NimbRo-OP2(X): RoboCup AdultSize-winning Open-source Humanoid Soccer Robots

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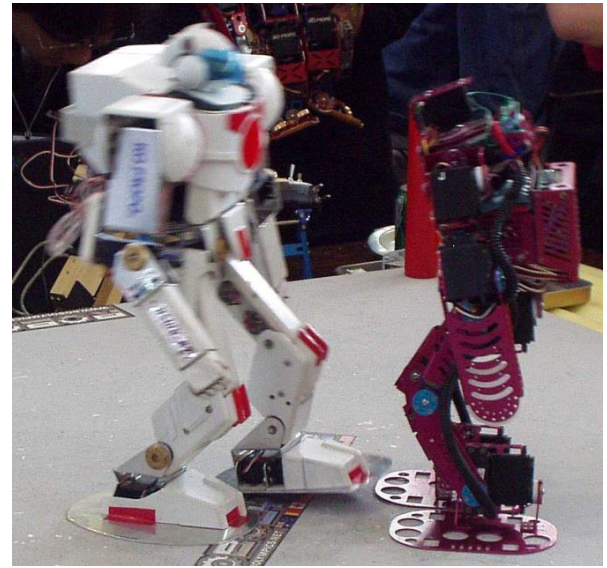
Issues of Robotic Performance Evaluation

- **Benchmarking** robotics research inherently **difficult**
- Often, results reported only for a specific robotic system and a **self-chosen task**, solved in **own lab**
- Impossible to **compare** results
- Commonly used "**proof by video**" has same difficulties as "**proof by example**"

[Boston Dynamics: Handle]

Robot Competitions and Challenges

- Bring together researchers, students, and enthusiasts in the pursuit of a technological challenge
- Popular competitions include
  - RoboCup
  - DARPA Robotics Challenge
  - Mohamed Bin Zayed International Robotics Challenge (MBZIRC)
  - International Aerial Robotics Competition
- Provide a **standardized test bed**
  - in a different environment
  - at a scheduled time
- **Directly compare** different approaches



[Robo-one]

RoboCup German Open 2005

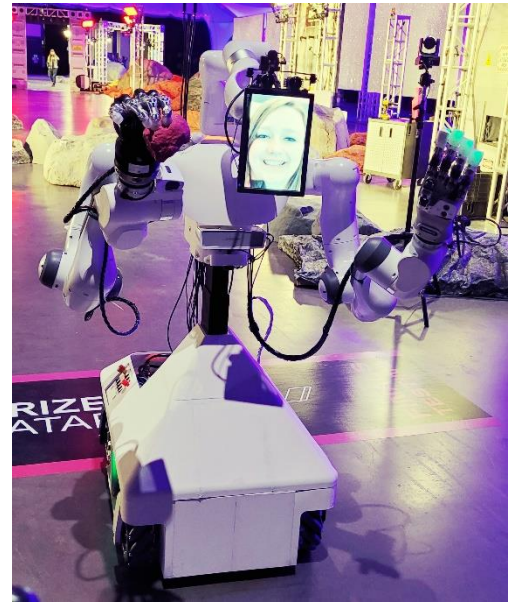
Some of our Humanoid Robots

- Equipped with numerous sensors and actuators
- Complex demonstration scenarios

Soccer

Domestic service

Mobile manipulation

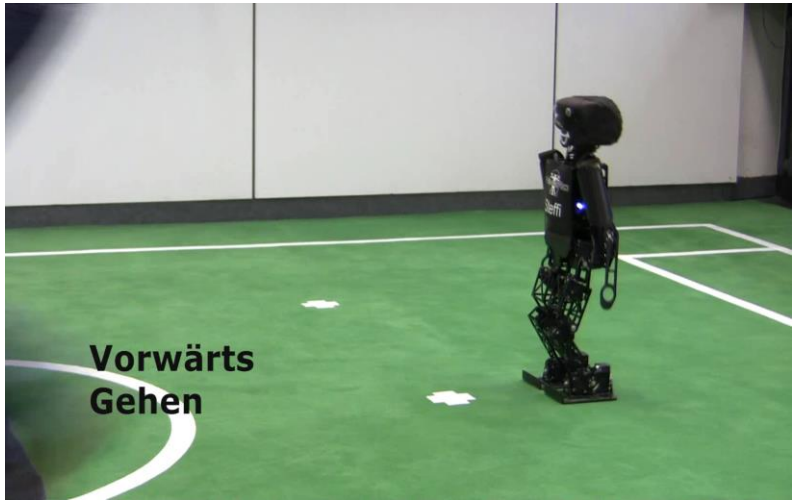


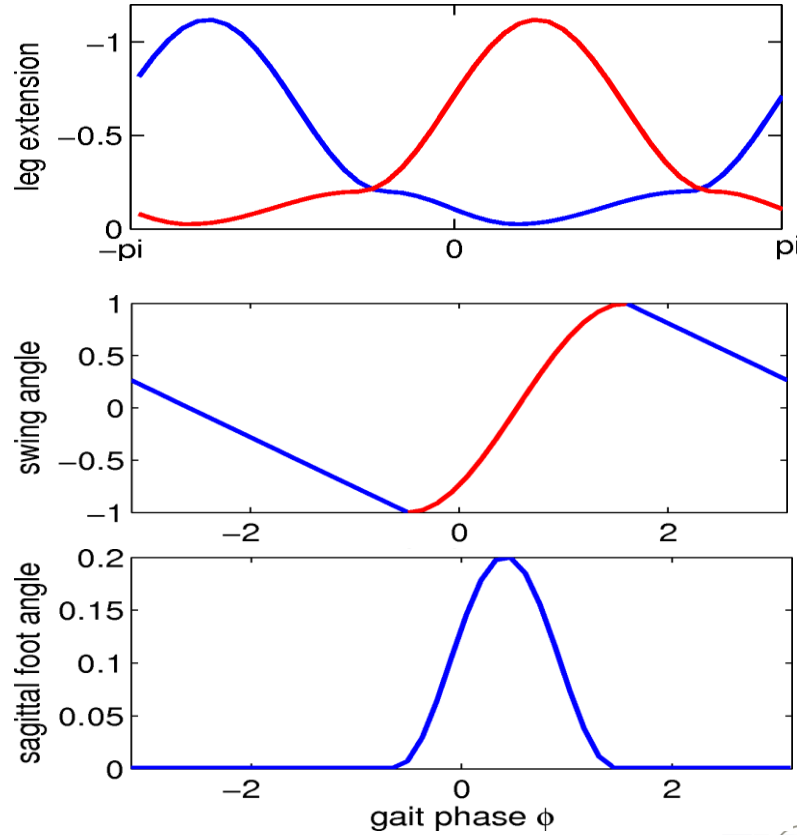
Telepresence

RoboCup 2008 KidSize Final
NimbRo vs. Team Osaka

Omnidirectional Walking

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





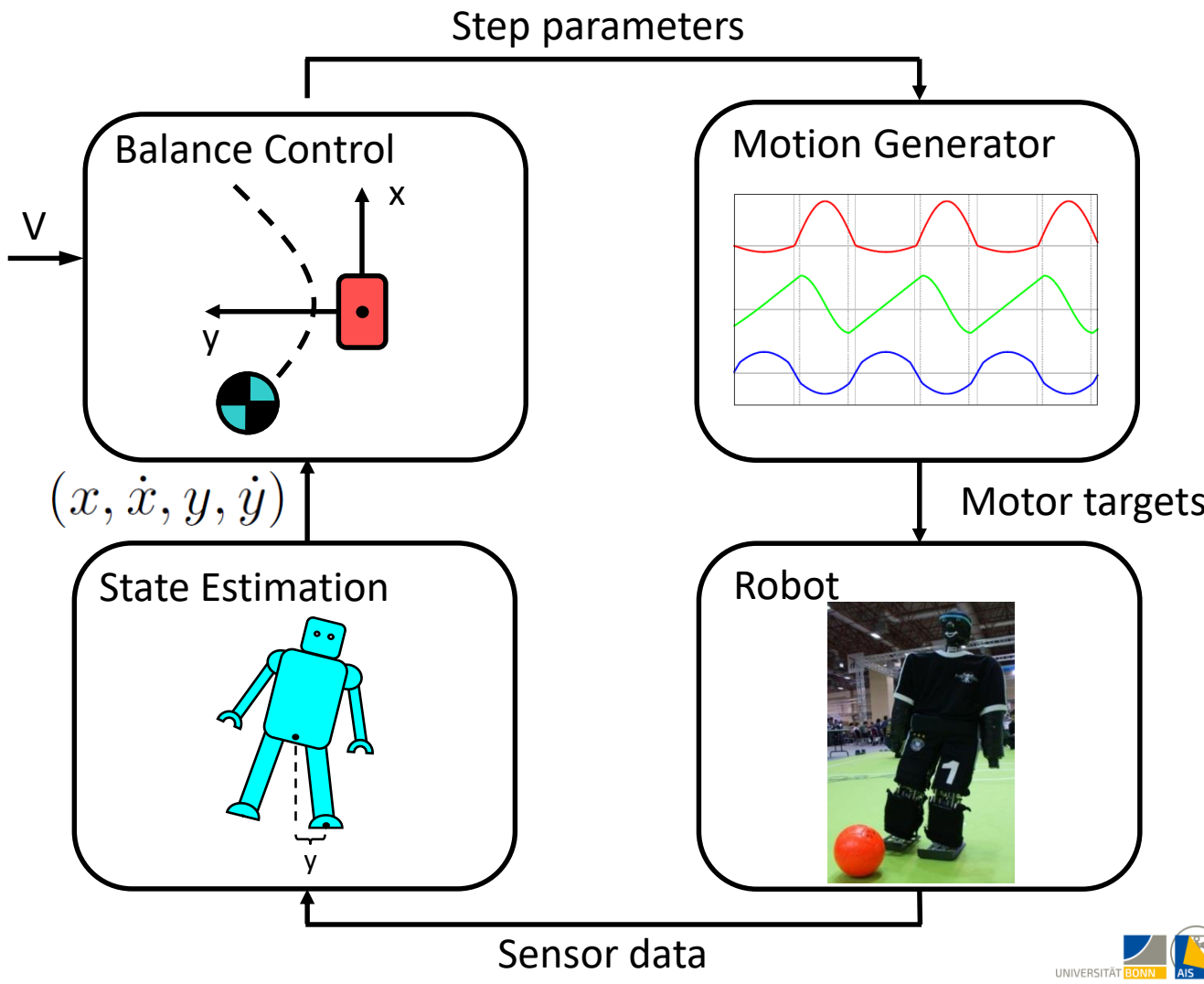
[Behnke: ICRA 2006]

RoboCup 2013 Final

Capture Step Framework

Velocity input:

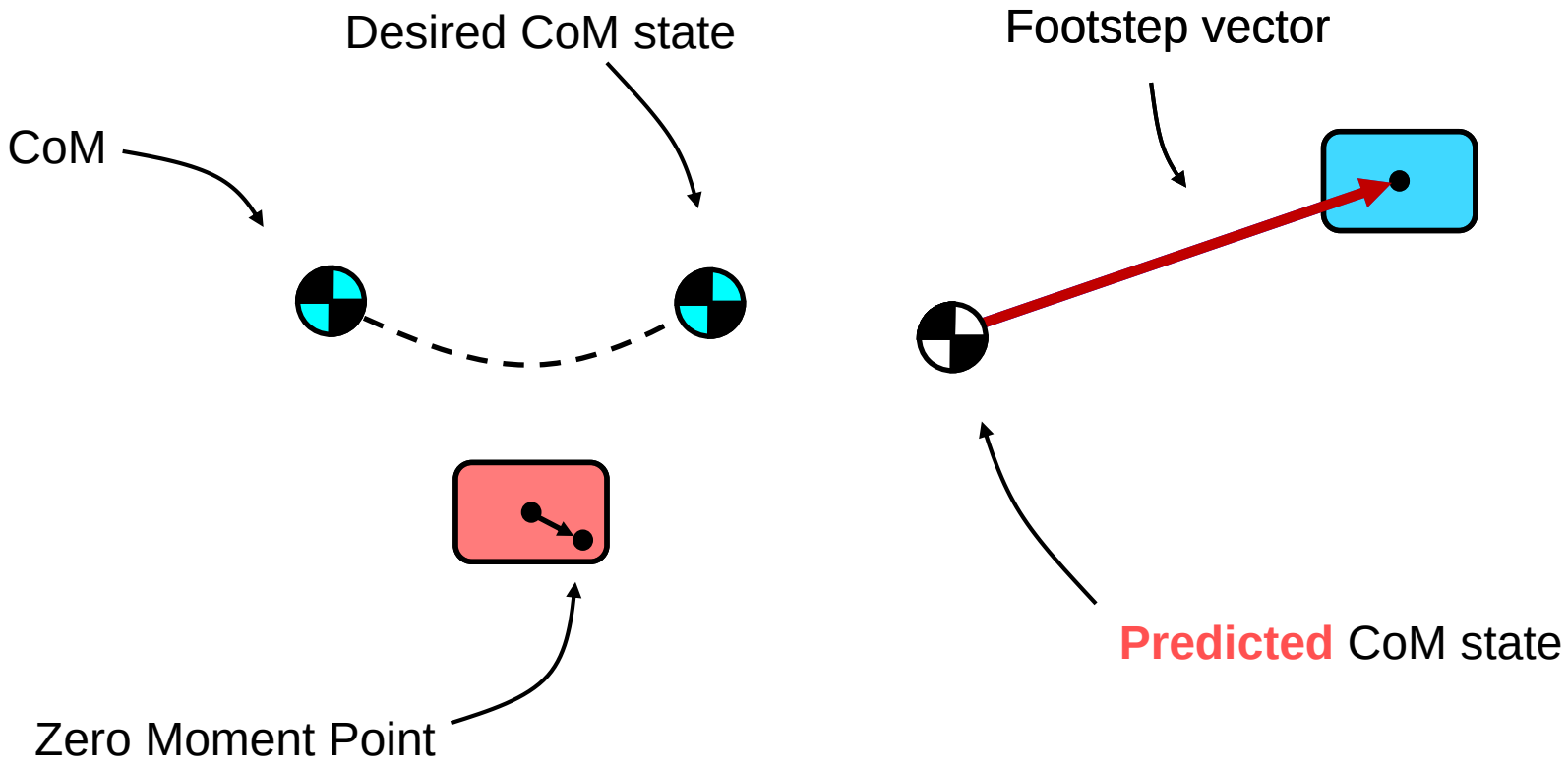
- LIP model
- Determines when and where to make the next step to regain balance and continue walking



[Missura, Behnke: Humanoids 2013, RoboCup 2014]

Balance Control

- Adapt ZMP, timing, and foot placement



[Missura and Behnke: Humanoids 2013, RoboCup 2014]

Omnidirectional Capture Steps

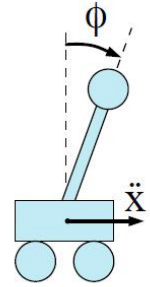
[Missura and Behnke: Humanoids 2013, RoboCup 2014]

Online Learning of Foot Placement

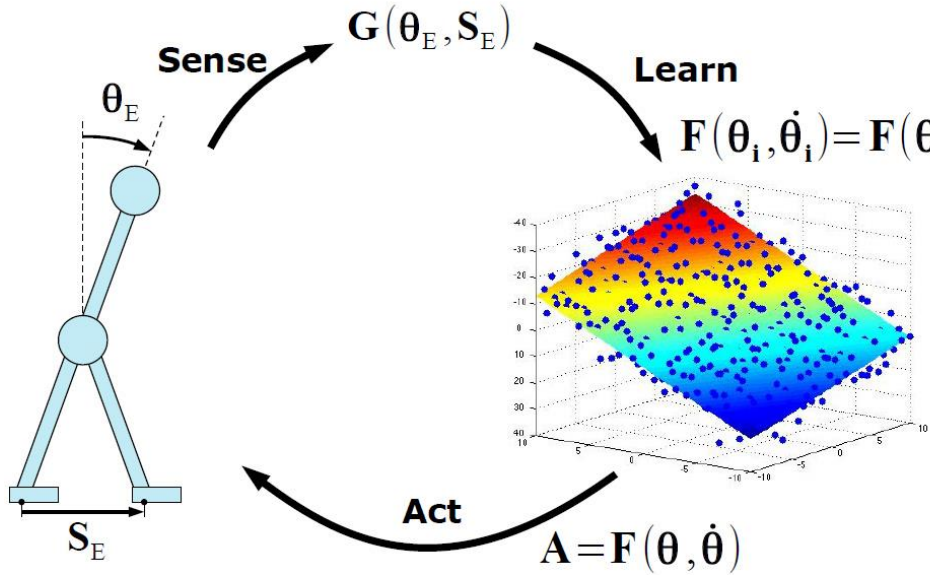
[Missura and Behnke: IROS 2015]

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]

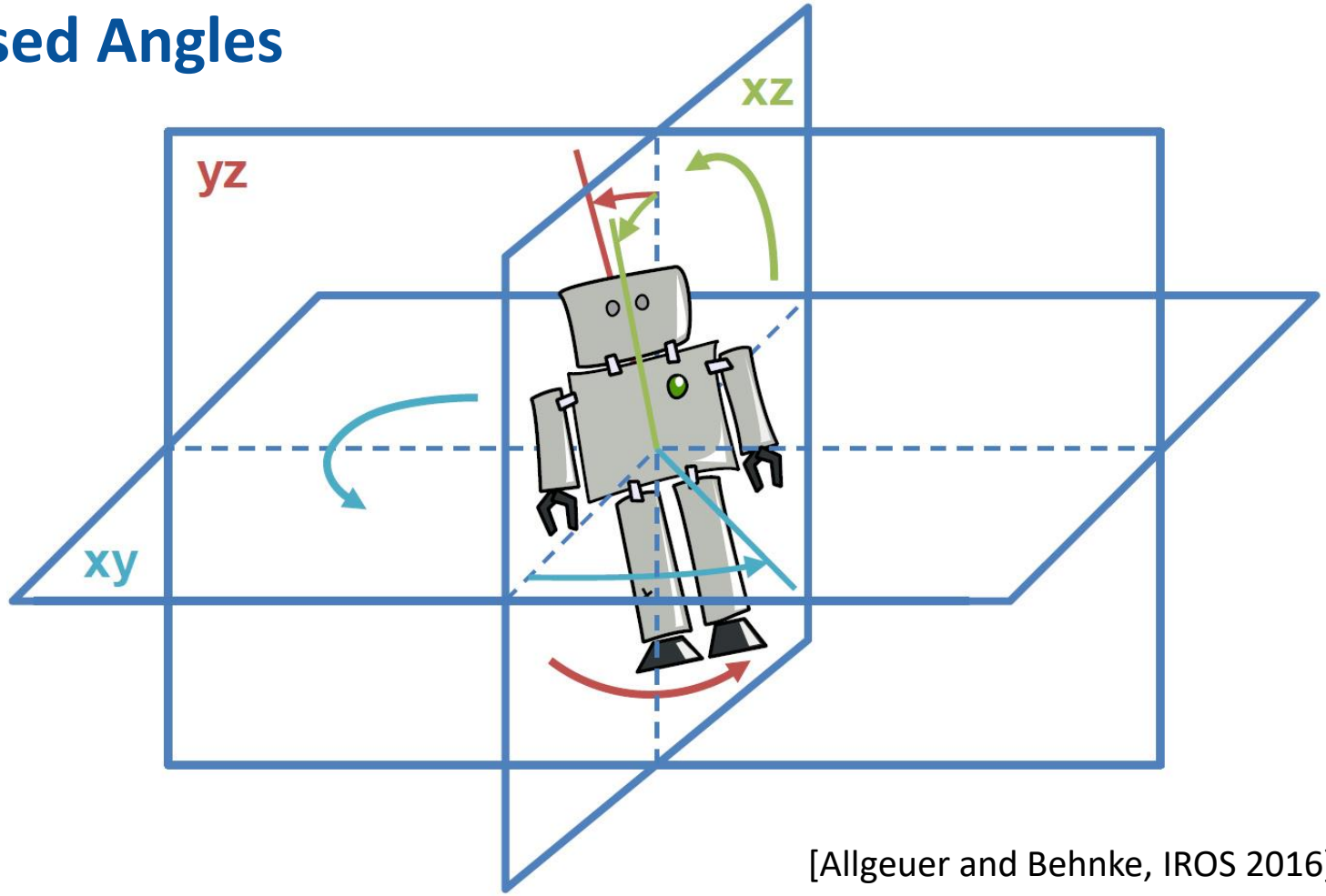
Online Learning of Foot Placement

[Missura and Behnke: IROS 2015]

Visual Perception of Soccer Scene

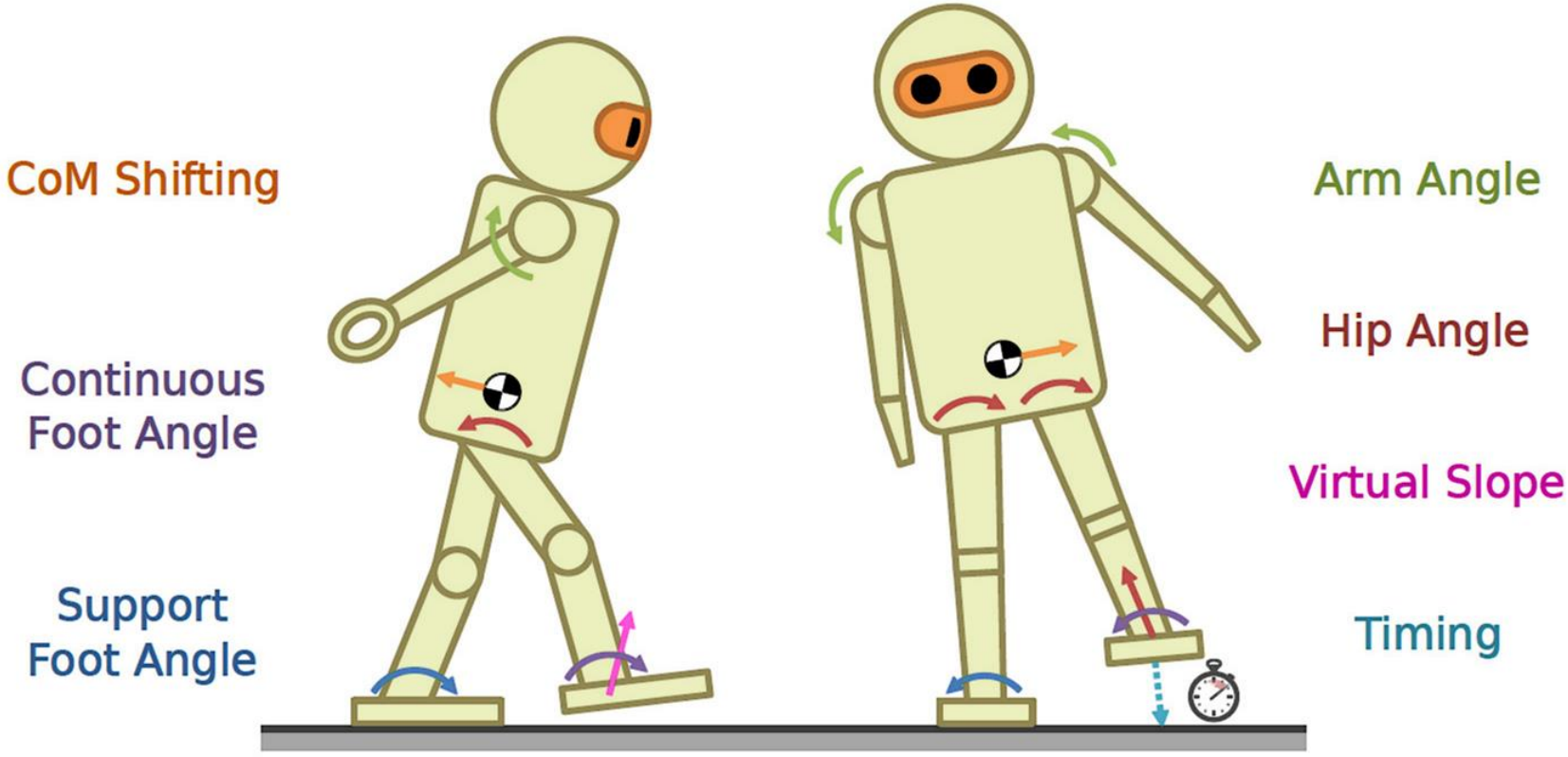
[Farazi & Behnke, RoboCup 2016]

Fused Angles



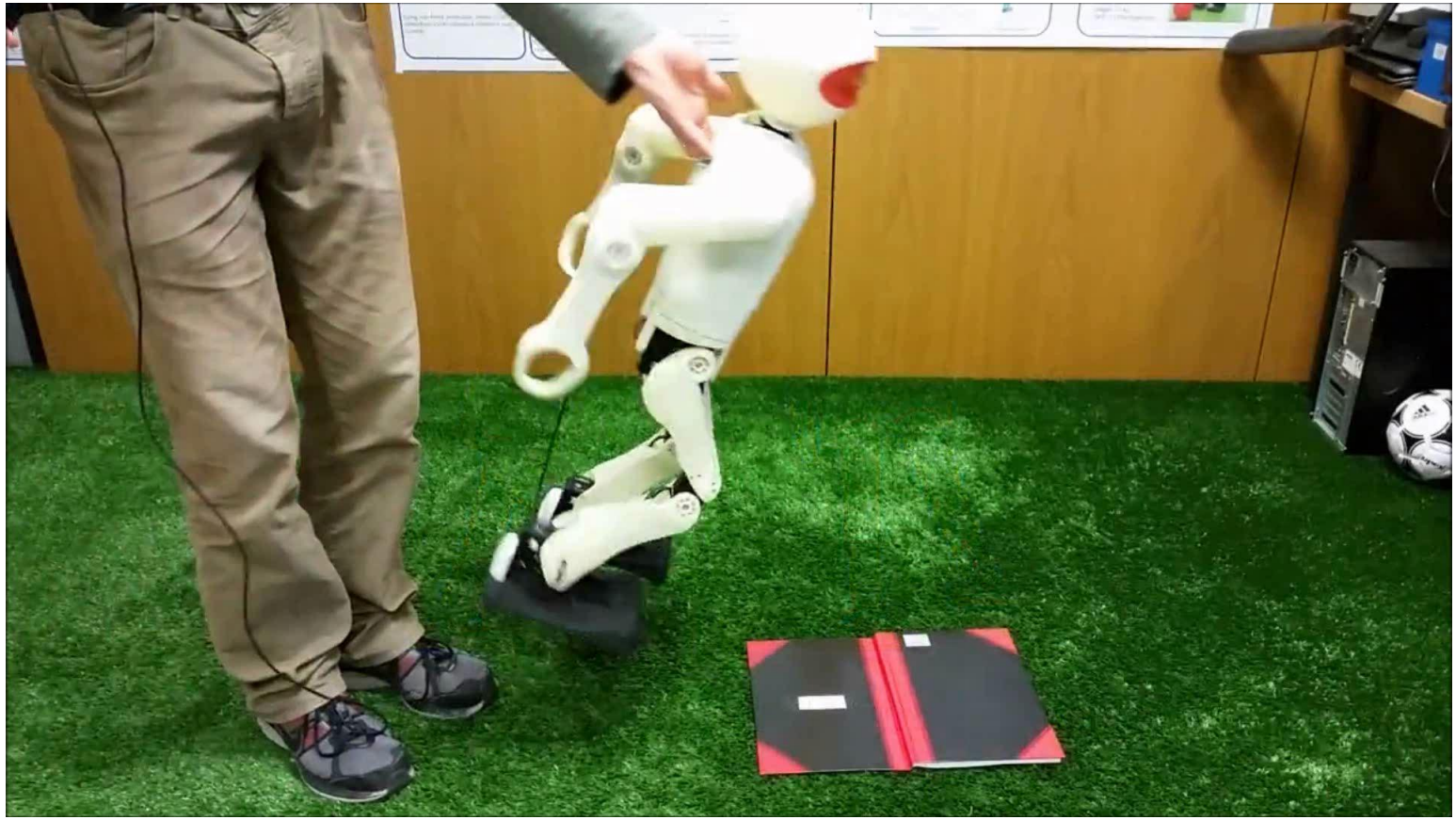
[Allgeuer and Behnke, IROS 2016]

Feedback Mechanisms



[Allgeuer and Behnke: Humanoids 2016]

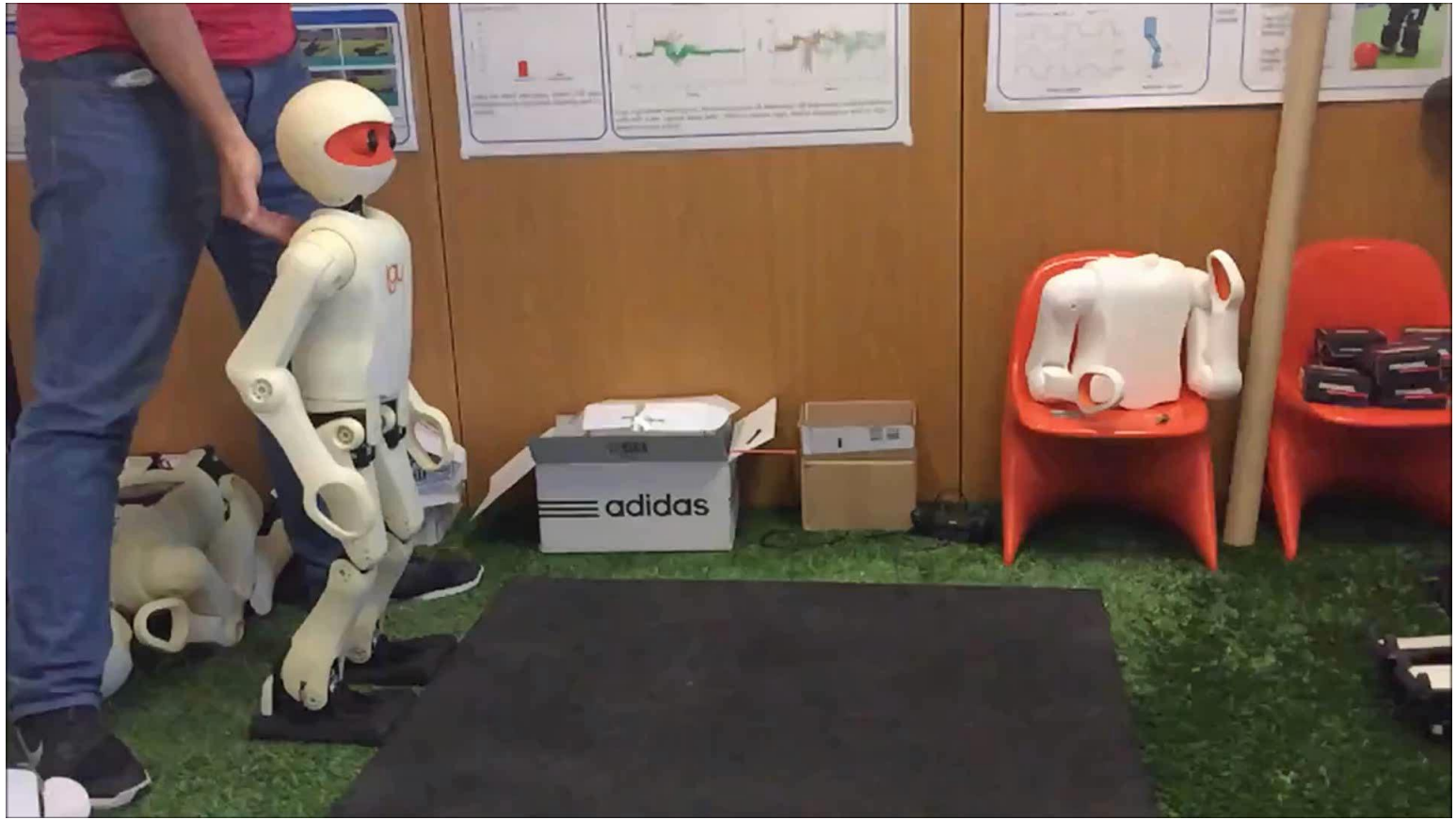
PD Feedback



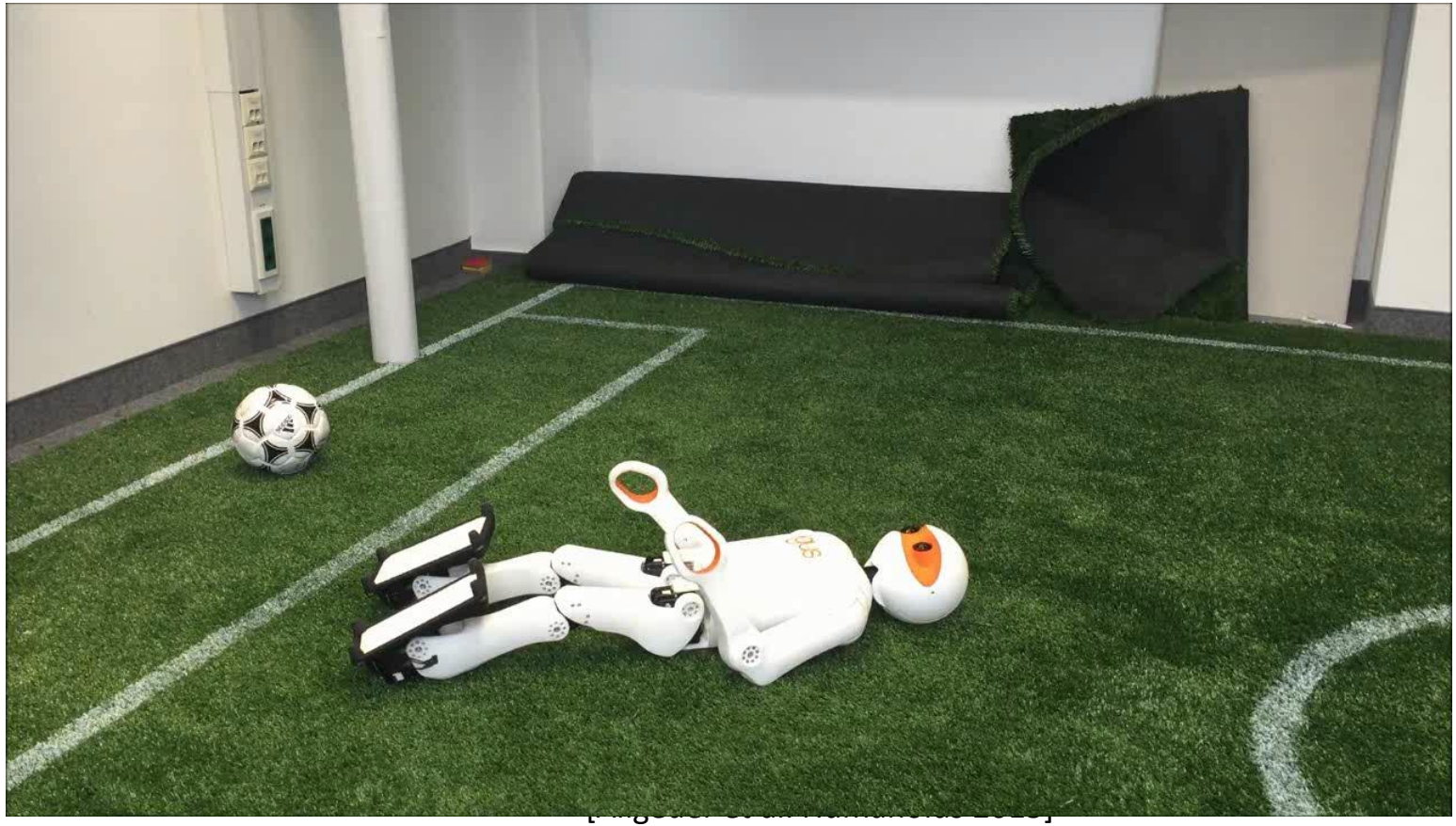
[Allgeuer and Behnke: Humanoids 2016]

Landing Motion Backwards

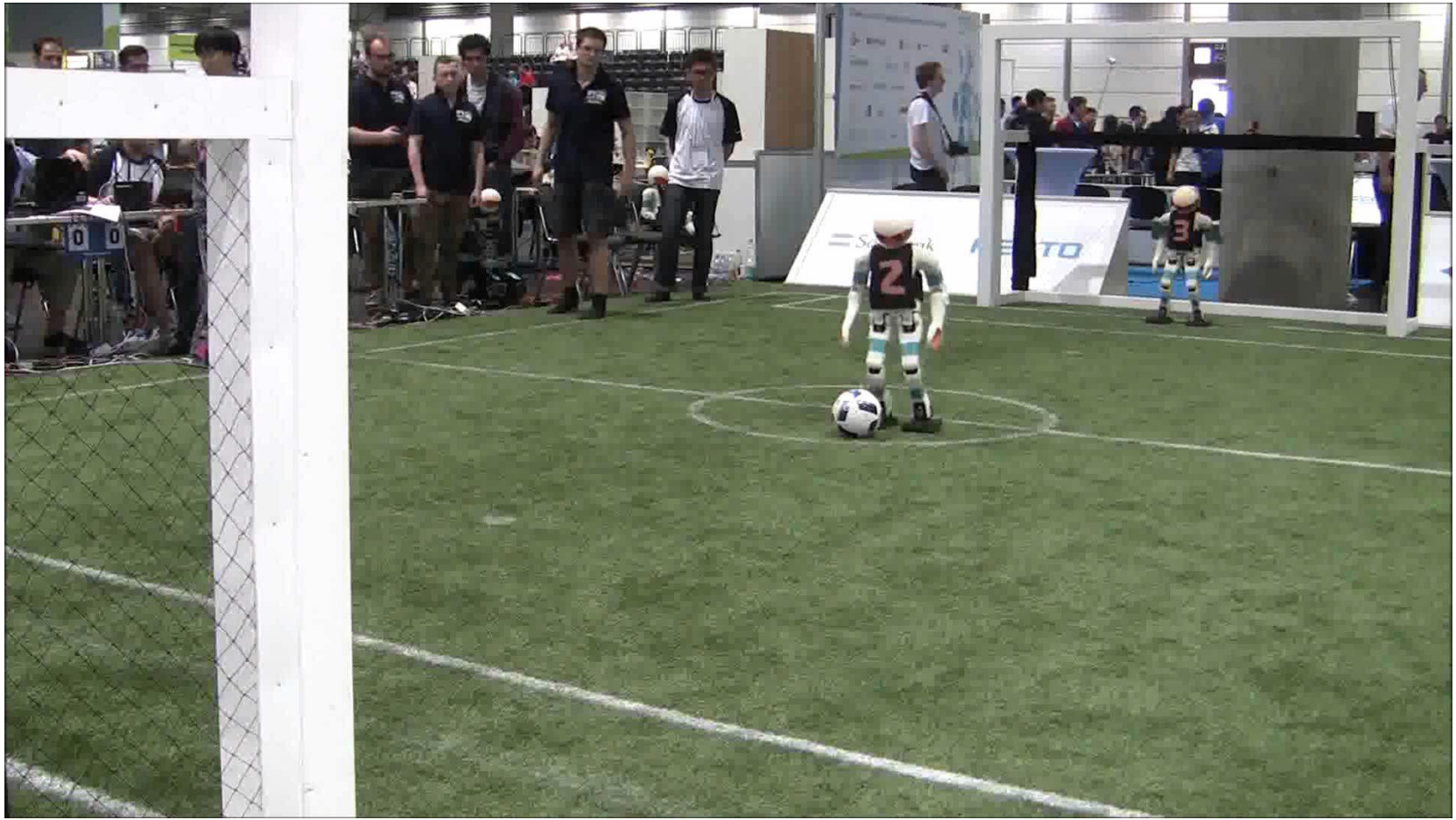
Landing Motion Forwards



Getting Up

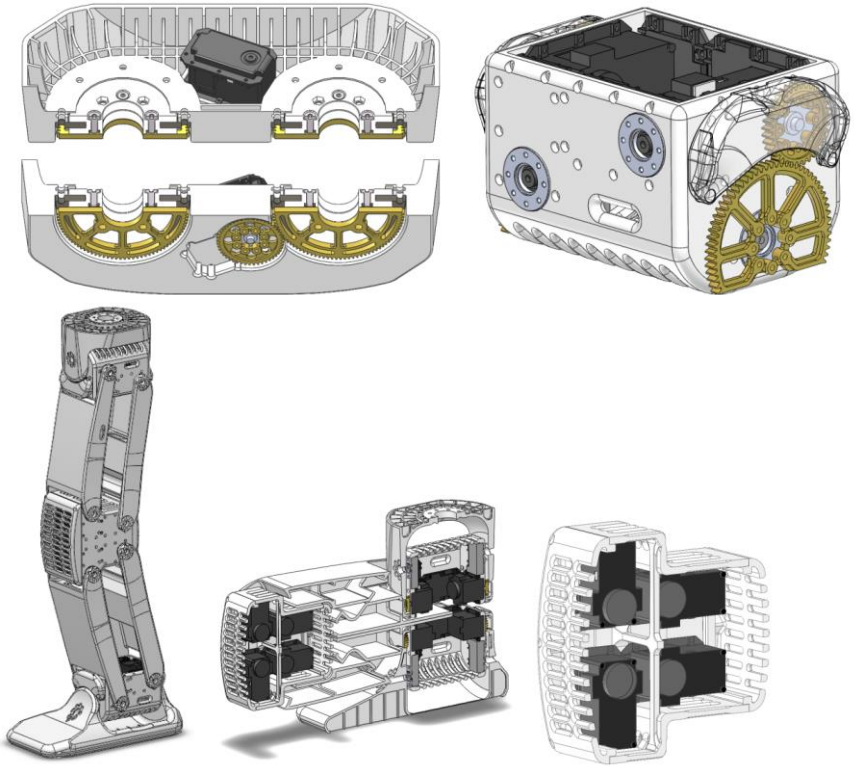


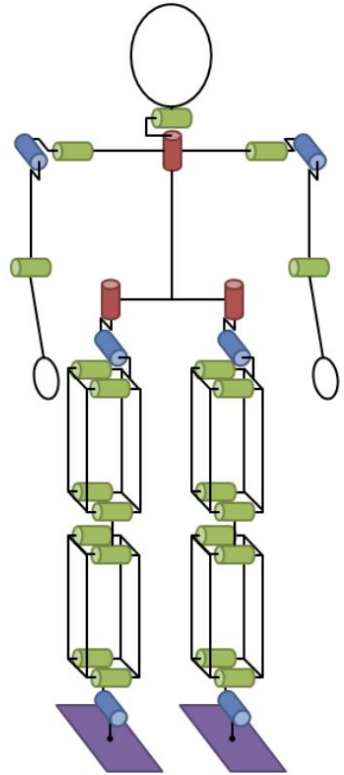
RoboCup 2016 TeenSize Final

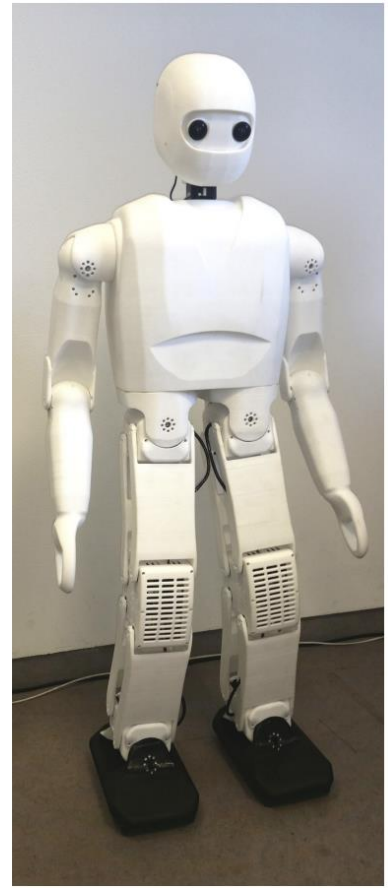


NimbRo-OP2

- 3D printed structure, driven by Dynamixel

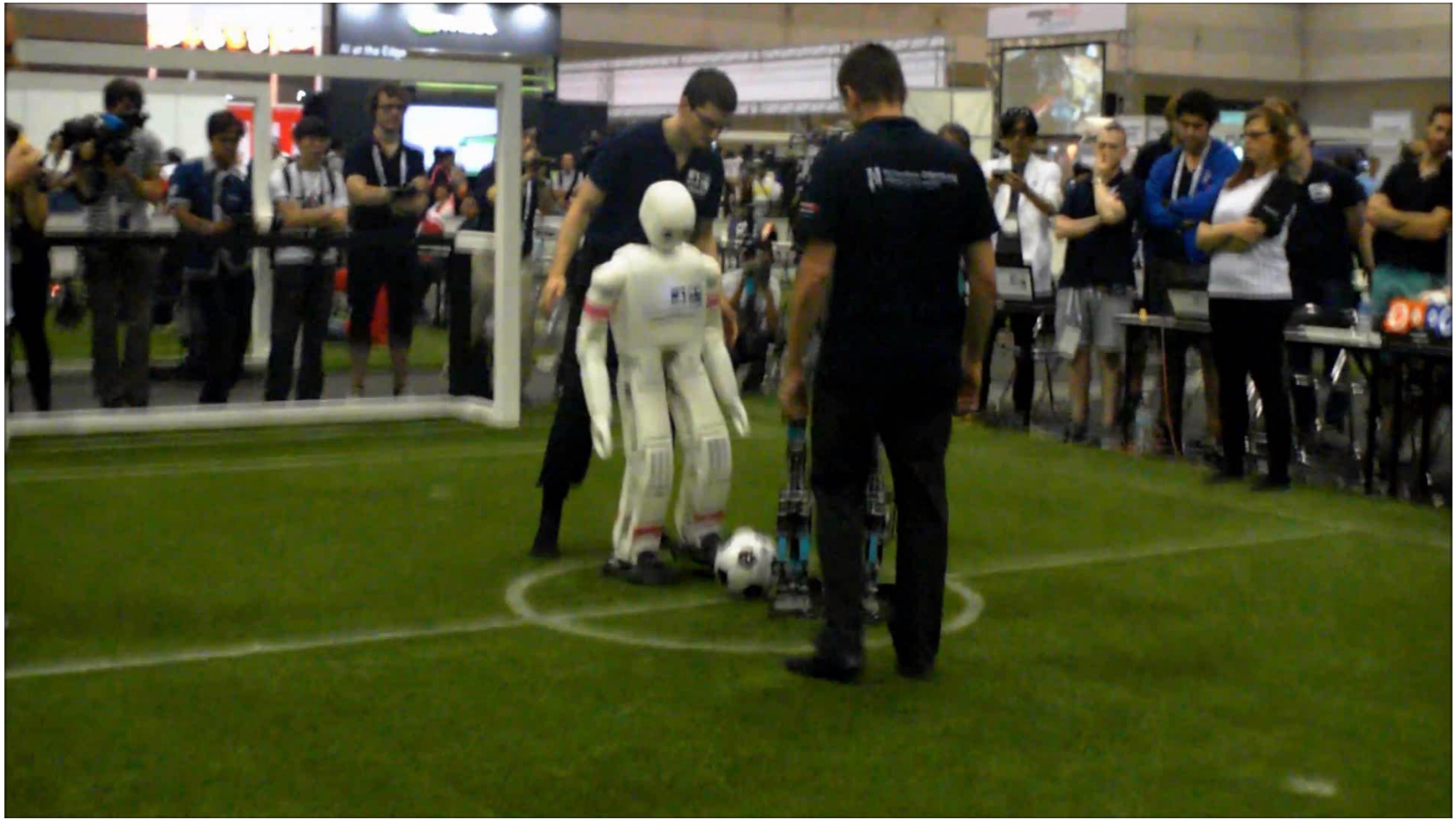






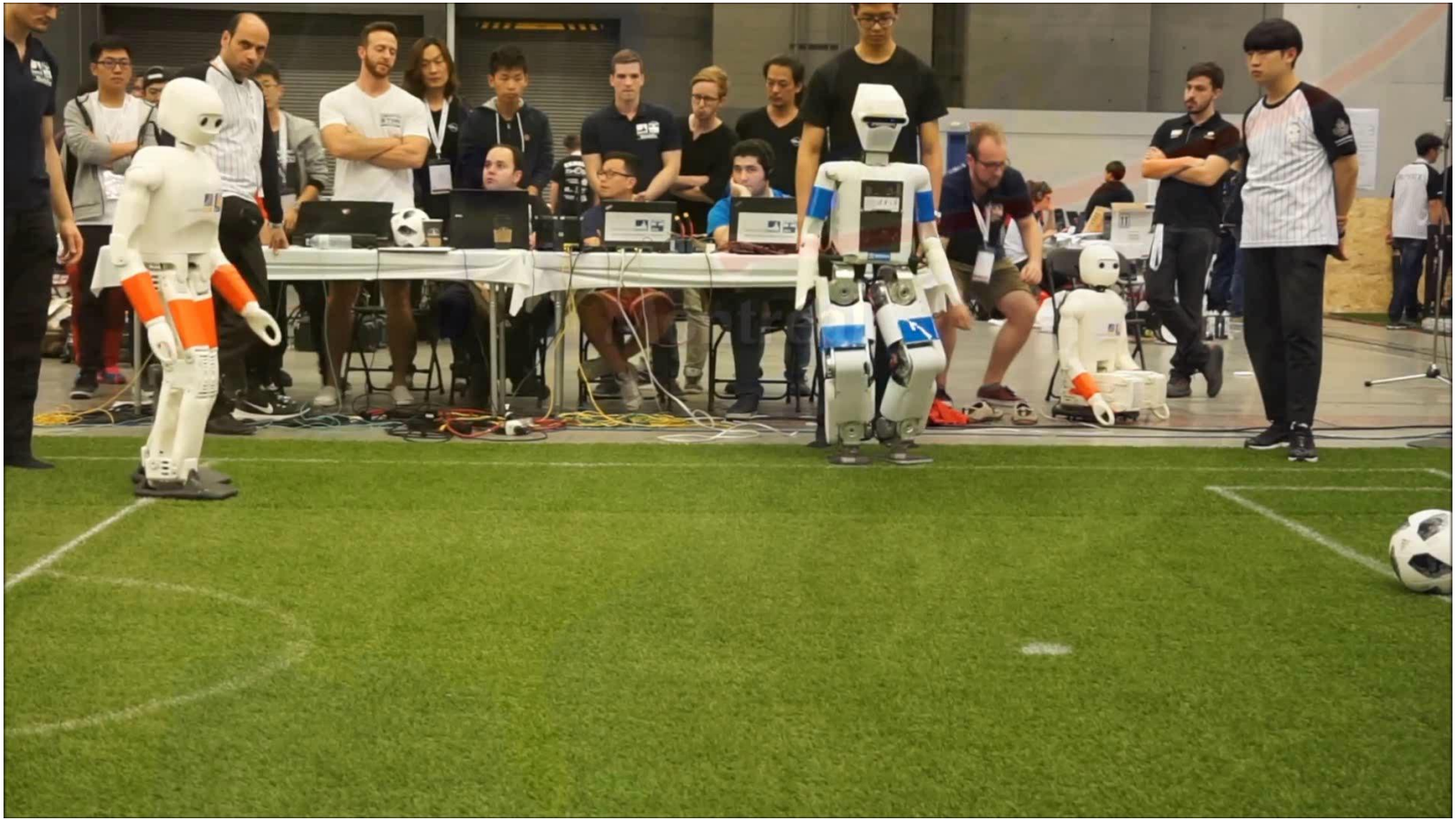
[Ficht et al.: Humanoids 2017]

NimbRo-OP2 @ RoboCup 2017 AdultSize Final



NimbRo-OP2 Omnidirectional Gait with Capture Steps

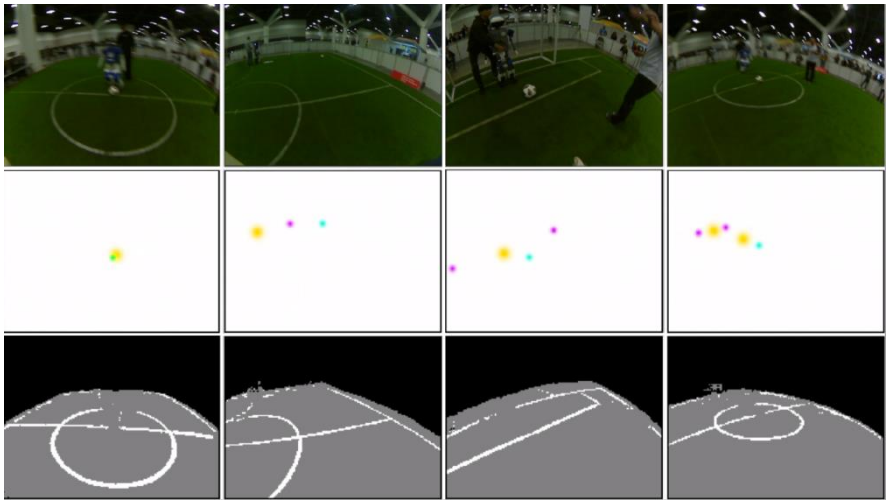
NimbRo-OP2X @ RoboCup 2018

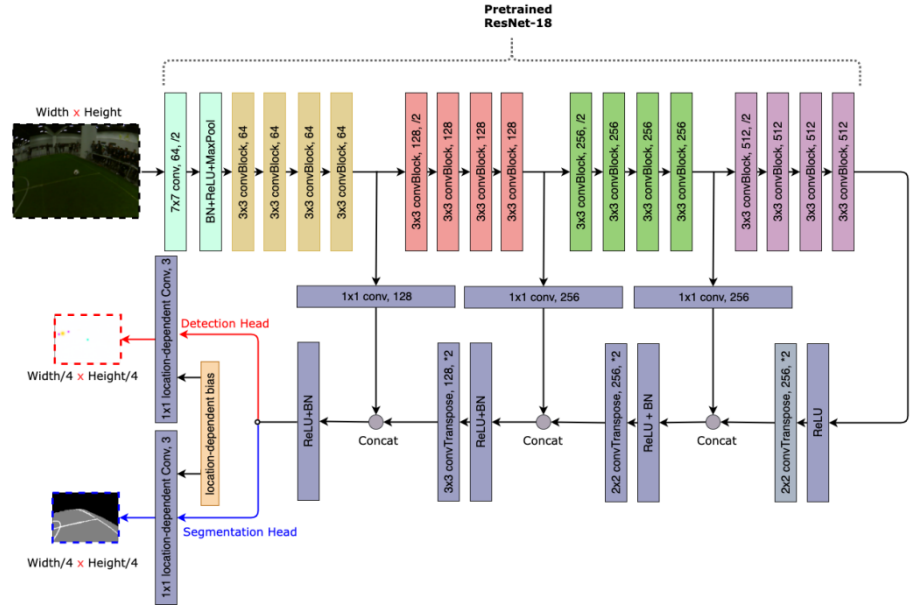


[Ficht et al.: Humanoids 2018]

Transfer Learning for Visual Perception

- Encoder-decoder network
- Two outputs
  - Object detection
  - Semantic segmentation
- Location-dependent bias

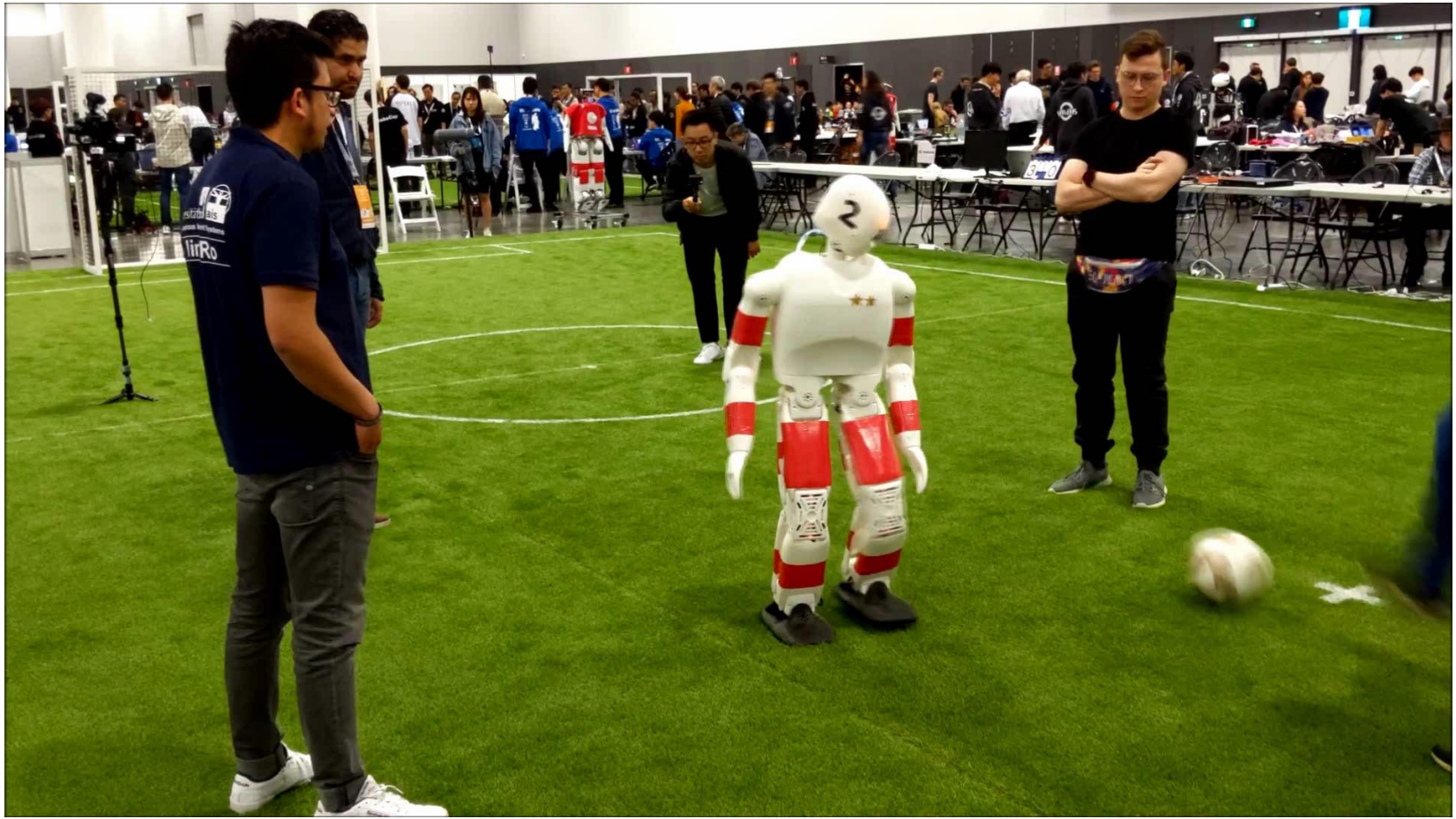




- Detects objects that are hard to recognize for humans
- Robust to lighting changes

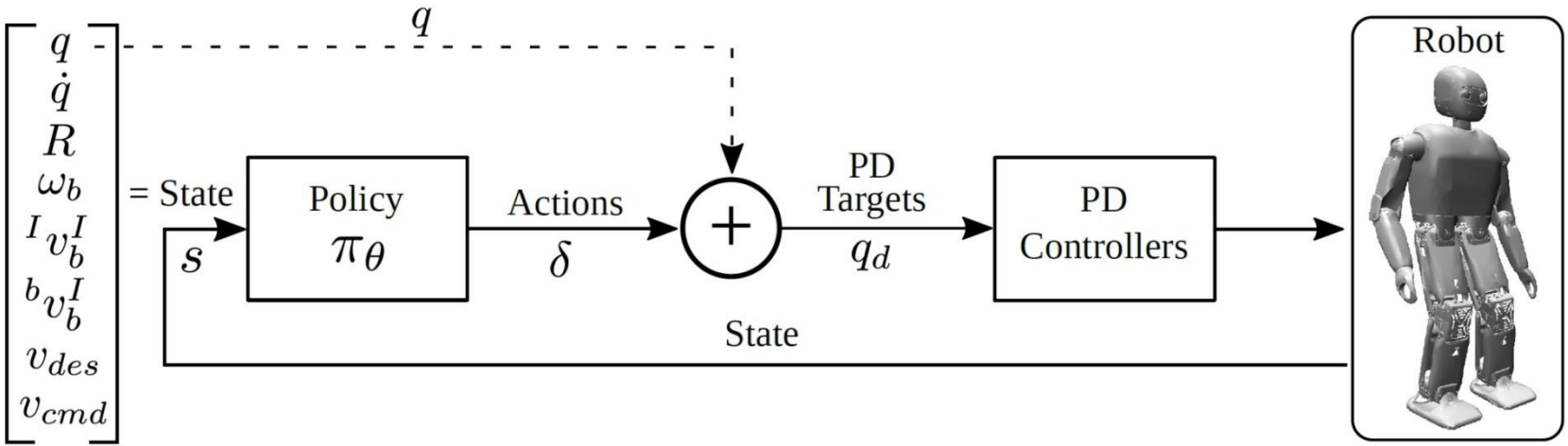
[Rodriguez et al. RoboCup 2019]

RoboCup 2019 in Sydney



Learning Omnidirectional Gait from Scratch

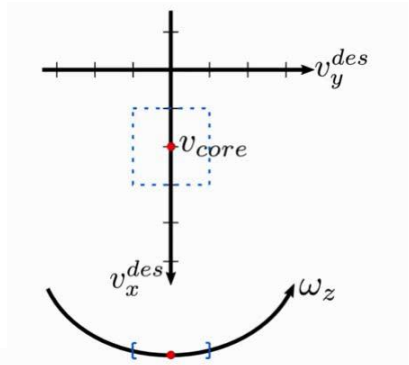
- State includes joint positions and velocities, robot orientation, robot speed
- Actions are increments of joint positions
- Simple reward structure
  - Velocity tracking
  - Pose regularization
  - Not falling

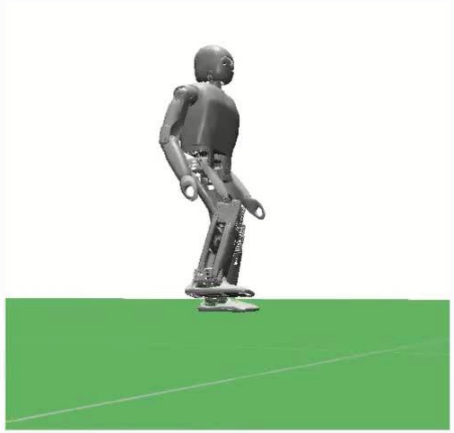


[Rodriguez and Behnke, ICRA 2021]

Learning Curriculum

- Start with small velocities
- Increase range of sampled velocities





[Rodriguez and Behnke, ICRA 2021]

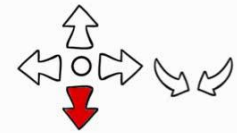
Learned Omnidirectional Gait

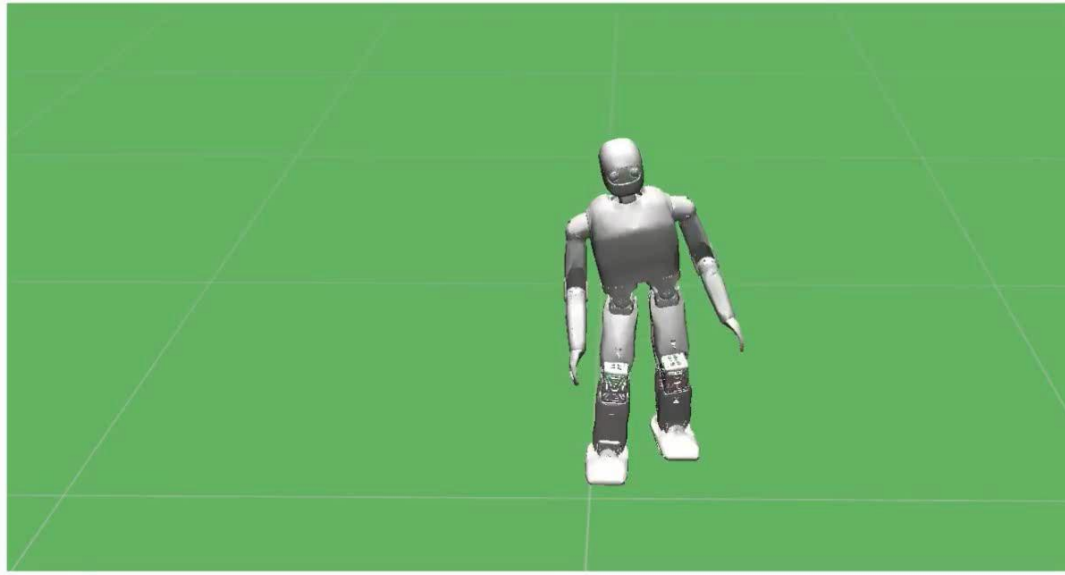
- Target velocity can be changed continuously

Our locomotion controller is able to:

Walk Forward

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



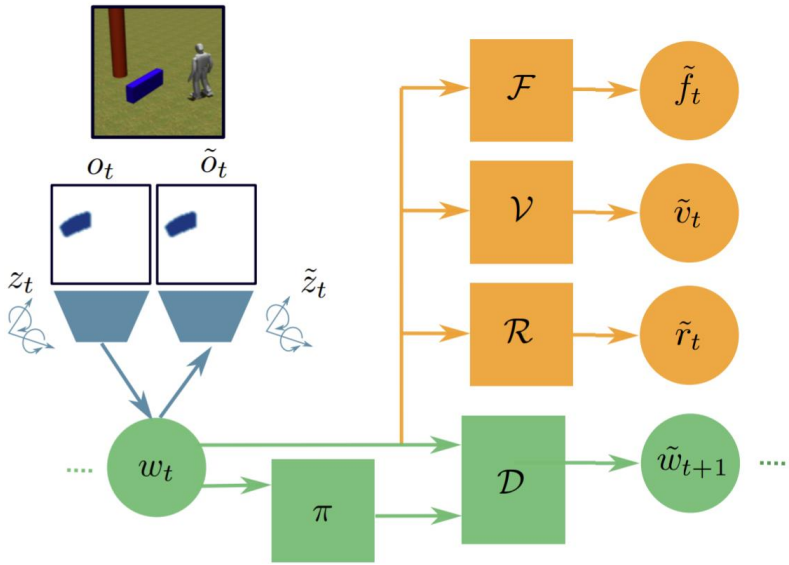


[Rodriguez and Behnke, ICRA 2021]

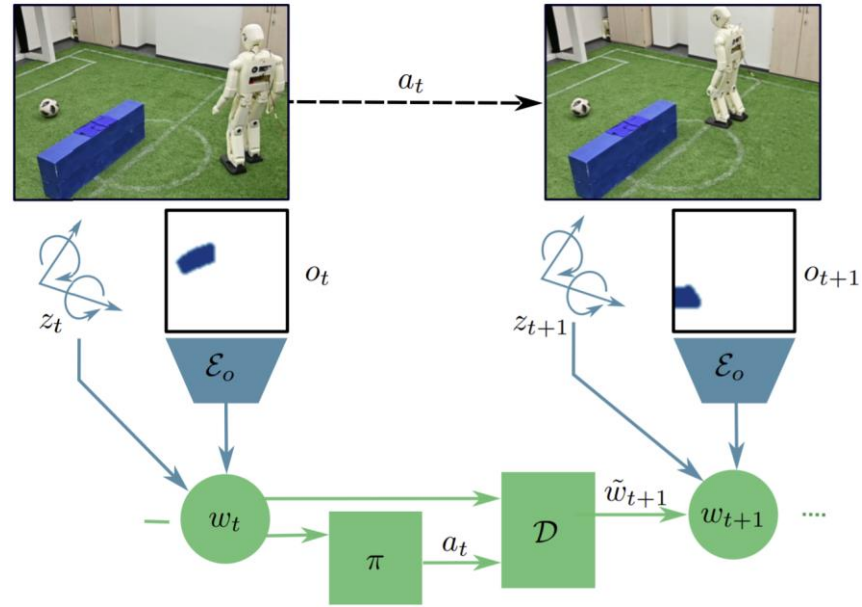
Learning Mapless Humanoid Navigation

- 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

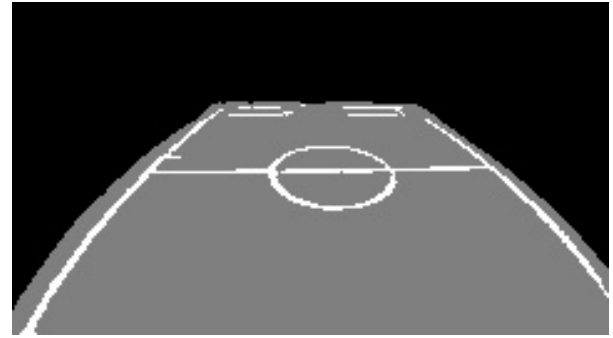
[Brandenburger et al. IROS 2021]

Improved Vision System

- New 5 MPixel camera: Logitech C930e
- Wider field-of-view
- New GPU: Nvidia RTX A2000
- Data augmentation with multiple ball designs
- More robust perception for far-away objects and field lines
- Improved localization

Wide-angle image

Object detection

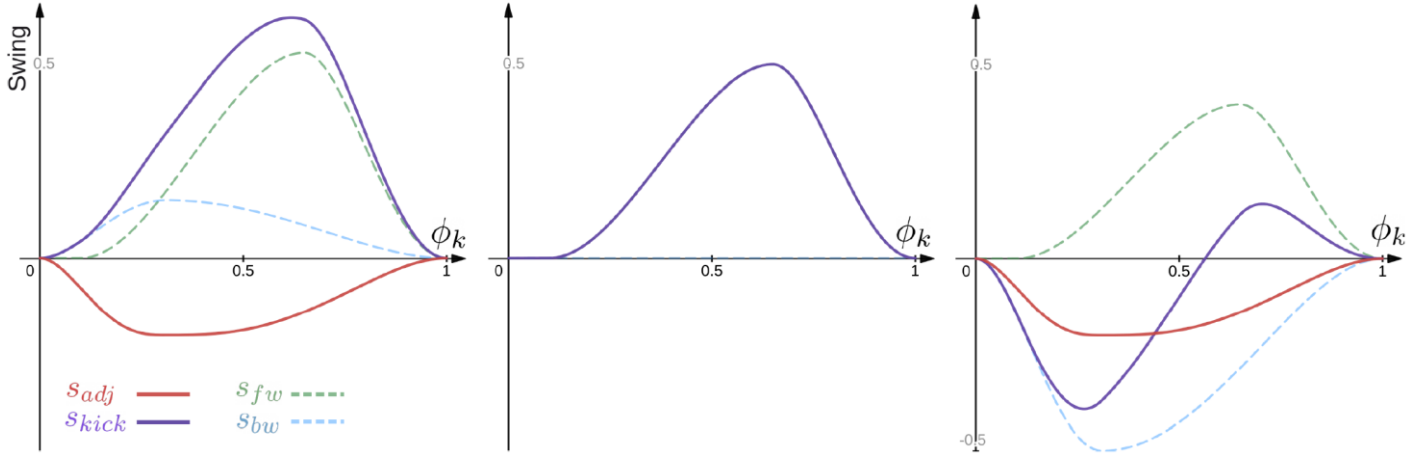


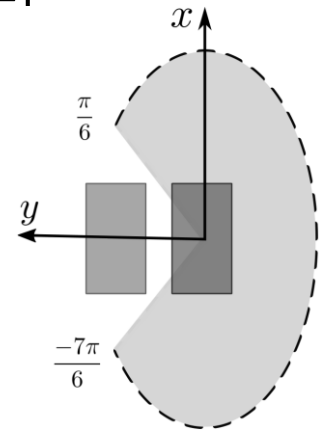
Semantic segmentation

[Pavlichenko et al. Robot World Cup XXV, Springer 2022]

Robust Omnidirectional Gait with Diagonal Kick

- Gait based on Capture Step Framework [Missura et al. IJHR 2019]
- Improved balance state estimation [Ficht and Behnke, CLAWAR 2022]
- Phase-based in-walk kicks in many directions
- Adapts to relative ball position



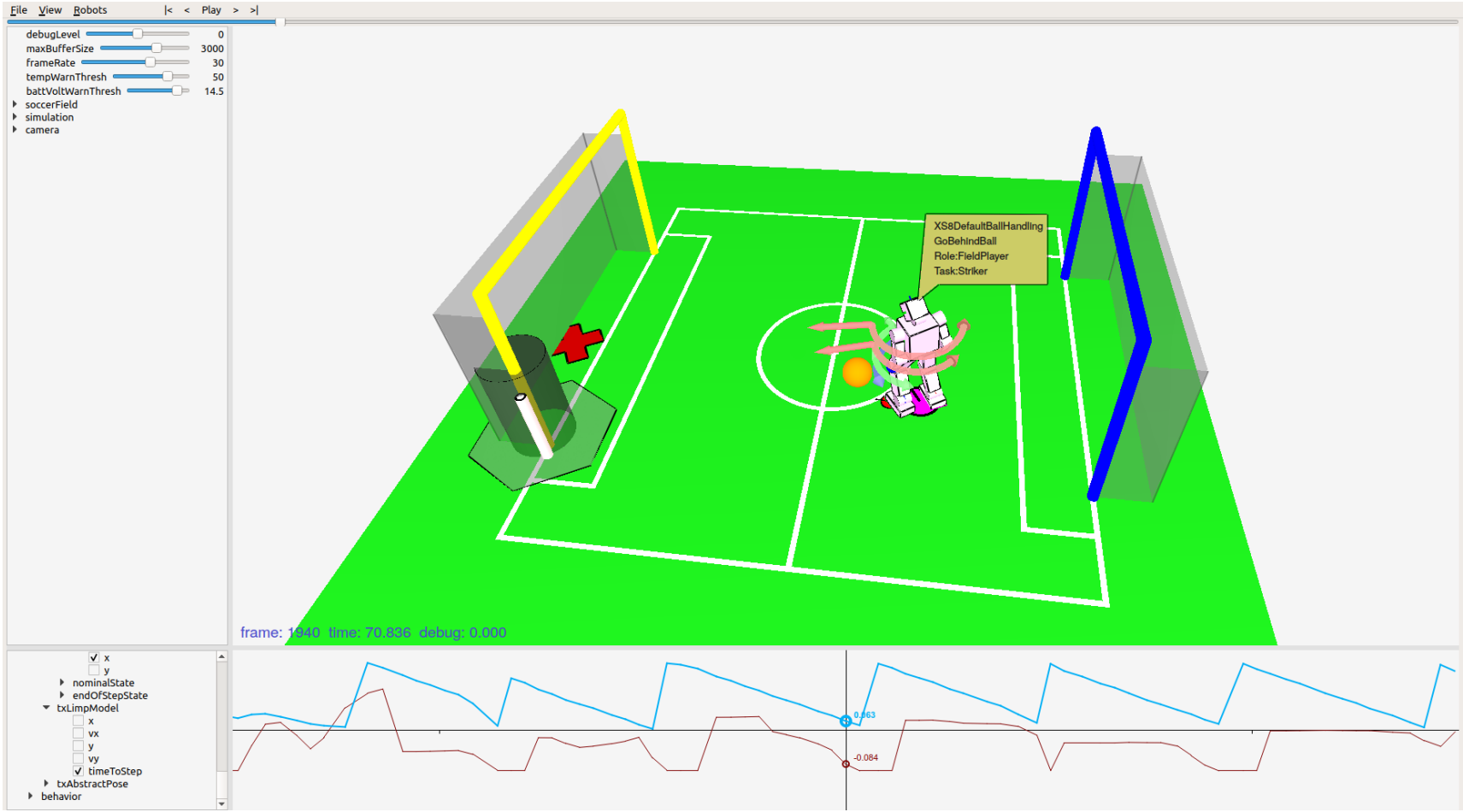


[Pavlichenko et al. Robot World Cup XXV, Springer 2022]

Phase-based In-walk Kicks in Many Directions

[Pavlichenko et al. Robot World Cup XXV, Springer 2022]

Graphical Debugging and Diagnostics



[Pavlichenko et al. Robot World Cup XXV, Springer 2022]

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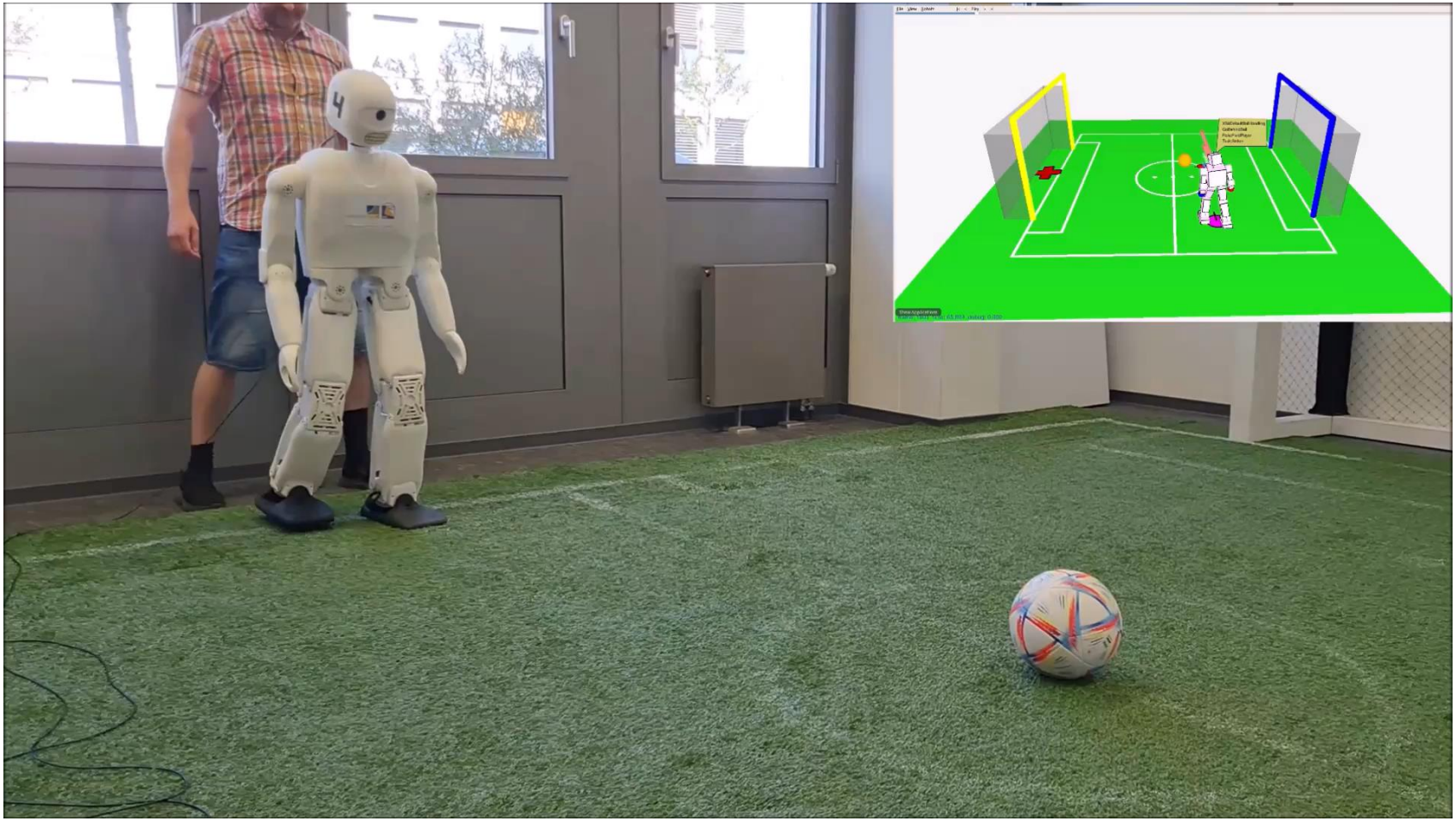

[Pavlichenko et al. Robot World Cup XXV, Springer 2022]

RoboCup 2022 in Bangkok

[Pavlichenko et al. Robot World Cup XXV, Springer 2022]

Conclusions

- Developed capable bipedal soccer robots
  - 3D printed structure
  - Deep learning-based visual perception
  - Omnidirectional gait
  - Capture steps
  - Flexible kicks
  - Debugging tools
- Open-source hard- and software
- Future challenges
  - Running
  - Dynamic whole-body motion
  - Other applications, such as personal assistance

NimbRo-OP2X