computer Science Institute VI –
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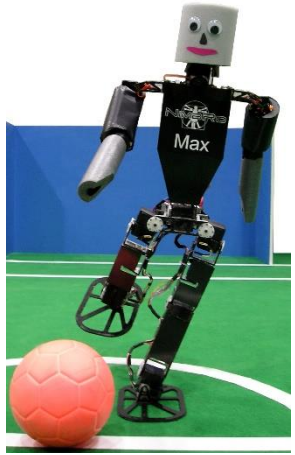
# NimbRo Humanoid Soccer Robots Since 2004


Toni 2004



KidSize 2005

KidSize 2006

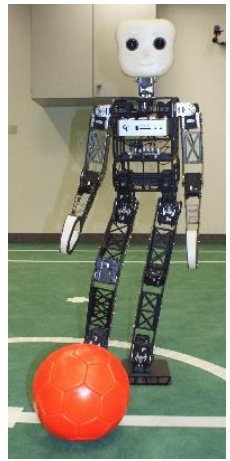
KidSize 2007

TeenSize 2007

KidSize 2008


Dynaped, TeenSize 2008


Copedo, TeenSize 2012


NimbRo-OP 2012

igus Hum. OP 2015


NimbRo-OP2 2017

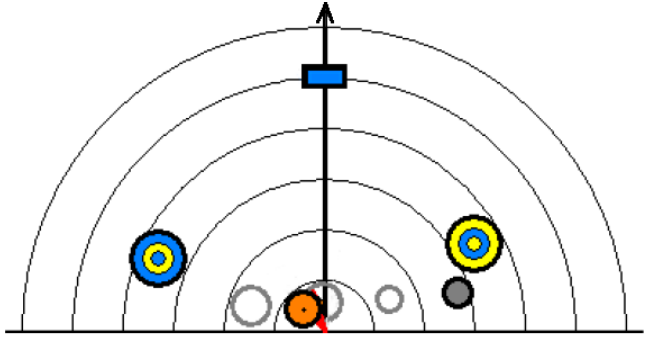

NimbRo-OP2X 2018

# Visual Perception 2007

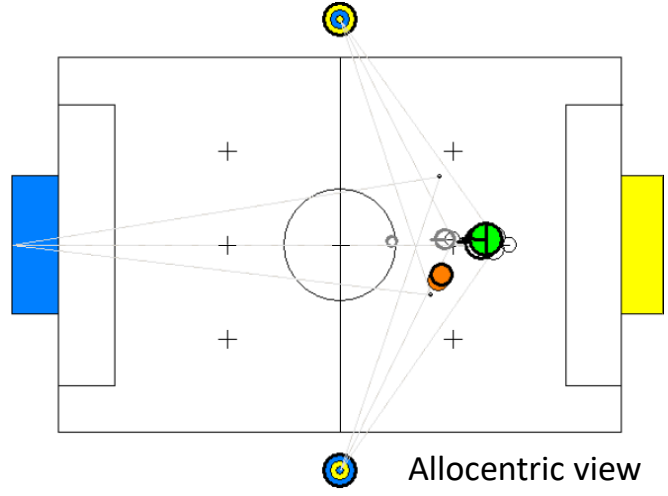
Front left

Front center

Front right

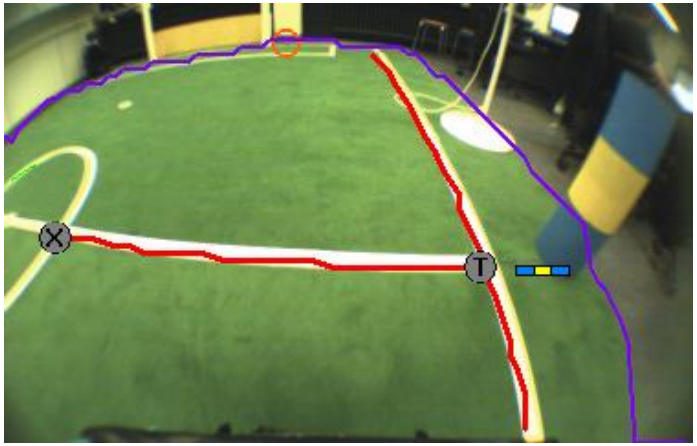


Egocentric view

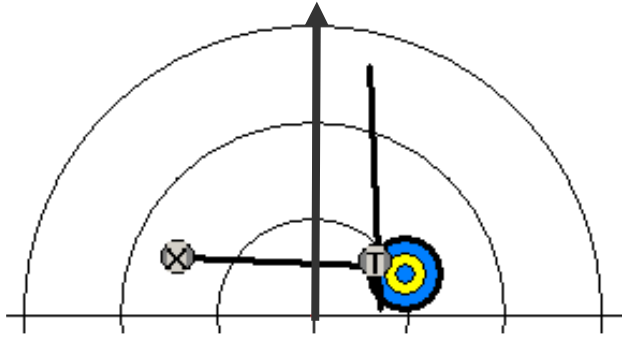


Allocentric view

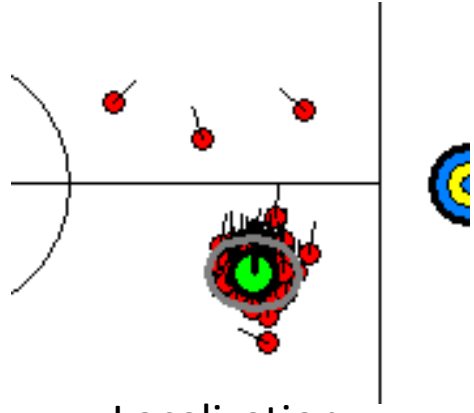
# Features for Localization



- Goals
- Field lines
- Corners of lines
- Side poles



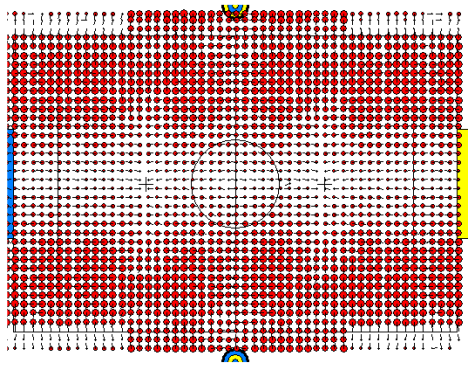
Egocentric view



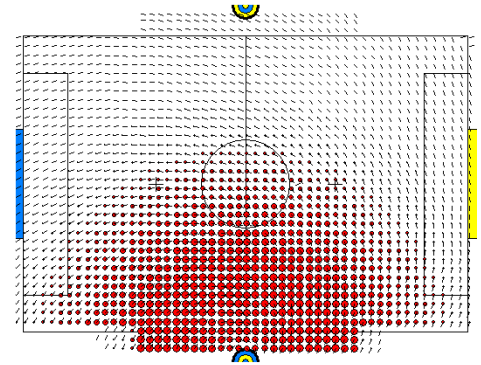
Localization

[Schulz, Liu, Stückler, Behnke: RoboCup'10]

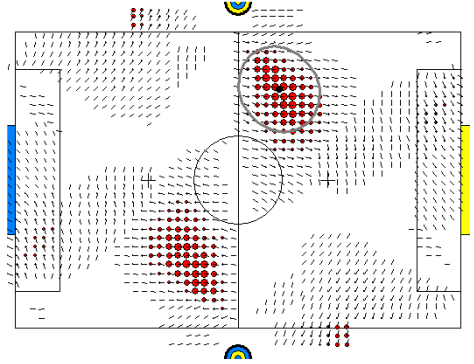
# Observation Likelihood



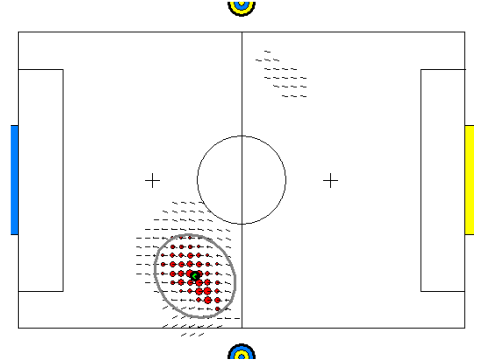
Lines



Side poles



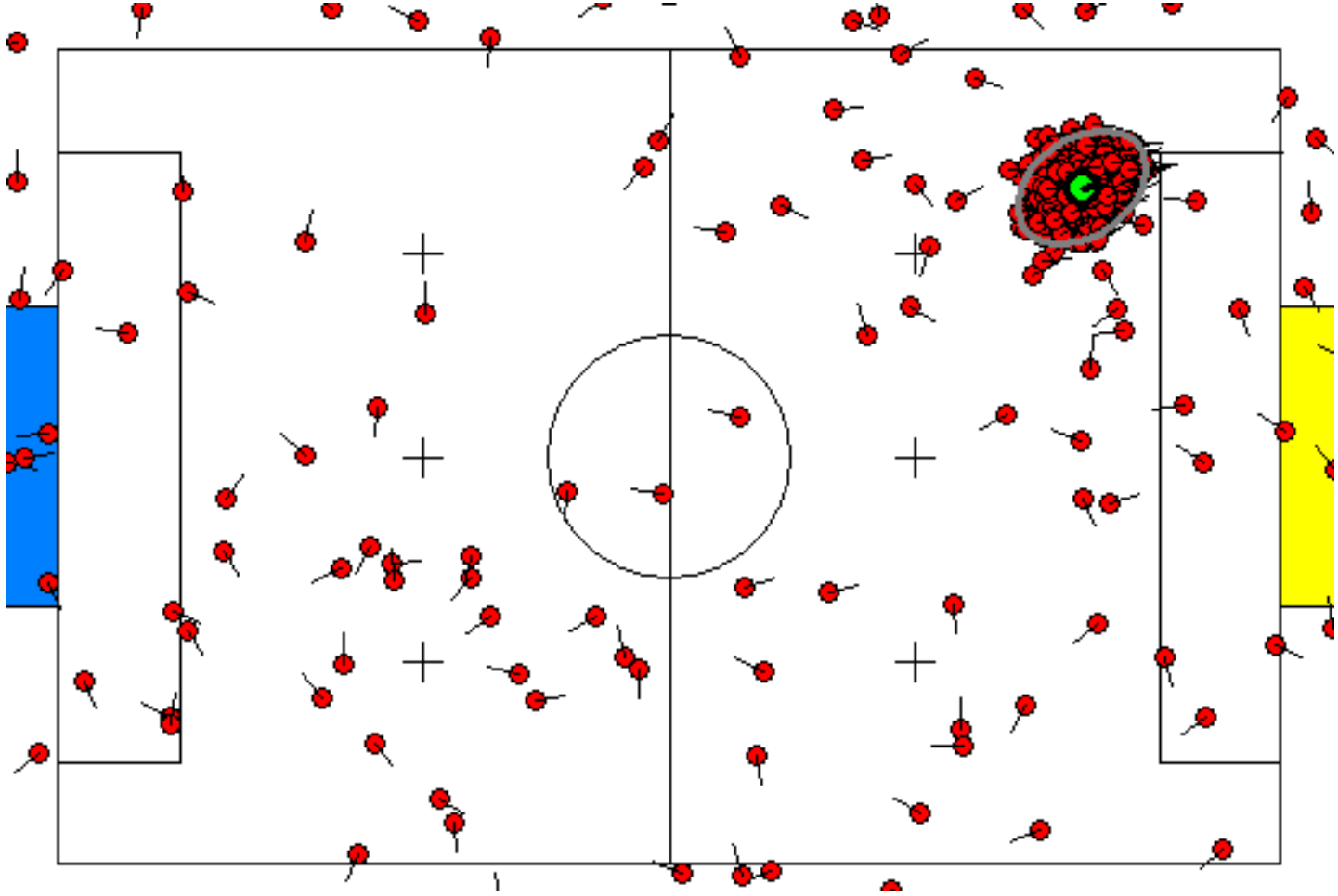
Line corners



All features

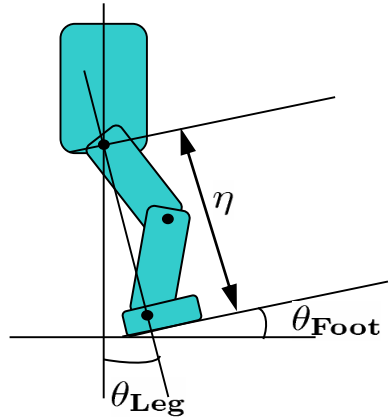
[Schulz, Behnke: Advanced Robotics 2012]

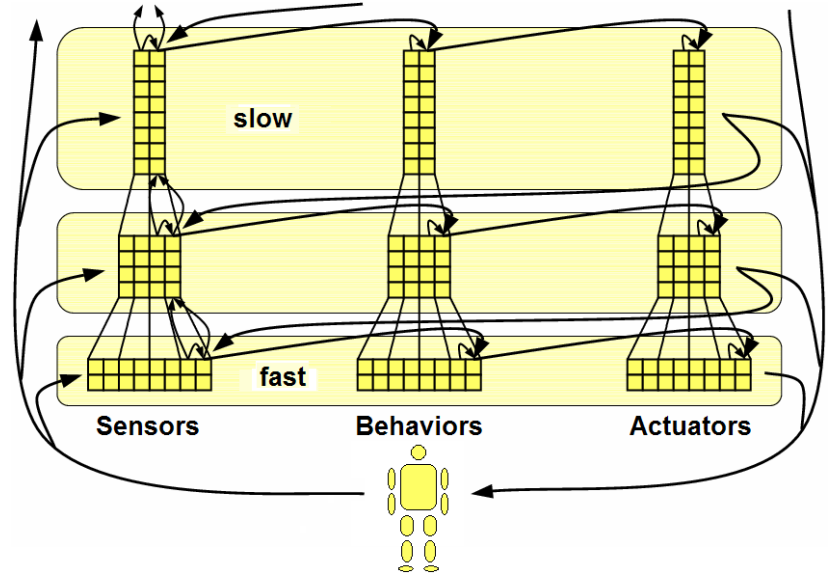
# Particle Filter Localization



# Behavior Control

- **Hierarchy of reactive behaviors**
  - **Time hierarchy** (kHz, 83Hz, 41.5Hz)
  - **Agent hierarchy** (individual joint, body part, robot, team)
  - **Complexity reduction** through interaction constraints
- **Leg interface**
  - Leg angle
  - Foot angle
  - Leg extension

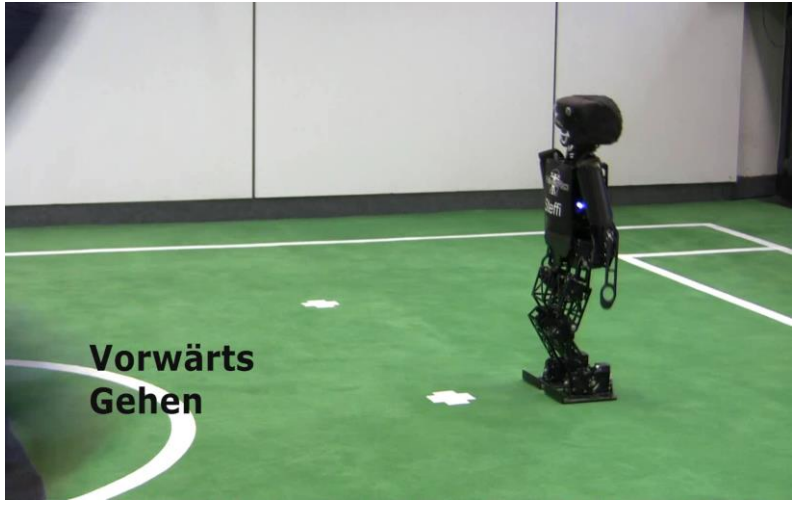


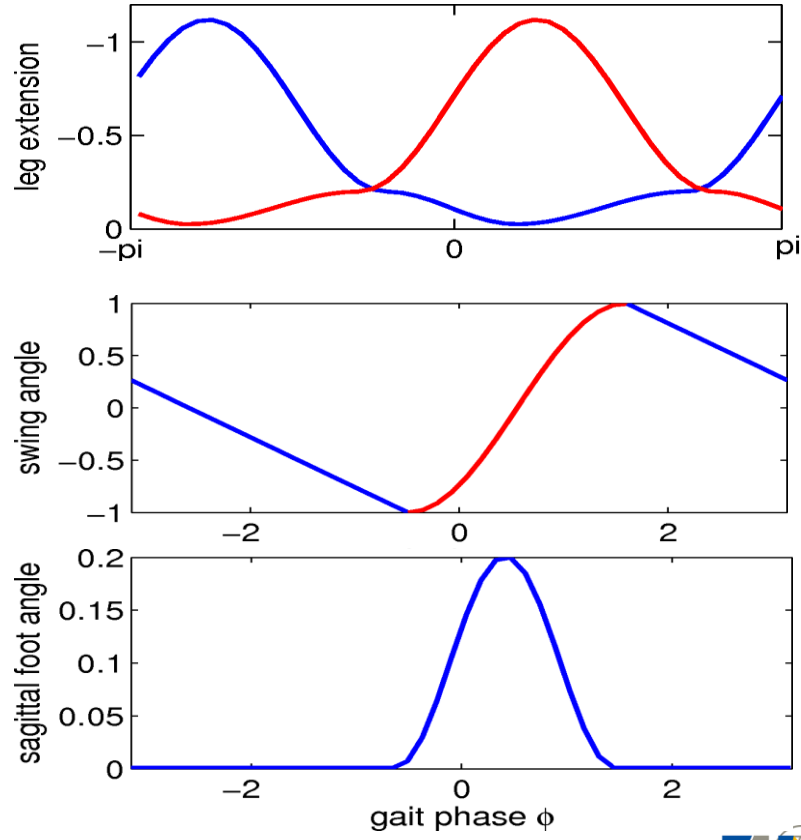




[Behnke, Stückler: IJHR 2008]

# Omnidirectional Walking

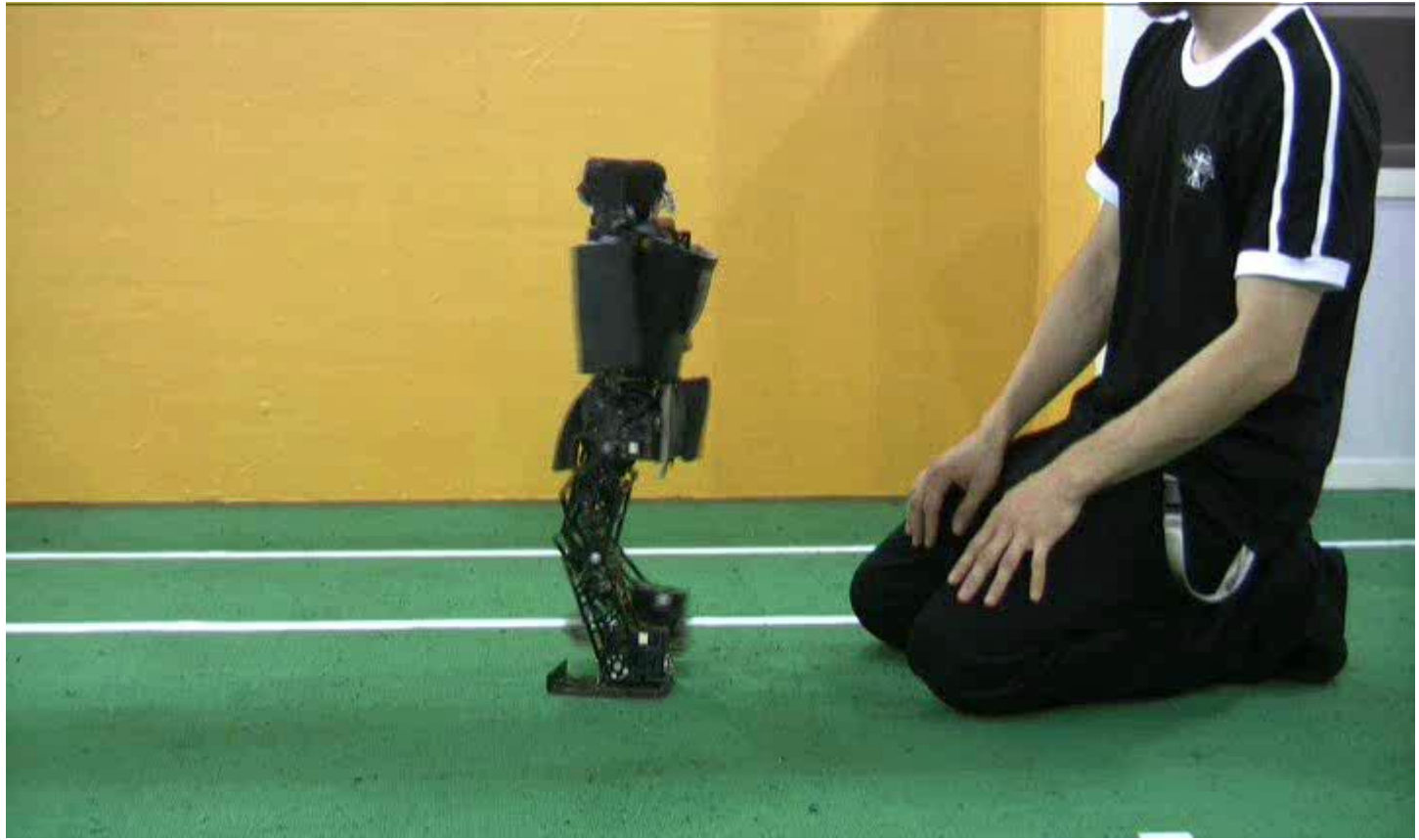
- Continuously changing walking speeds: sagittal, lateral, yaw
- Key ingredients:
  - Rhythmic weight shifting
  - Leg shortening
  - Swing in walking direction



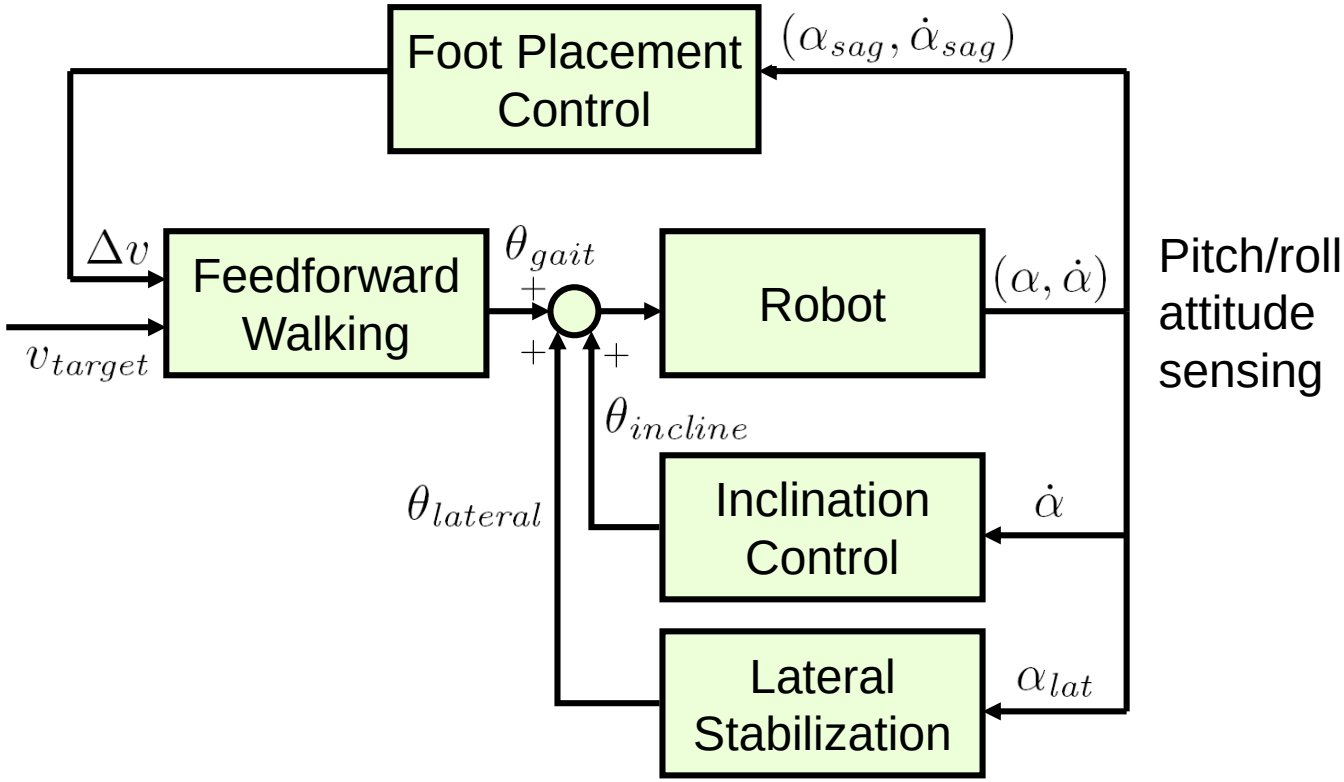

[Behnke: ICRA 2006]

# Dynamic Walking Stabilization



[Behnke et al. RoboCup 2009]

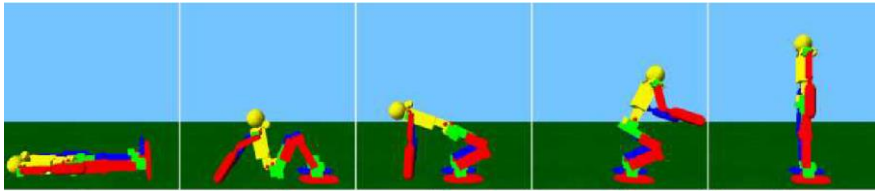
# Gait Stabilization Control

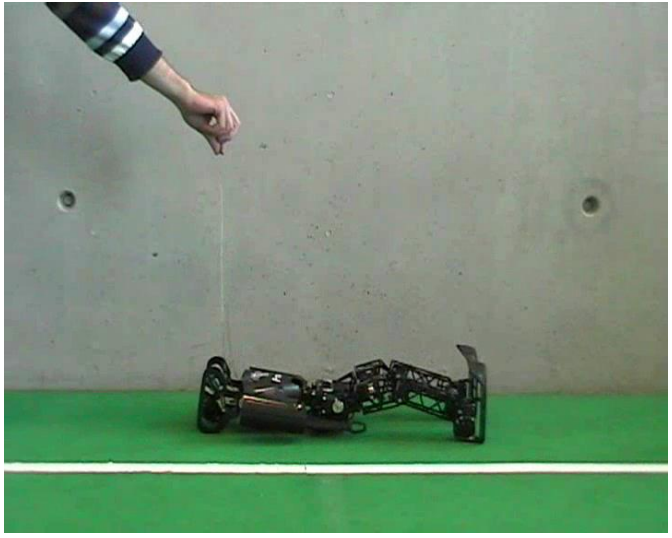



[Behnke et al. RoboCup 2009]

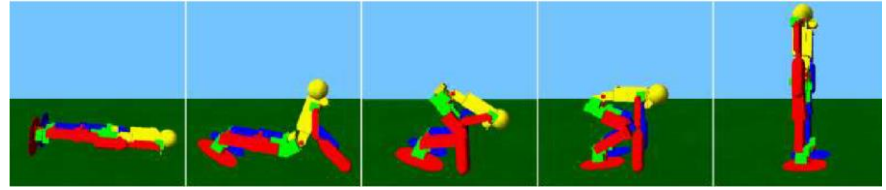
# Getting-up

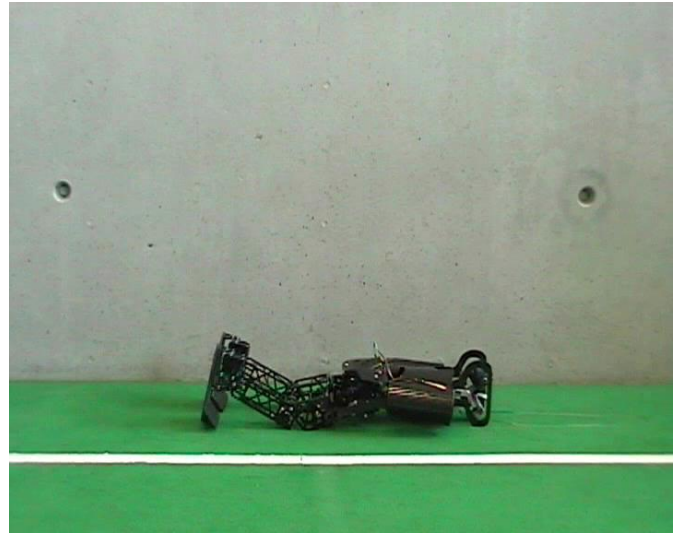
supine





prone

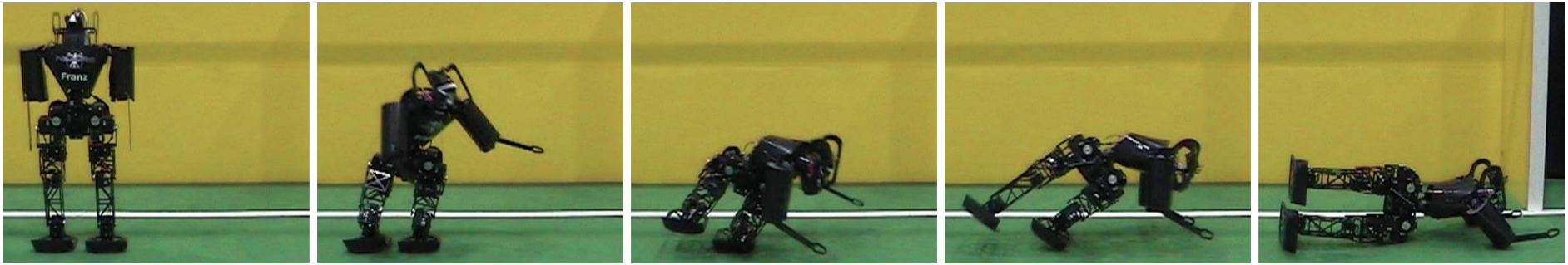




[Stückler, Schwenk, Behnke: IAS-2006]

# Goalie Diving Motion

- NimbRo KidSize 2006 Robots; Bodo, Atlanta 2007

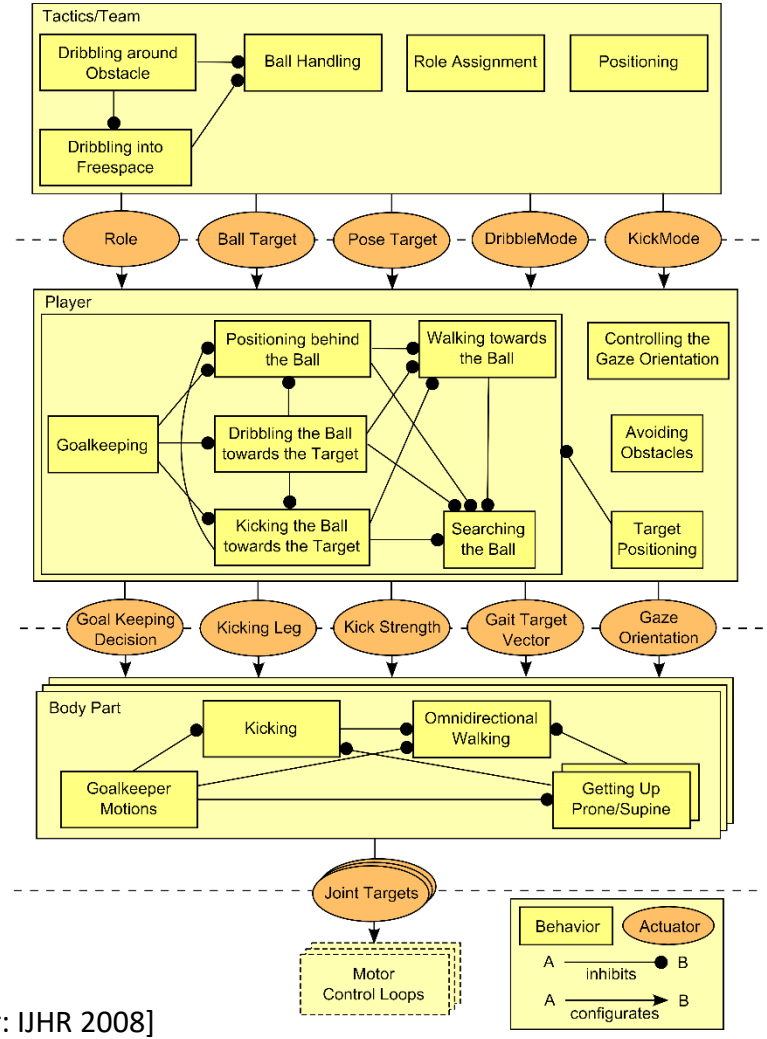



- Dynaped, Graz 2009

[Missura, Wilken, Behnke: RoboCup 2010]

# Behavior Hierarchy

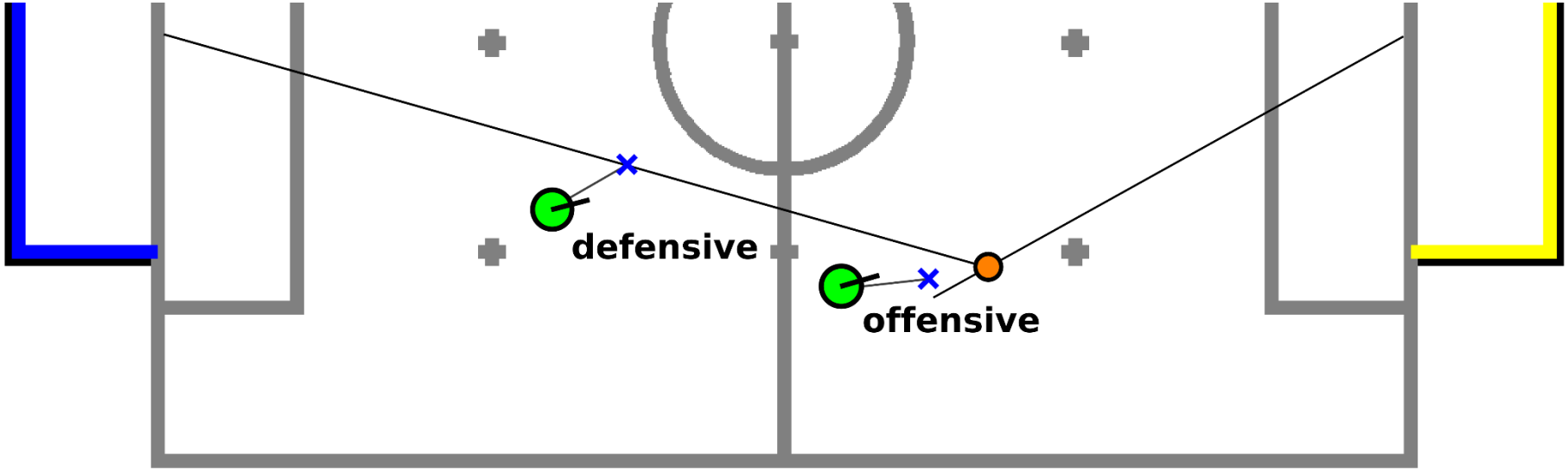
- **Tactics and Team Behaviors**
  - **Role** assignment
  - **Positioning**
  - **Ball handling**
  - Dribble **around obstacles**
  - Dribble into **free space**
- **Soccer Behaviors**
  - **Searching** for the ball
  - **Walking** towards the ball
  - **Positioning** behind the ball
  - **Kicking** ball towards target
  - **Dribbling** ball towards target
  - **Avoiding** obstacles
  - Controlling **gaze orientation**
  - **Goalkeeping**
- **Basic Skills**
  - **Omnidirectional walking**
  - **Kicking**
  - **Getting-up** from the ground
  - **Goalkeeper** motions




[Behnke, Stückler: IJHR 2008]

# Player Positioning

- Simple mechanisms

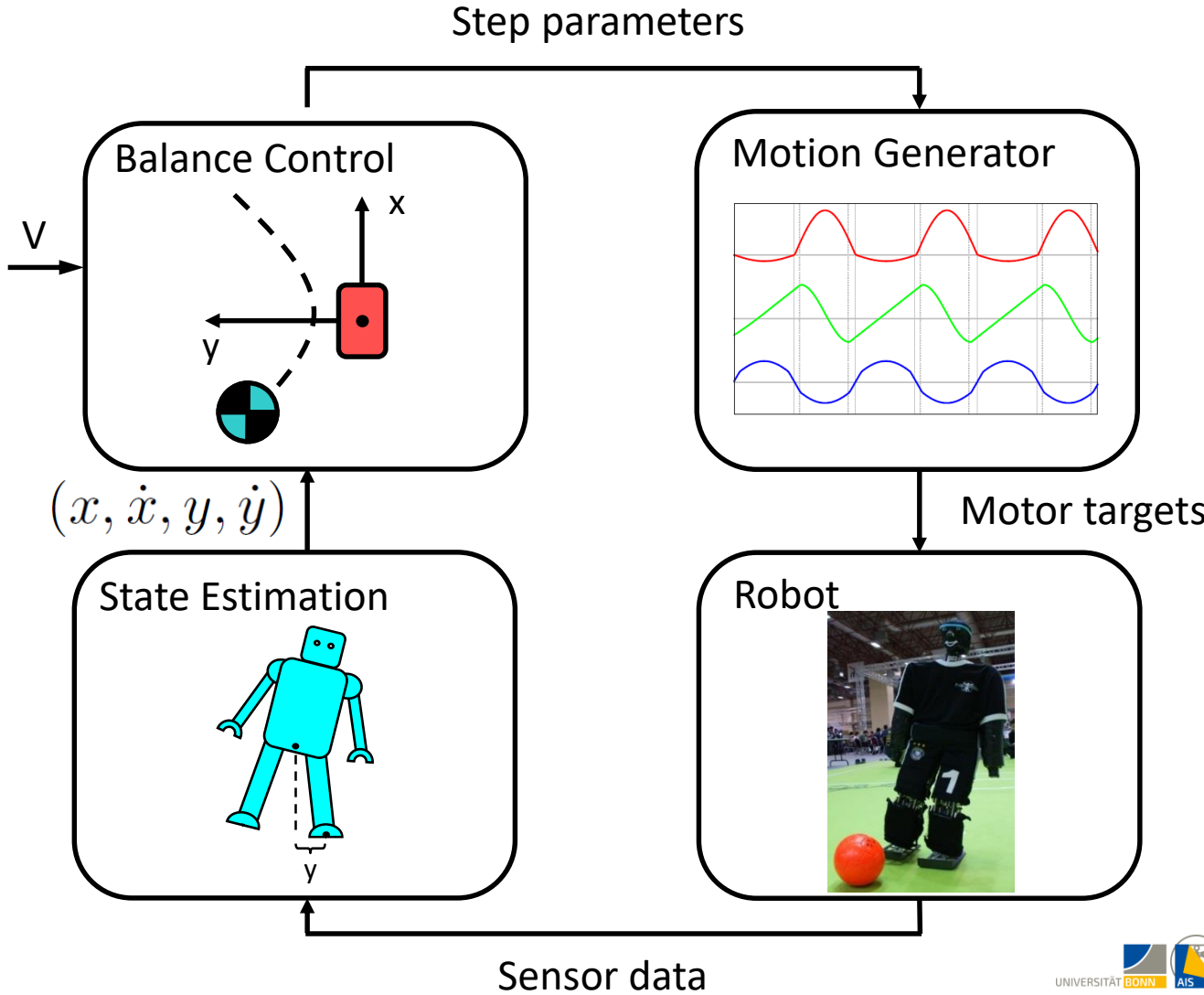


# RoboCup 2008 KidSize Final: NimbRo vs. Team Osaka

# Capture Step Framework

Velocity input:

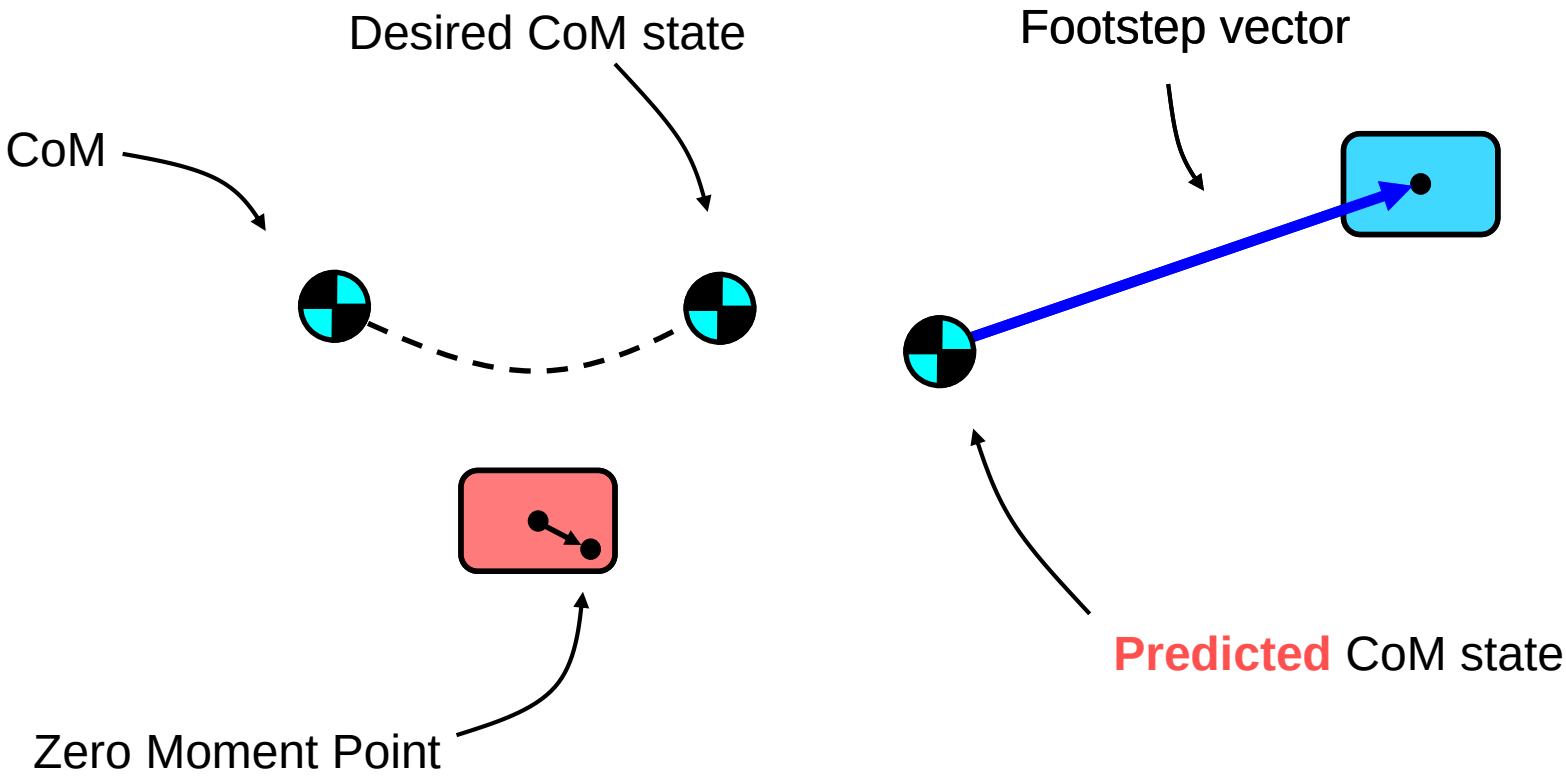
- LIP model
- Determines when and where to make the next step to regain balance and continue walking




[Missura, Behnke: Humanoids 2013, RoboCup 2014]

# Balance Control

- Adapt ZMP, timing, and foot placement




[Missura and Behnke: Humanoids 2013, RoboCup 2014]

# Omnidirectional Capture Steps


[Missura and Behnke: Humanoids 2013, RoboCup 2014]

# RoboCup 2013 Final

# Dynaped with Small Feet

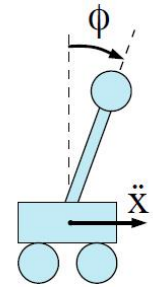

[Missura and Behnke: Humanoids 2013, RoboCup 2014]

# Online Learning of Foot Placement

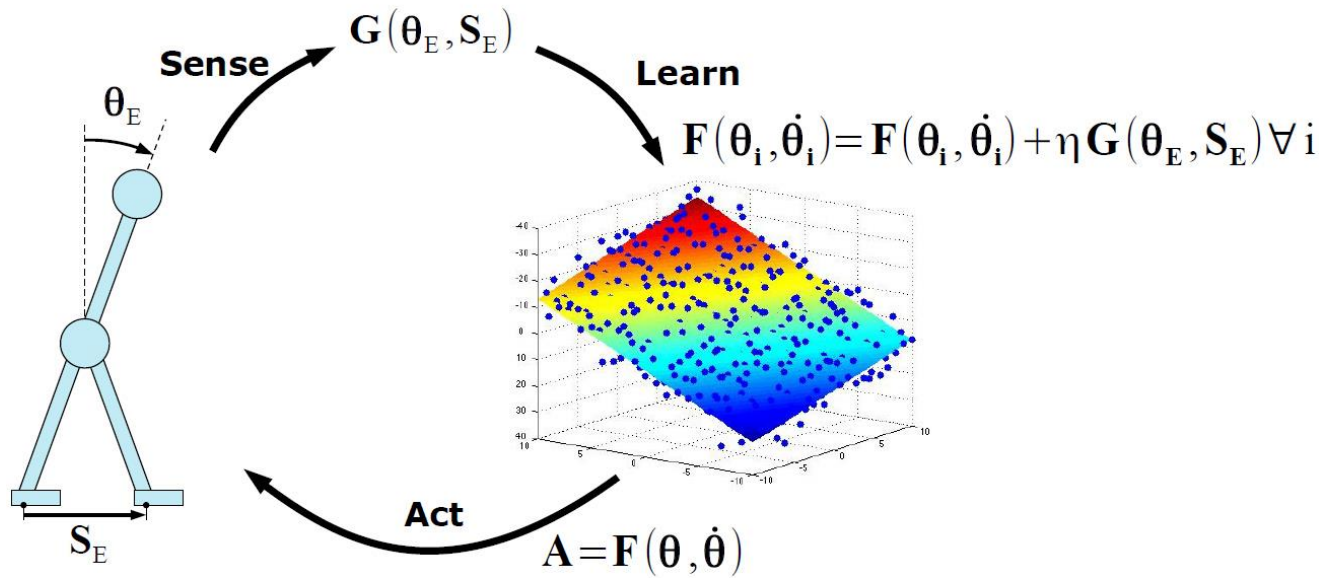
[Missura and Behnke: IROS 2015]

# Online Learning of Foot Placement

- Function approximator for step size
- Online update based on tilt and step size error

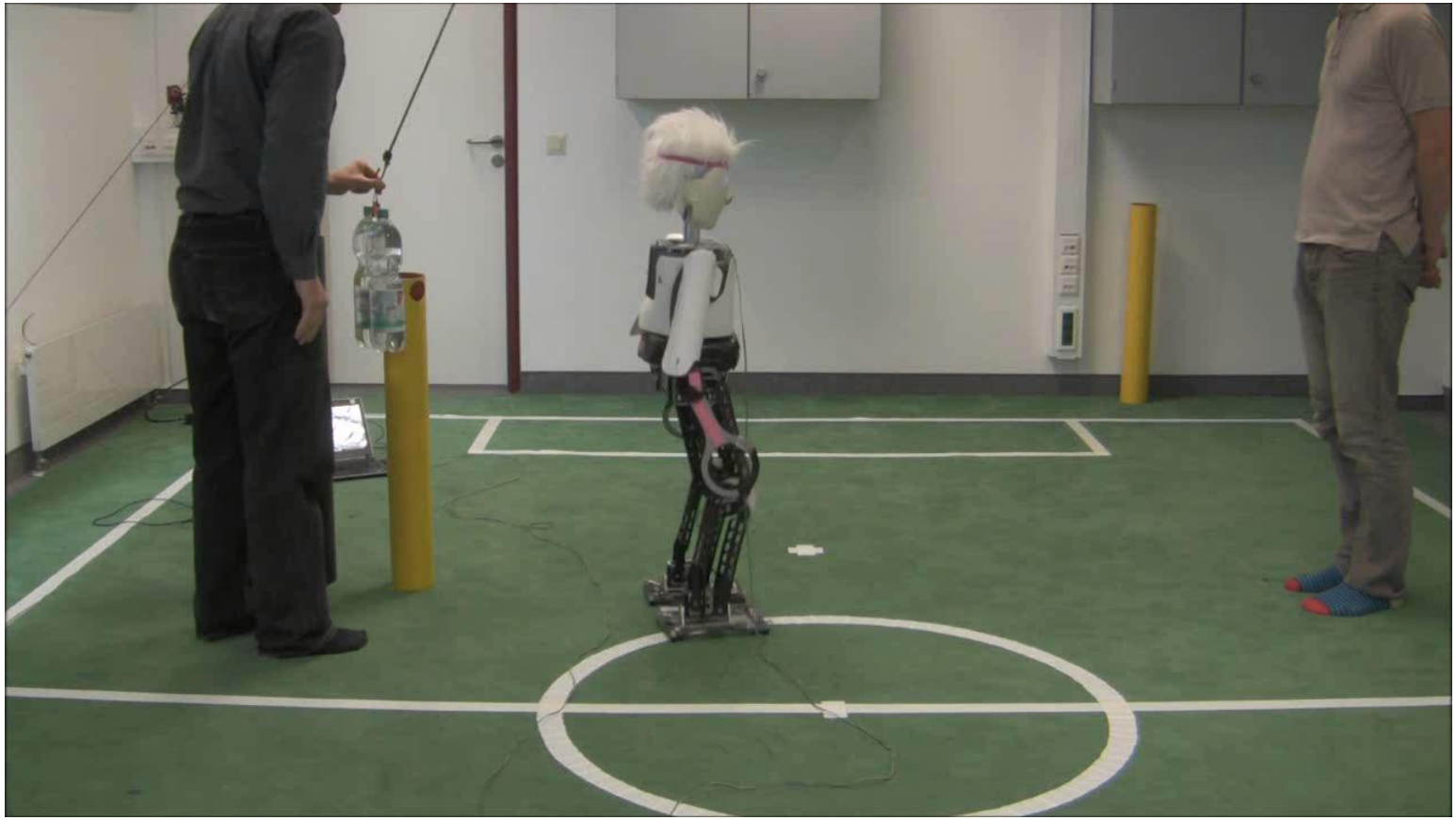



$$\mathbf{G}(\theta_E, S_E) = \theta_E + p_1 \tanh(p_2 S_E)$$



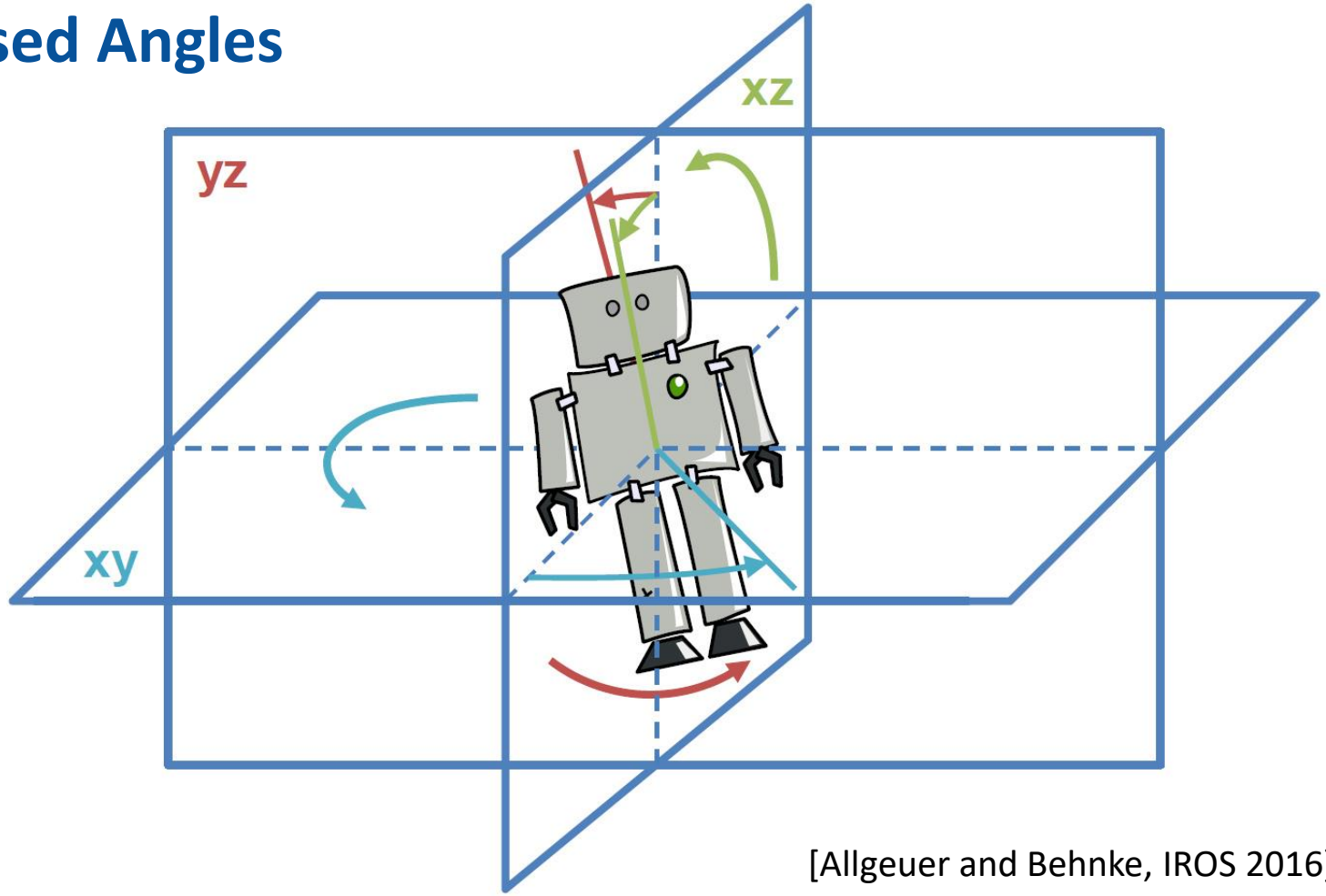

[Missura and Behnke: IROS 2015]

# Online Learning of Foot Placement



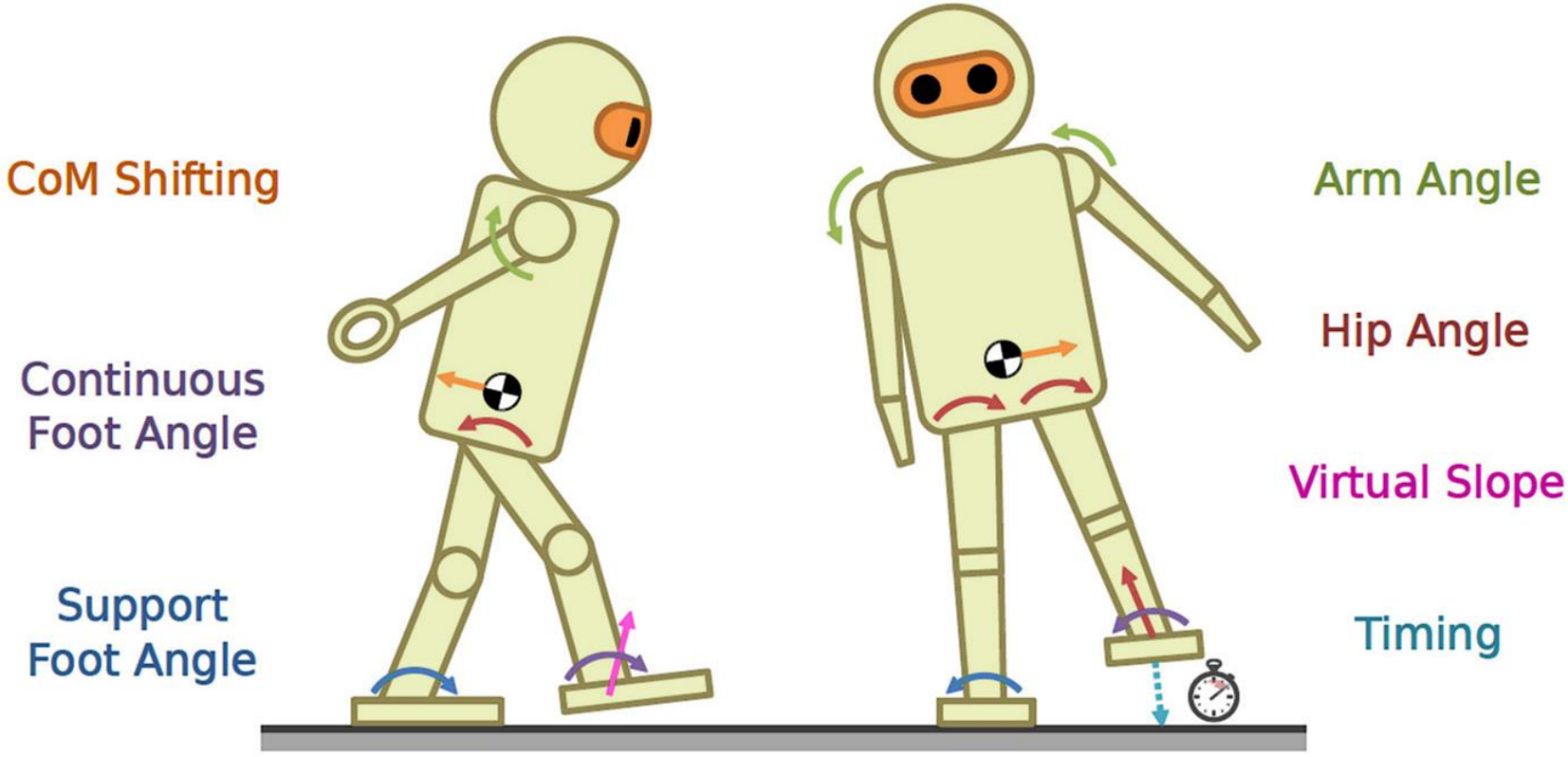
[Missura Behnke: IROS 2015]

# Fused Angles



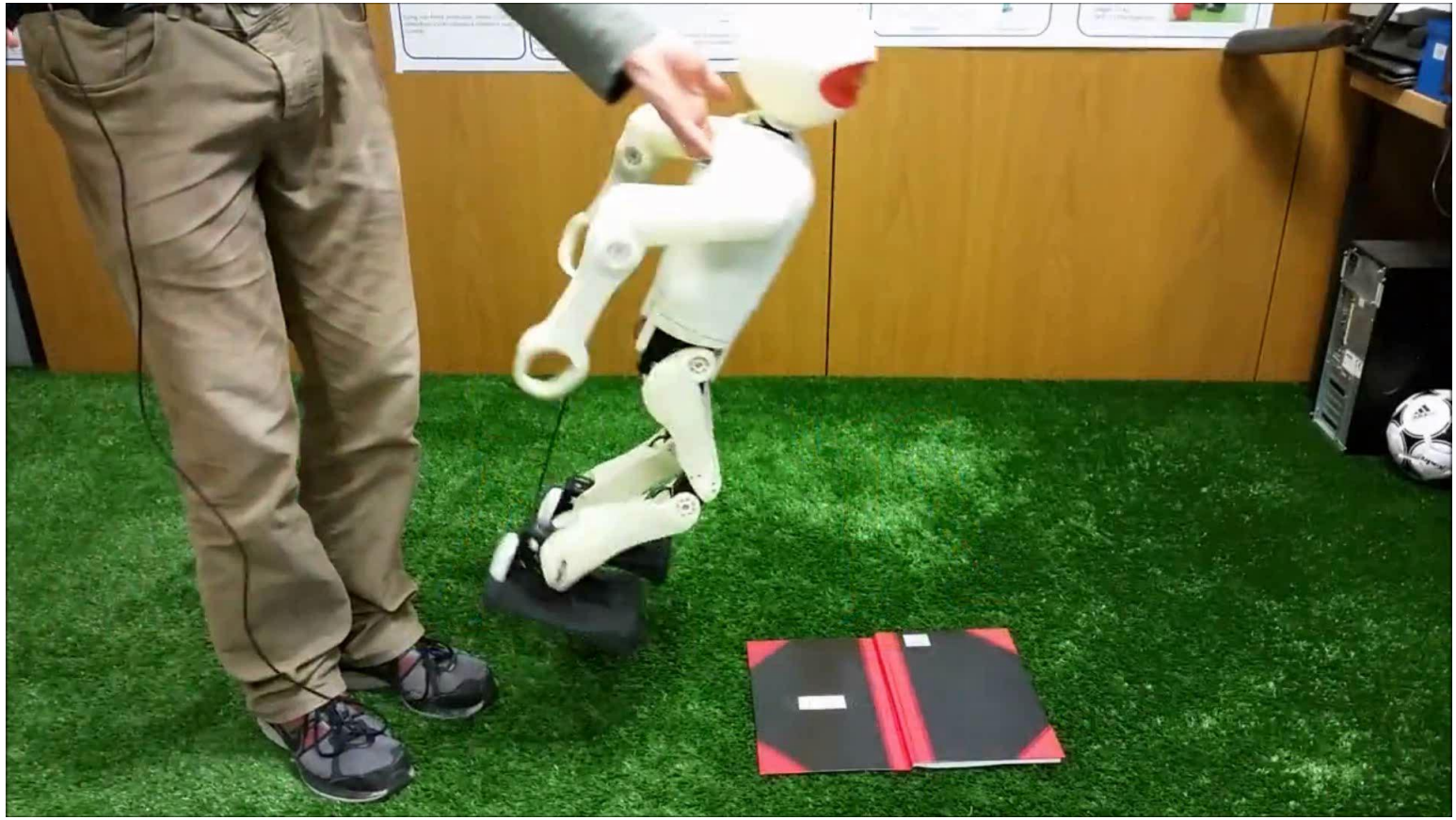

[Allgeuer and Behnke, IROS 2016]:

# Feedback Mechanisms




[Allgeuer and Behnke: Humanoids 2016]

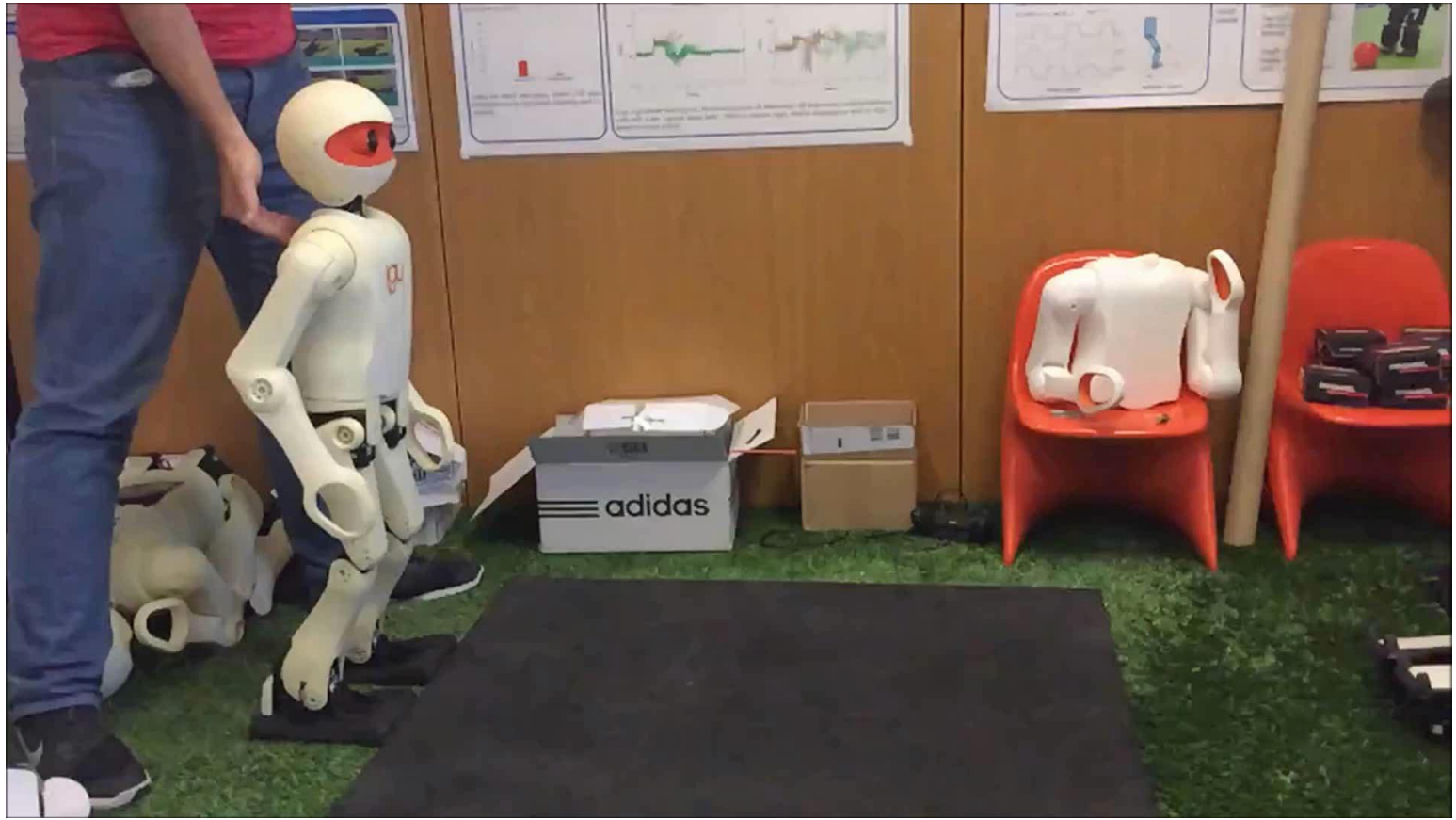
# PD Feedback



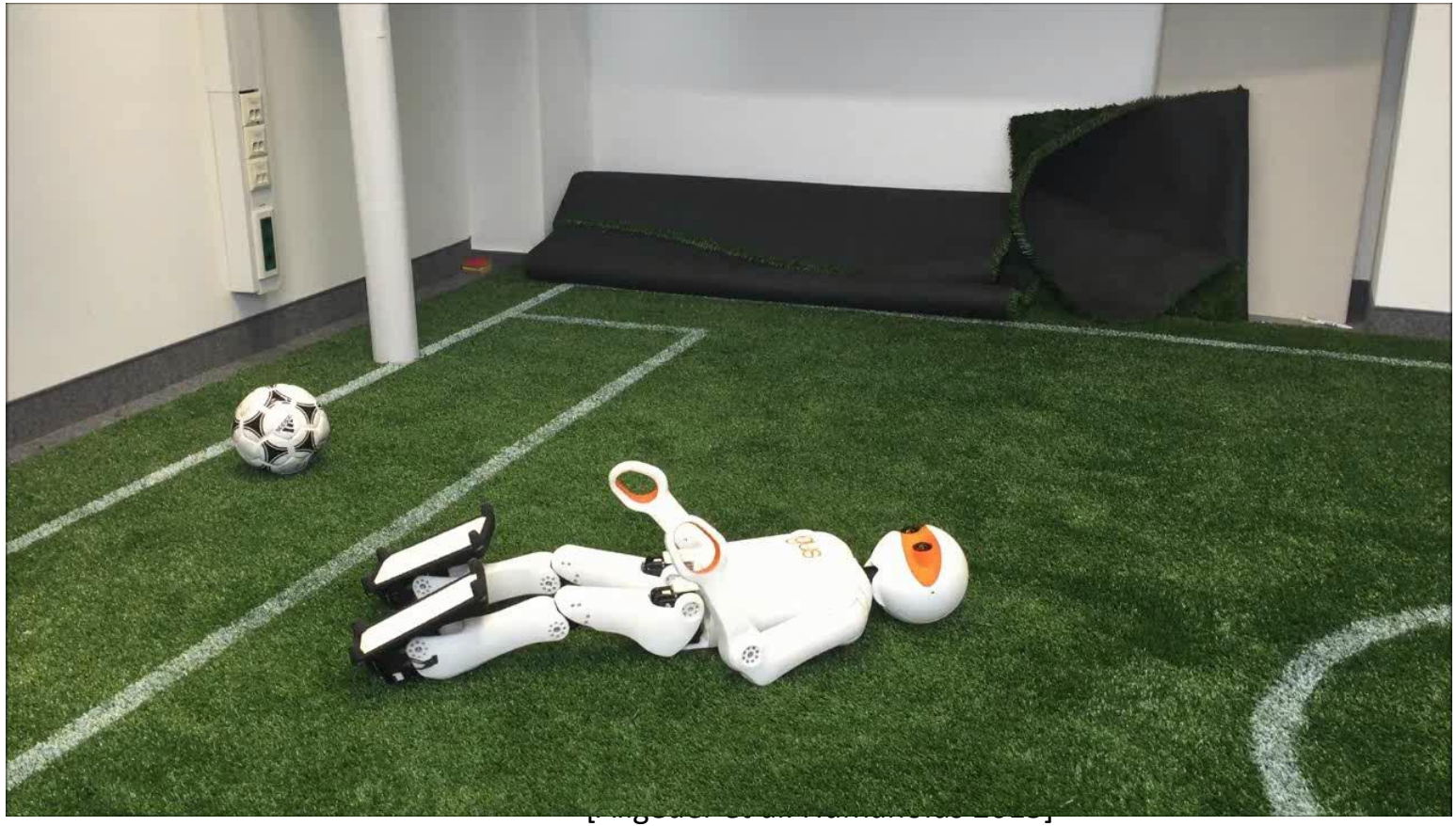
[Allgeuer and Behnke: Humanoids 2016]

# Landing Motion Backwards

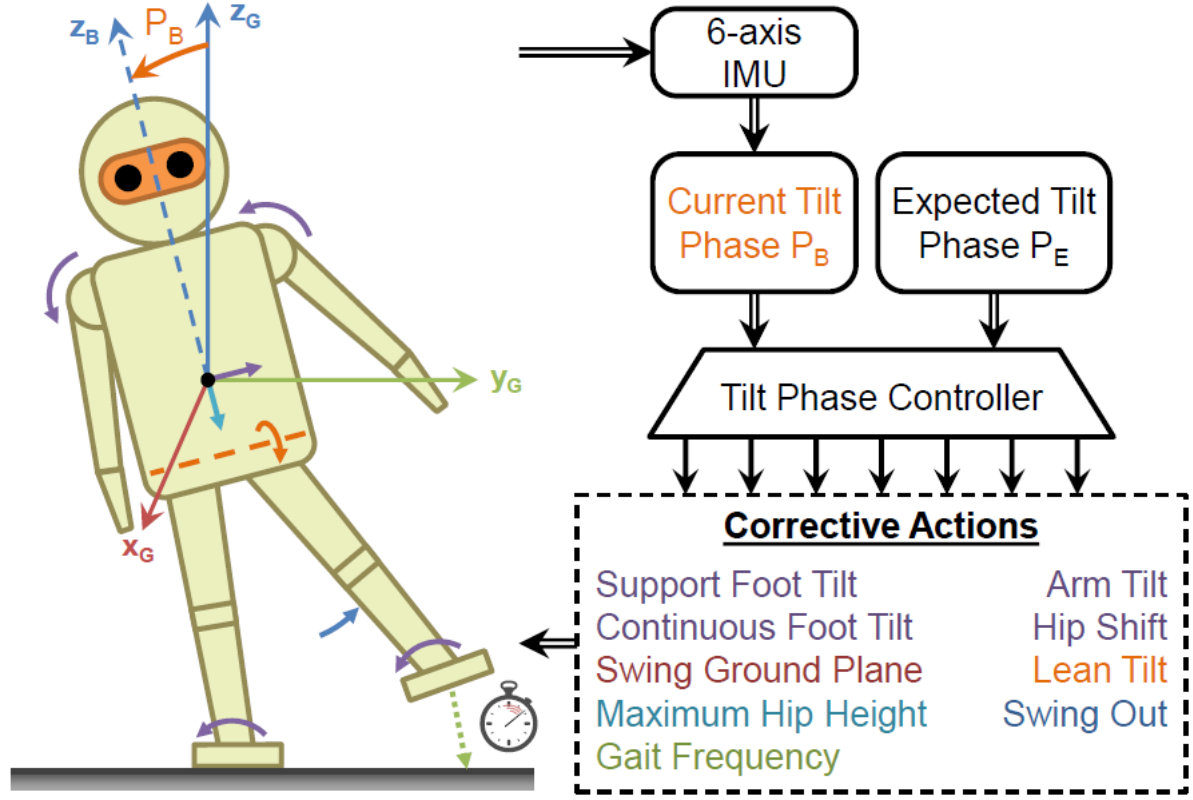
# Landing Motion Forwards



# Getting Up

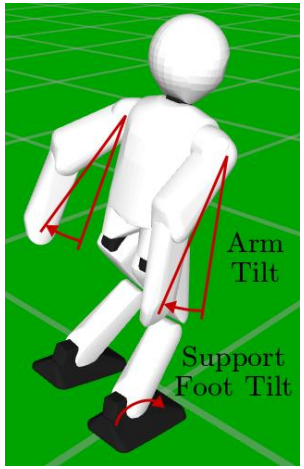


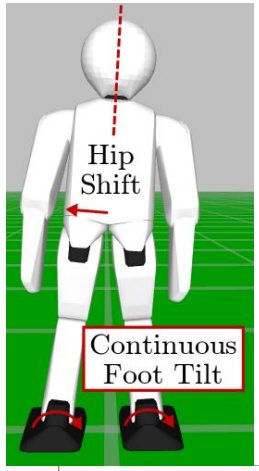
# Tilt Phase Corrective Actions

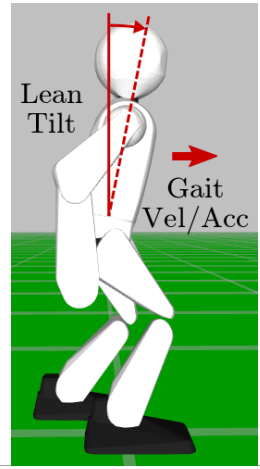


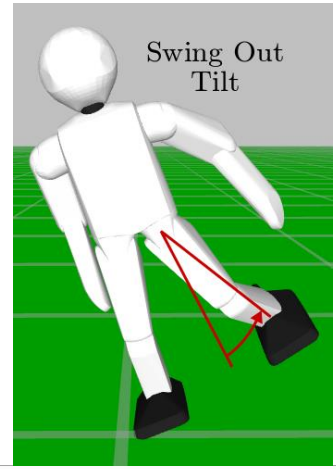

[Allgeuer and Behnke, Humanoids 2018]

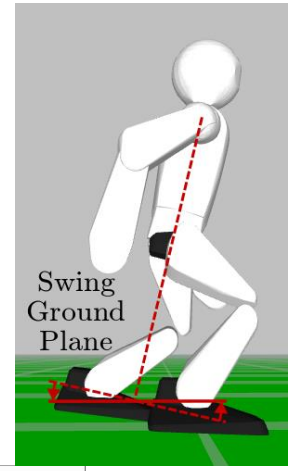
# Tilt Phase Corrective Actions

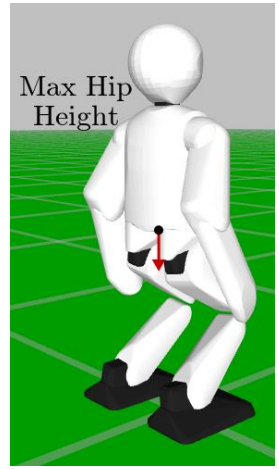



**PD Feedback: Arm and Support Foot Tilt**

The arms and feet are tilted to transiently reject disturbances and stabilise the robot.

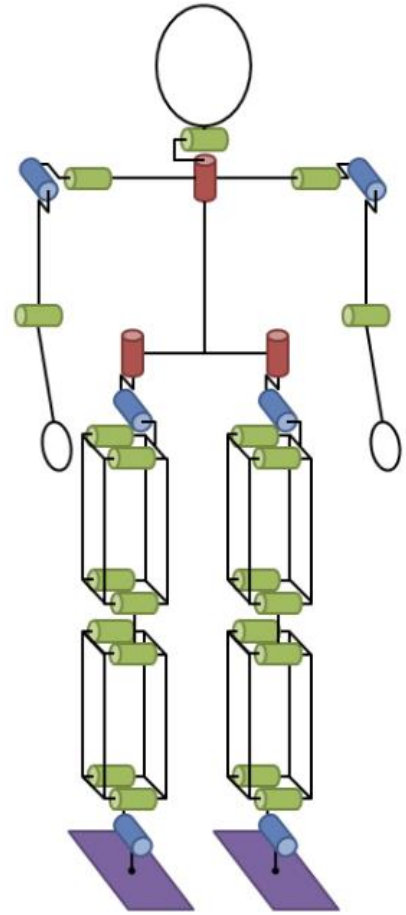
[Allgeuer and Behnke, Humanoids 2018]

# Visual Perception of Soccer Scene


[Farazi & Behnke, RoboCup 2016]

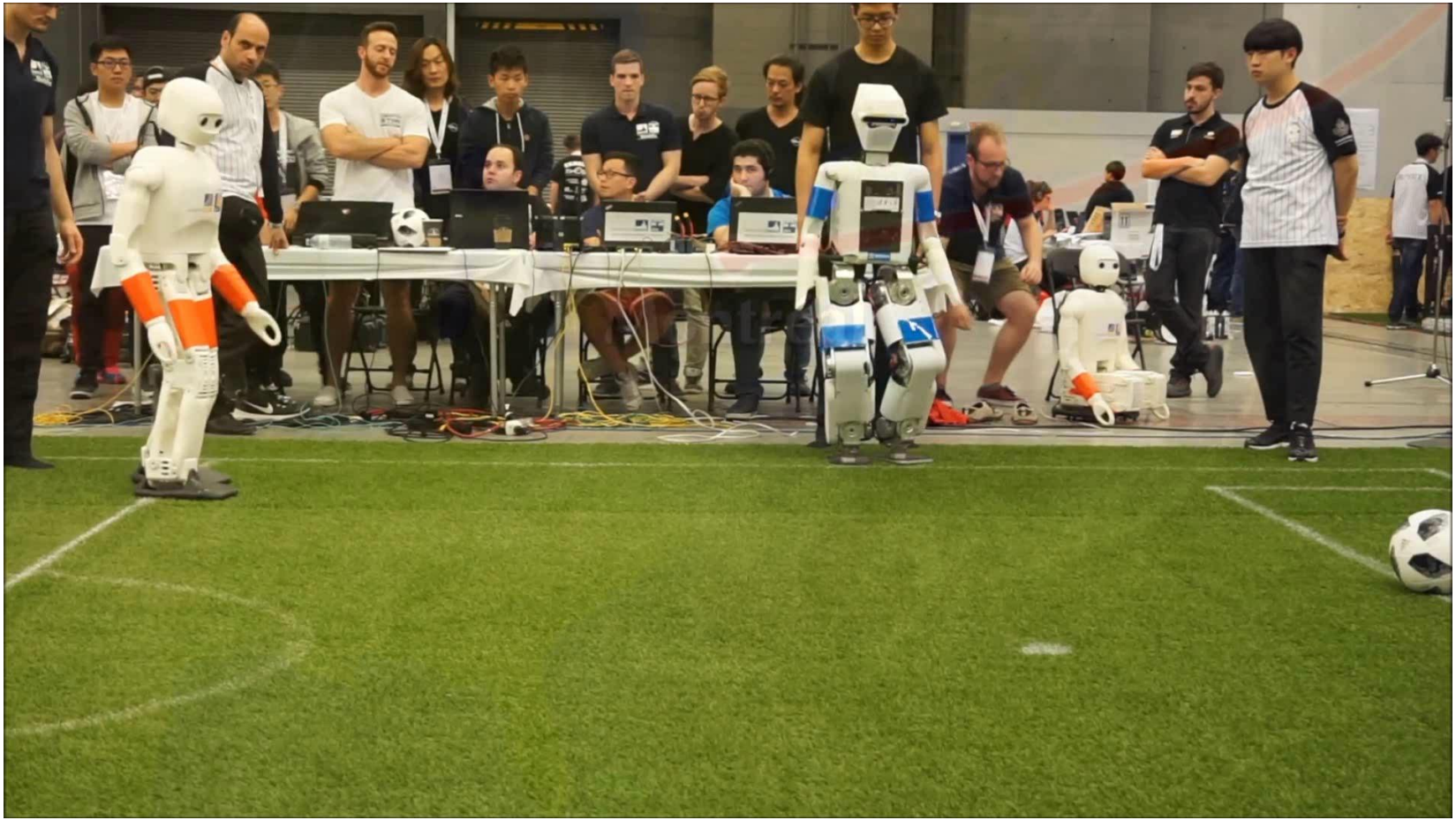
# NimbRo-OP2X

- 135 cm, 19 kg
- 18 DoF
  - 5 per leg (parallel kinematics)
  - 3 per arm
  - 2 in the neck
- 34 Dynamixel XH540 actuators
- Mini-ITX PC
- Nvidia SFF GPU
- Fisheye camera
- LiPo battery (14.8 V, 8 Ah)



[Ficht et al. IJHR 2020]

# NimbRo-OP2X @ RoboCup 2018

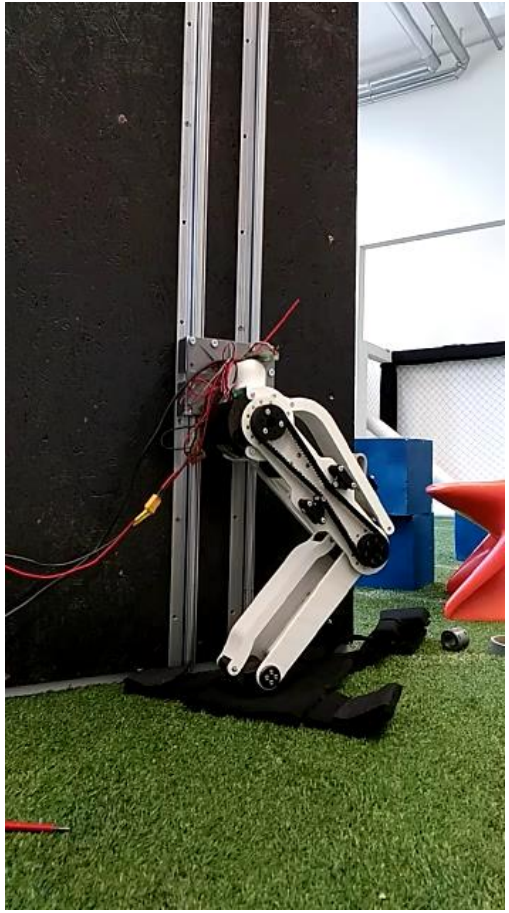


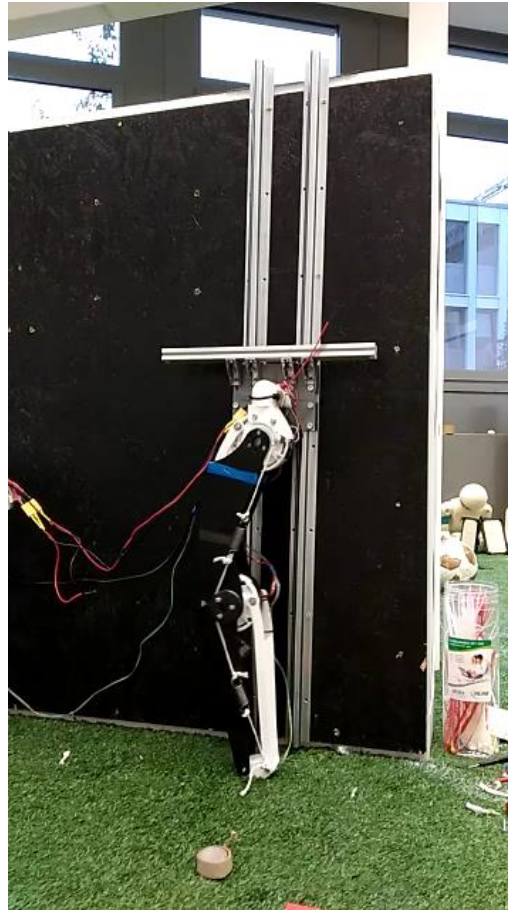
[Ficht et al.: Humanoids 2018]

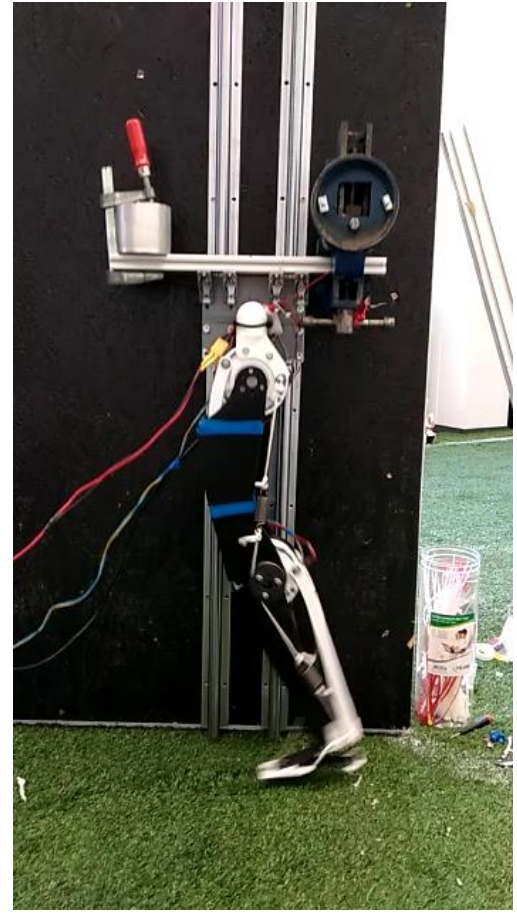
# Capture Steps with NimbRo-OP2

[Missura, Bennewitz, Behnke: International Journal of Humanoid Robotics (IJHR) 2019]

# Jumping Legs



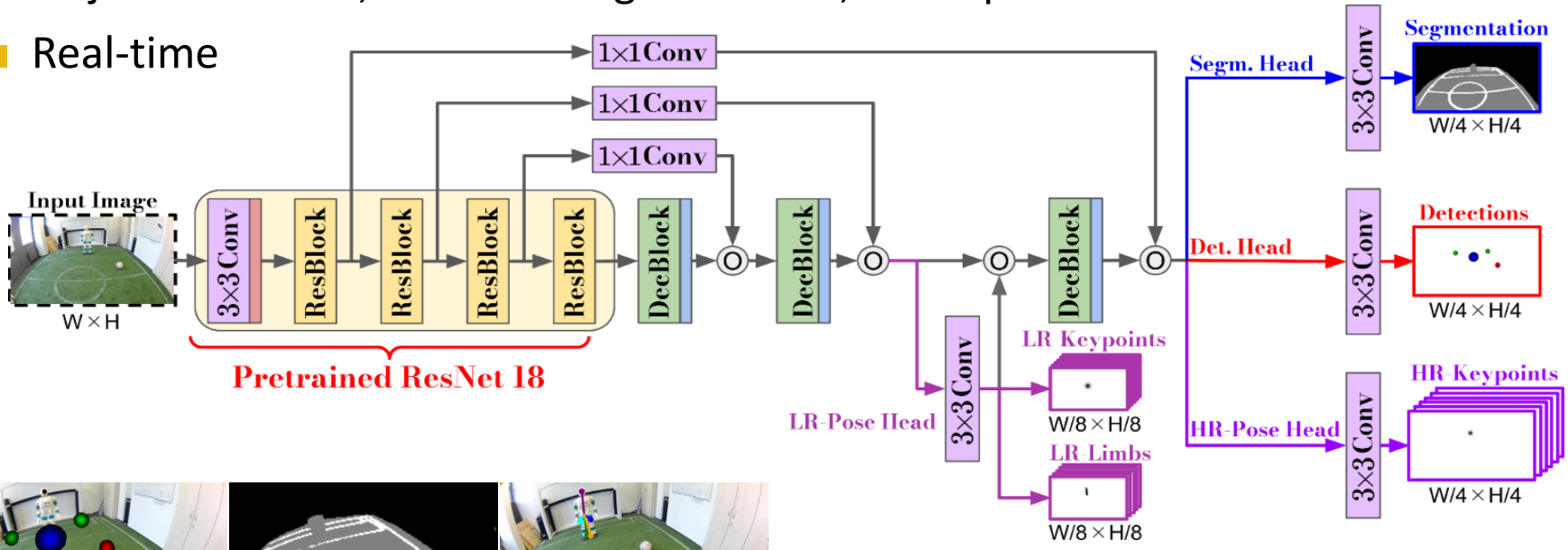


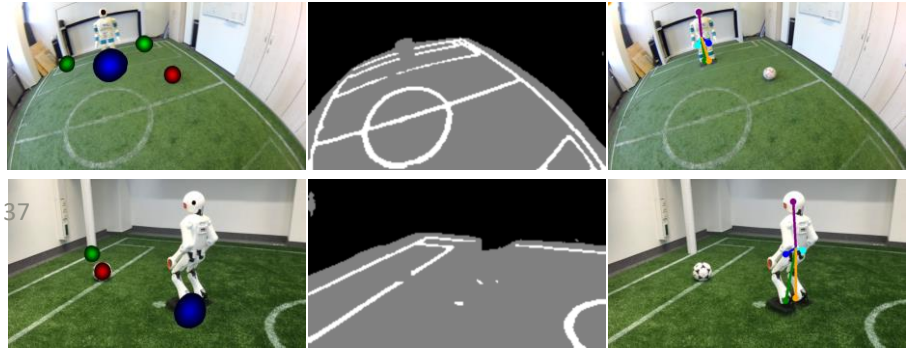


[Ficht 2020]

# NimbRoNet3 Visual Perception

- Object detection, semantic segmentation, robot pose estimation
- Real-time

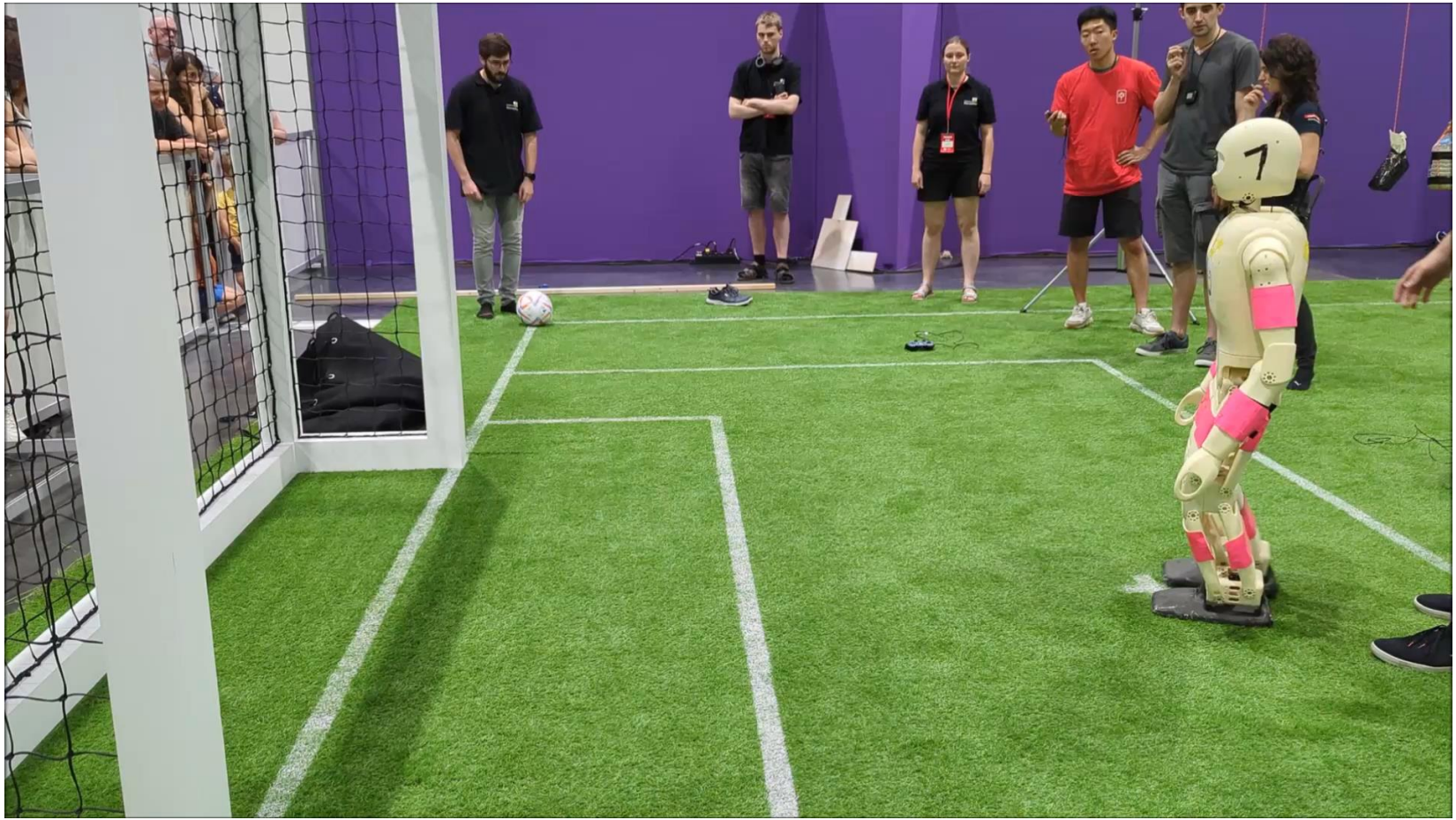


[Pavlichenko et al. RoboCup 2023]

# RoboCup 2023 Humanoid AdultSize Final

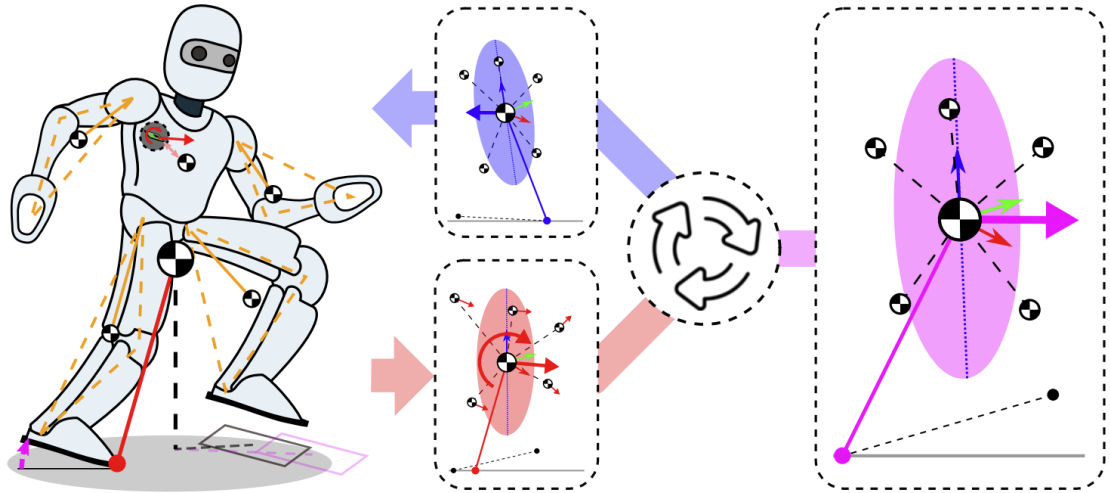
# RoboCup 2023 Passing Challenge

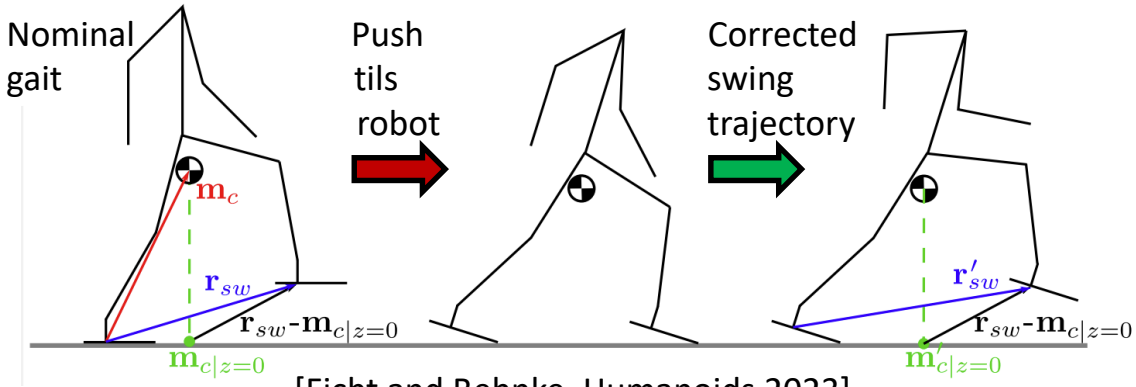



[Pavlichenko et al. RoboCup 2023]

# Centroidal State Estimation and Control

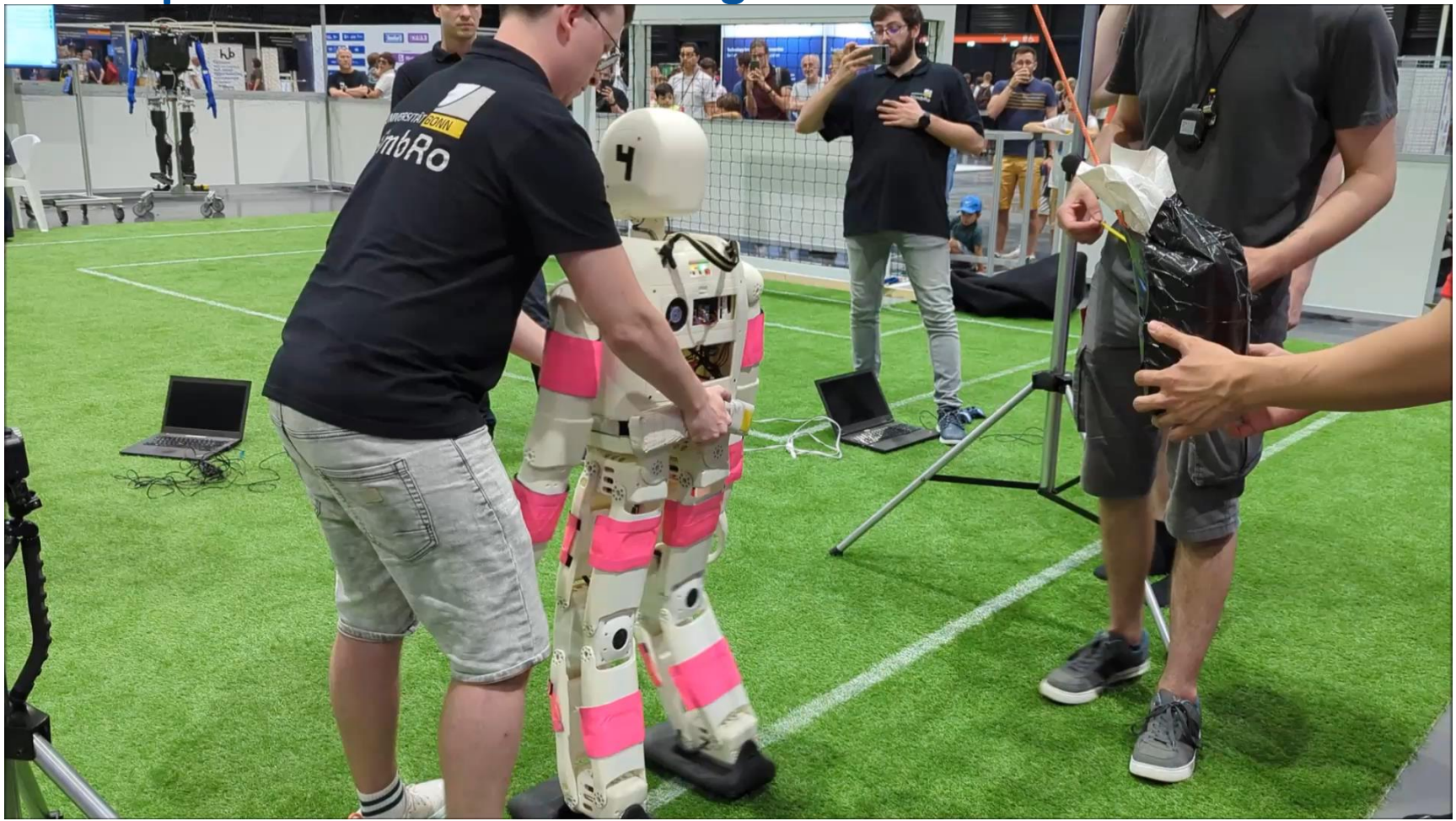
- Five mass model
  - Four limbs
  - Torso
- State estimation
  - IMU, joint positions
  - No F/T sensors
- Tilt-compensating step feedback
  - No ankle pitch joint
  - Stance foot may tilt
  - Step size is corrected






[Ficht and Behnke, Humanoids 2023]

# RoboCup 2023: Technical Challenges



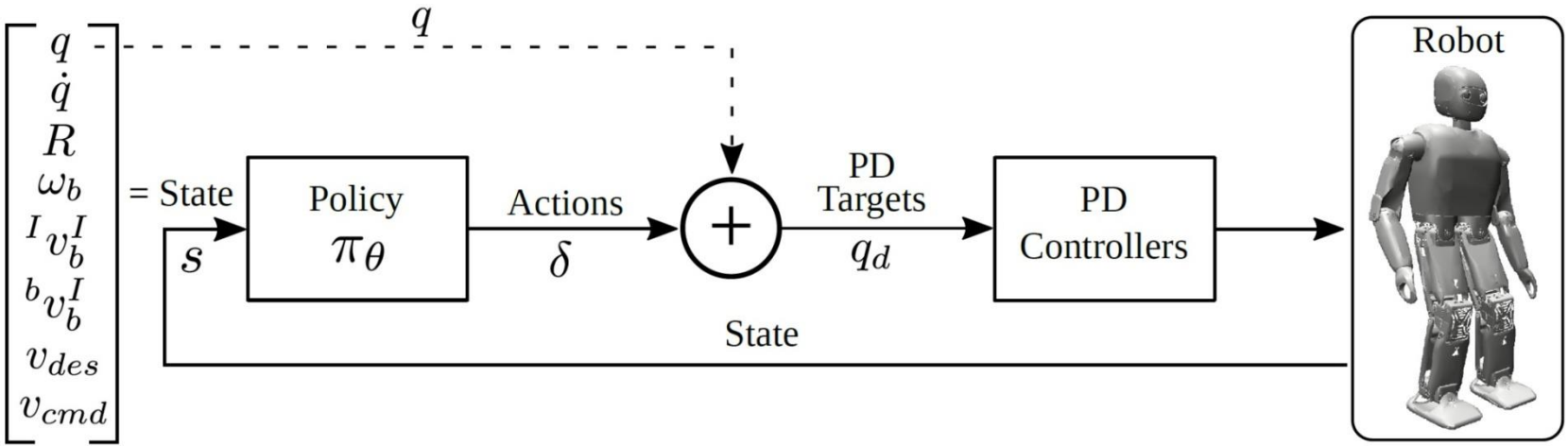

[Pavlichenko et al. RoboCup 2023]

# Team NimbRo @ RoboCup 2023


[Pavlichenko et al. RoboCup 2023]

# Learning Omnidirectional Gait from Scratch

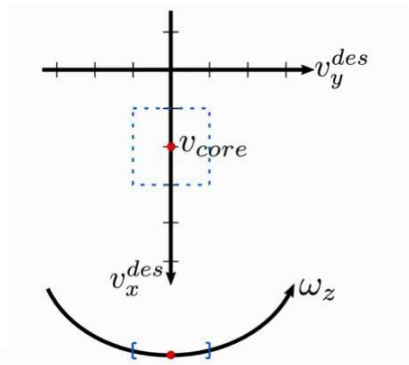
- State includes joint positions and velocities, robot orientation, robot speed
- Actions are increments of joint positions
- Simple reward structure
  - Velocity tracking
  - Pose regularization
  - Not falling

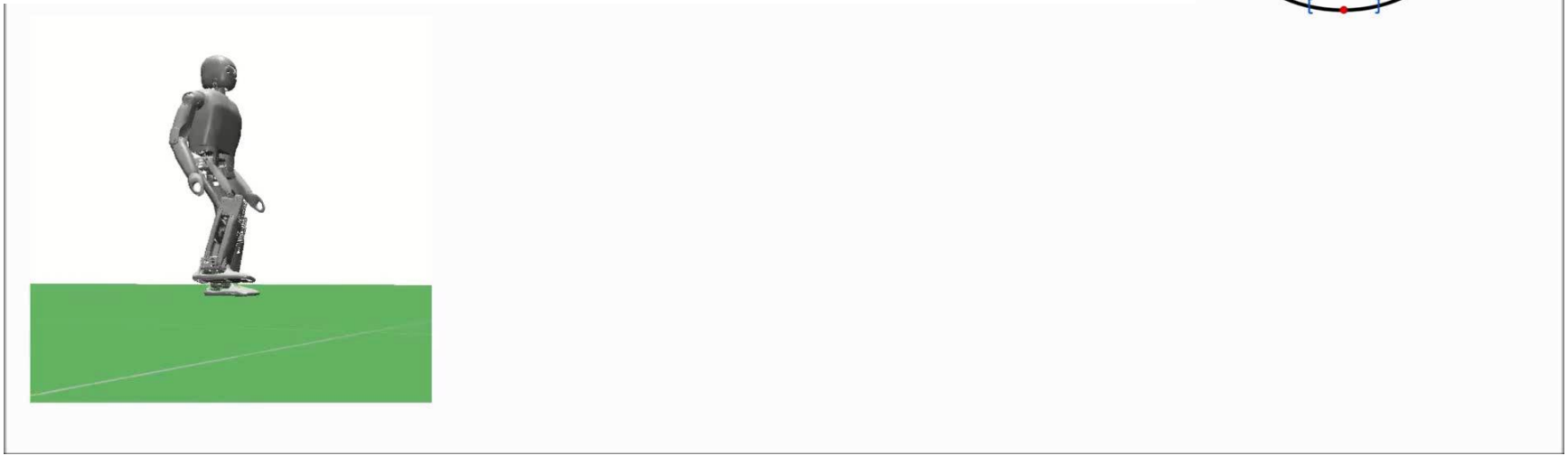



[Rodriguez and Behnke, ICRA 2021]

# Learning Curriculum

- Start with small velocities
- Increase range of sampled velocities



[Rodriguez and Behnke, ICRA 2021]

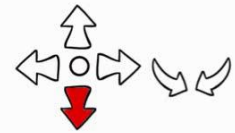
# Learned Omnidirectional Gait

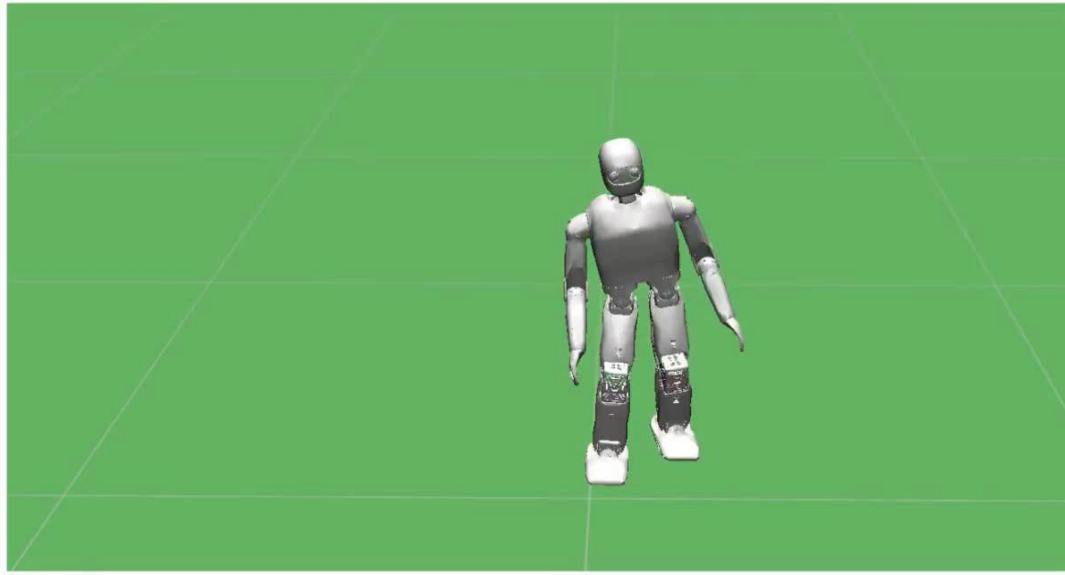
- Target velocity can be changed continuously

Our locomotion controller is able to:

**Walk Forward**

$v_x = 0.6\,\mathrm{m/s}$
$v_y = 0.0\,\mathrm{m/s}$
$\omega_z = 0.0\,\mathrm{rad/s}$



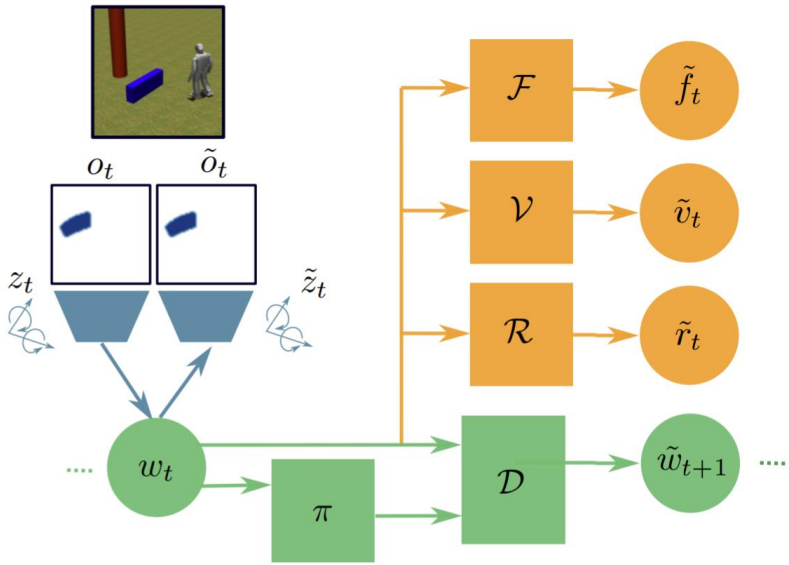


[Rodriguez and Behnke, ICRA 2021]

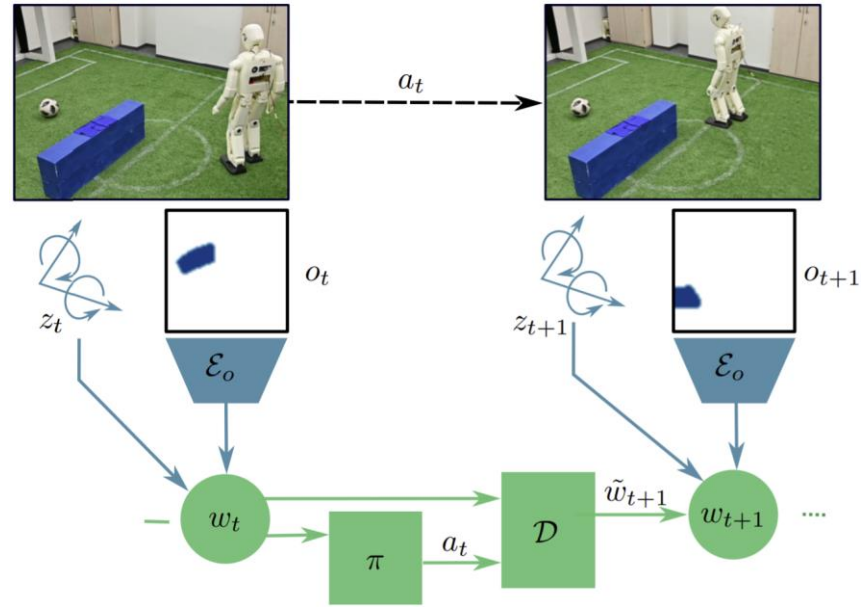
# Learning Mapless Humanoid Navigation

- Visual (RGB images) and nonvisual observations to learn a control policy and an environment dynamics model
- Anticipate terminal states of success and failure

Training




Inference




[Brandenburger et al. IROS 2021]

# Learning Mapless Humanoid Navigation


[Brandenburger et al. IROS 2021]

# RoboCup 2024 Eindhoven

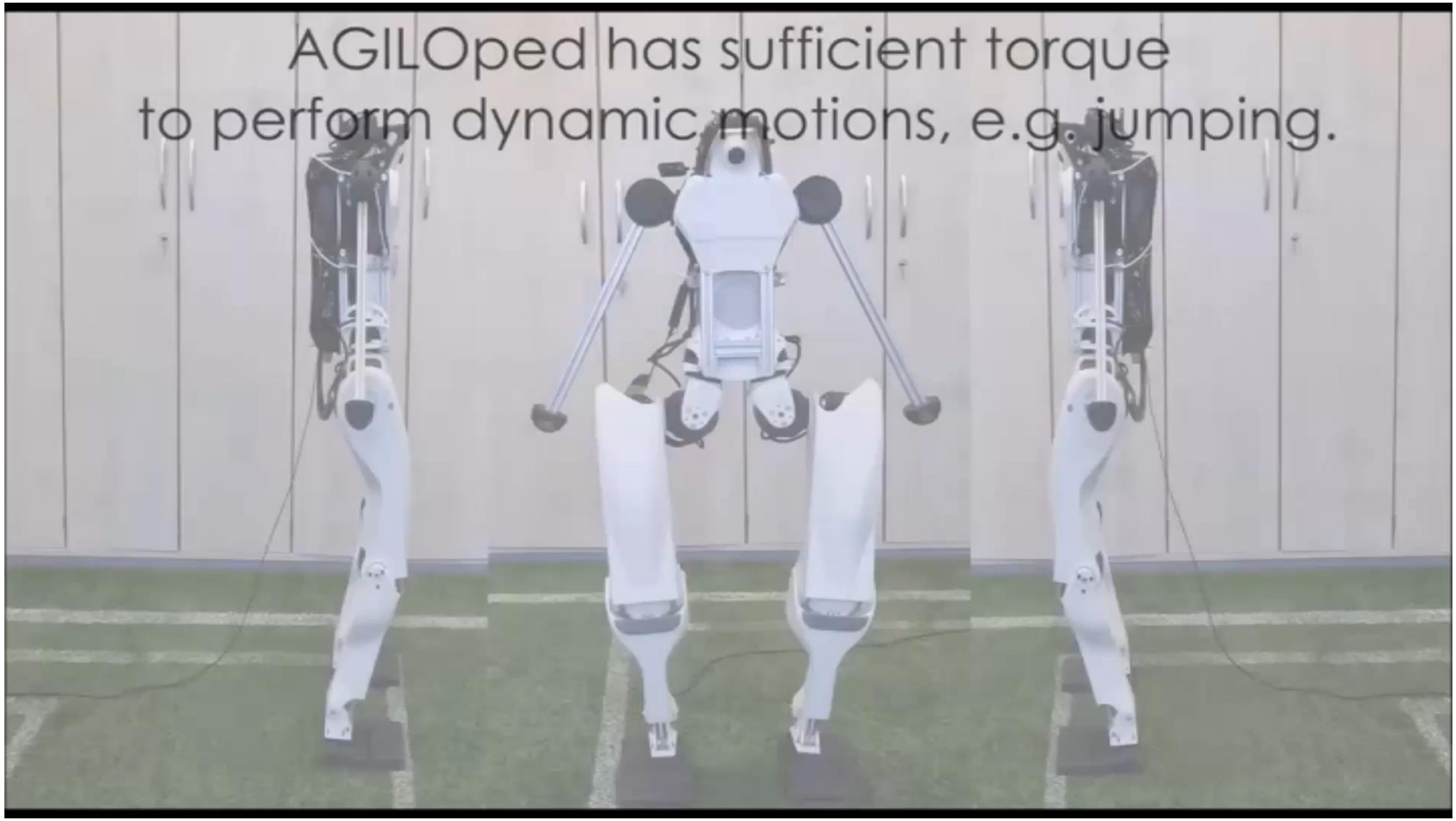
# Maximum-Impact Kick

[Ficht and Behnke, Humanoid Soccer WS 2024]

# Team NimbRo AdultSize 2024


- 2017: 1st & Design Award
- 2018: 1st & Best Humanoid
- 2019: 1st & Best Humanoid
- 2022: 1st & Best Humanoid
- 2023: 1st & 66:0 goal count
- 2024: 2nd & Best Humanoid

# New Robot AGILOped Jumping




[Ficht et al. 2024]

# Conclusions

- Humanoid AdultSize addresses 2050 RoboCup vision
- Progress over 20 years
  - Robot construction
  - Visual perception
  - Movement control, disturbance rejection
- Soccer performance still limited
- Advances needed in
  - Resilient mechanics (actuators, materials)
  - Reliable state estimation (including terrain)
  - Robust control (fall avoidance, safe landing)