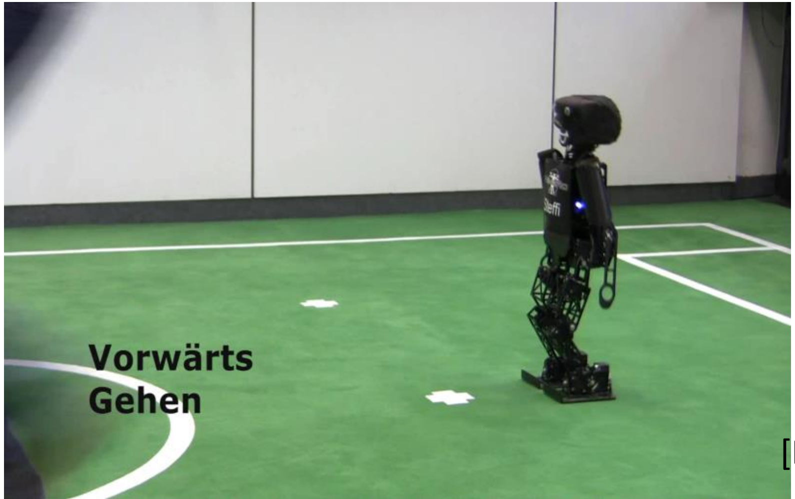
# PUSH RECOVERY, FALL SURVIVAL, AND GETTING-UP OF NIMBRO HUMANOID SOCCER ROBOTS

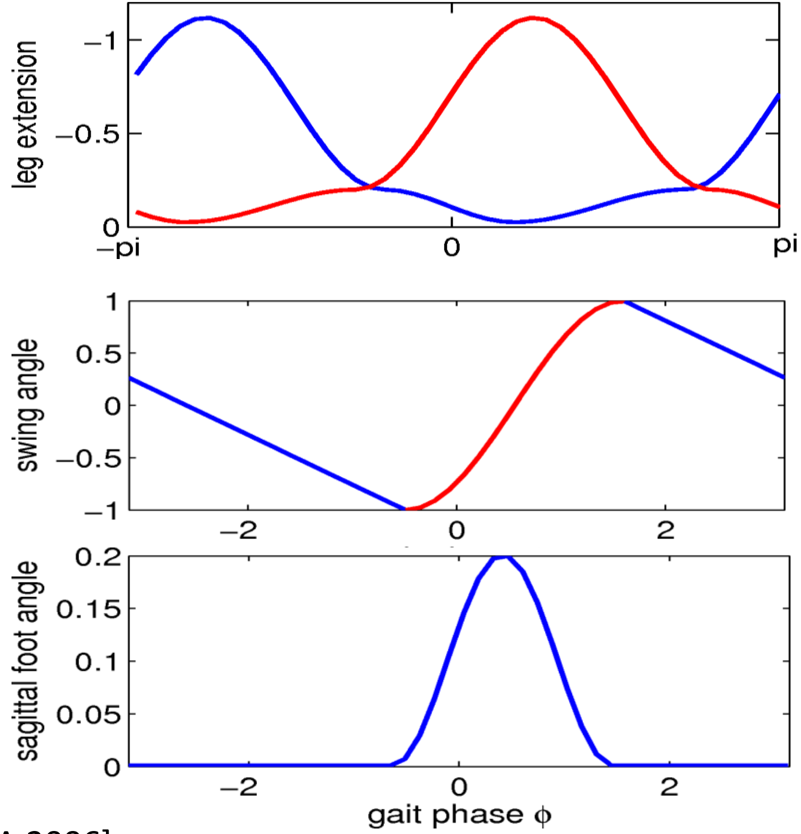
**Sven Behnke**

# 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



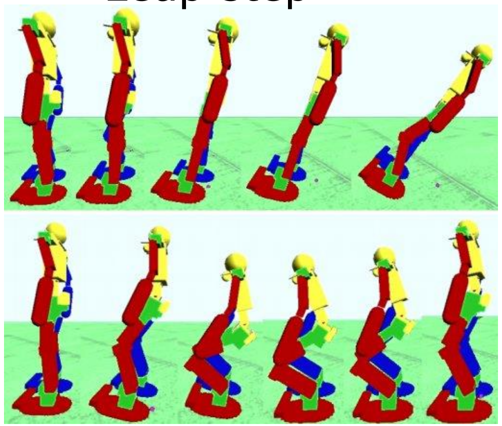




[Behnke: ICRA 2006]

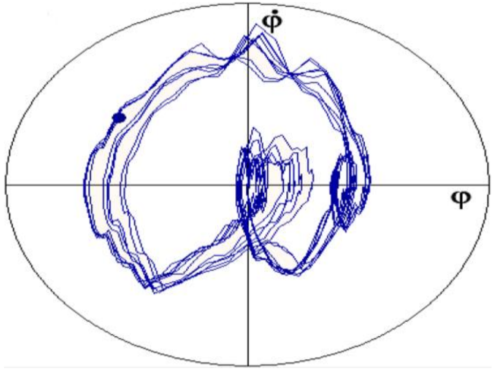
# FALL AVOIDANCE

[Renner, Behnke: IROS 2006]

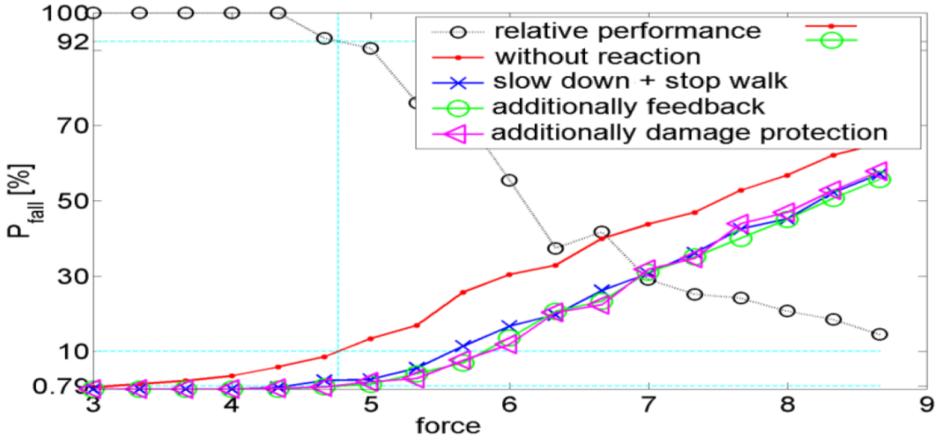
- Learn model of trunk attitude during undisturbed walking
- Aggregate deviations to instability measure
- Stabilizing reflexes
  - Slow down
  - Stop walking
  - Leap step



Lateral tilt



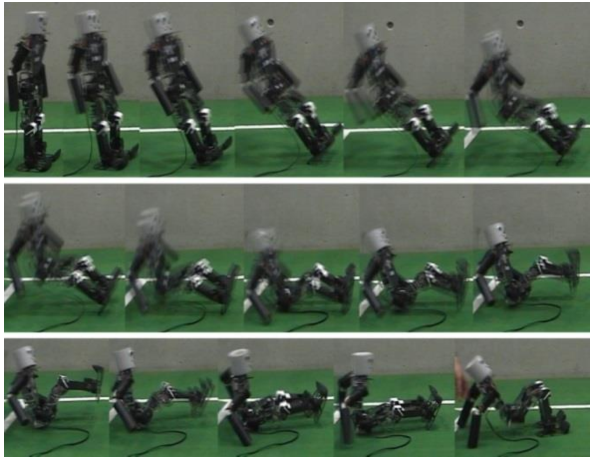

Results in simulation

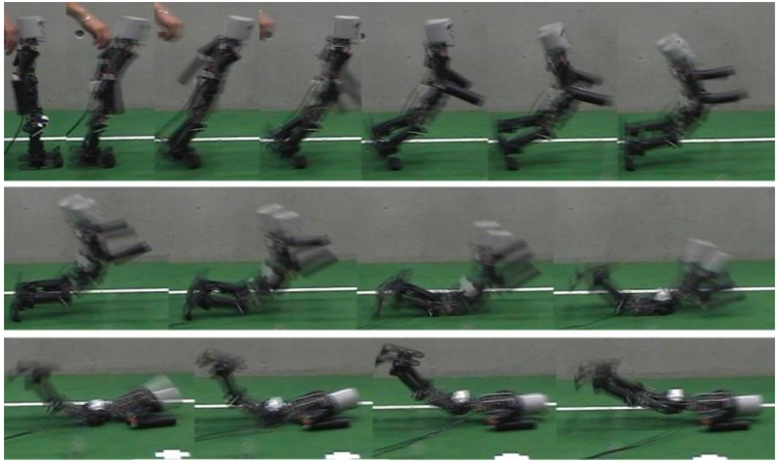


# CONTROLLED LANDING

[Renner 2006]

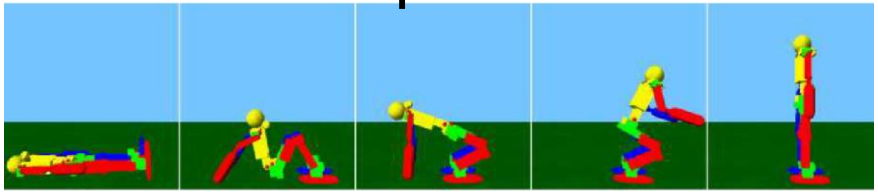
- Falls cannot be avoided completely
- Timely recognition by attitude estimation
- Landing at cushioned primary contact points
  - Knee (forward fall)
  - Lower back (backward fall)
- Arms as secondary contact points
- Relaxation of joints



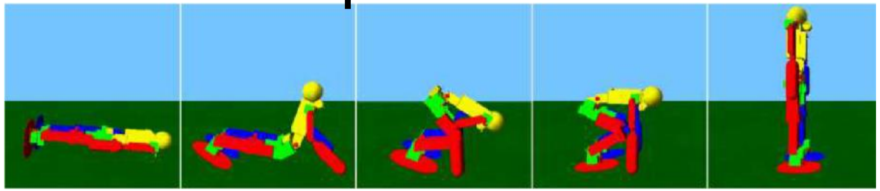


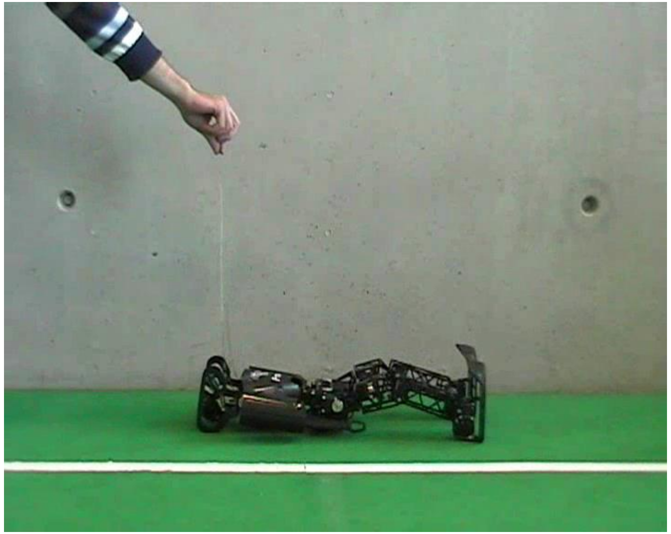
# GETTING-UP

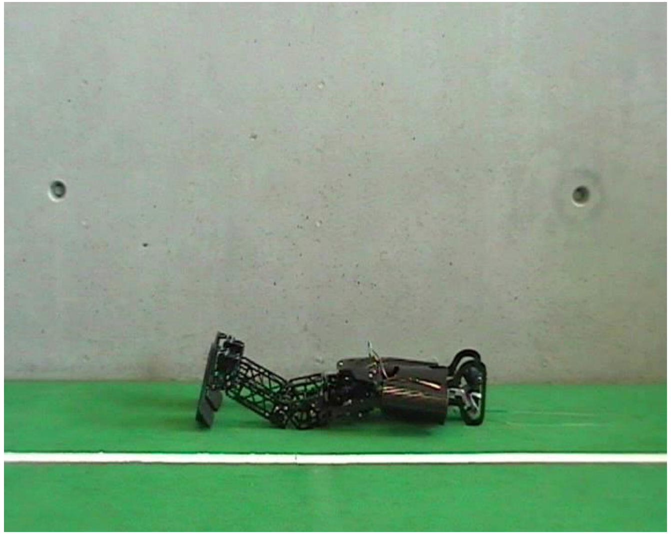
supine



prone





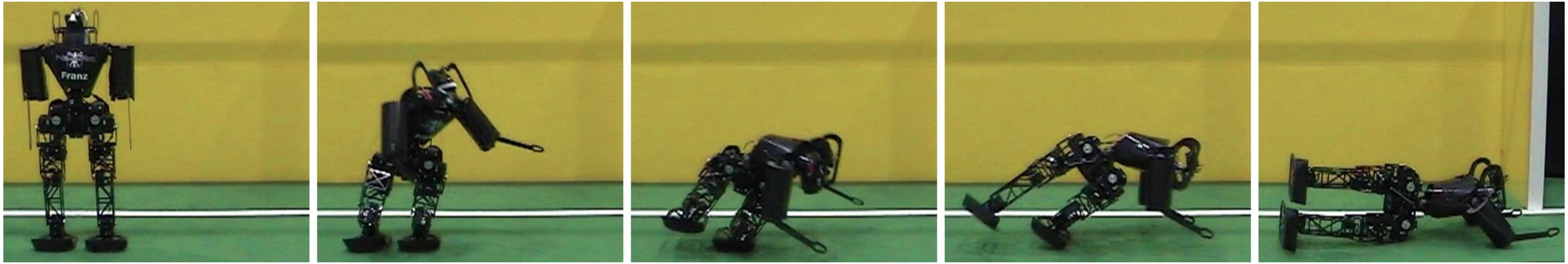


[Stückler, Schwenk, Behnke: IAS-2006]

# ROBOCUP 2013 FINAL

# GOALIE DIVING MOTION

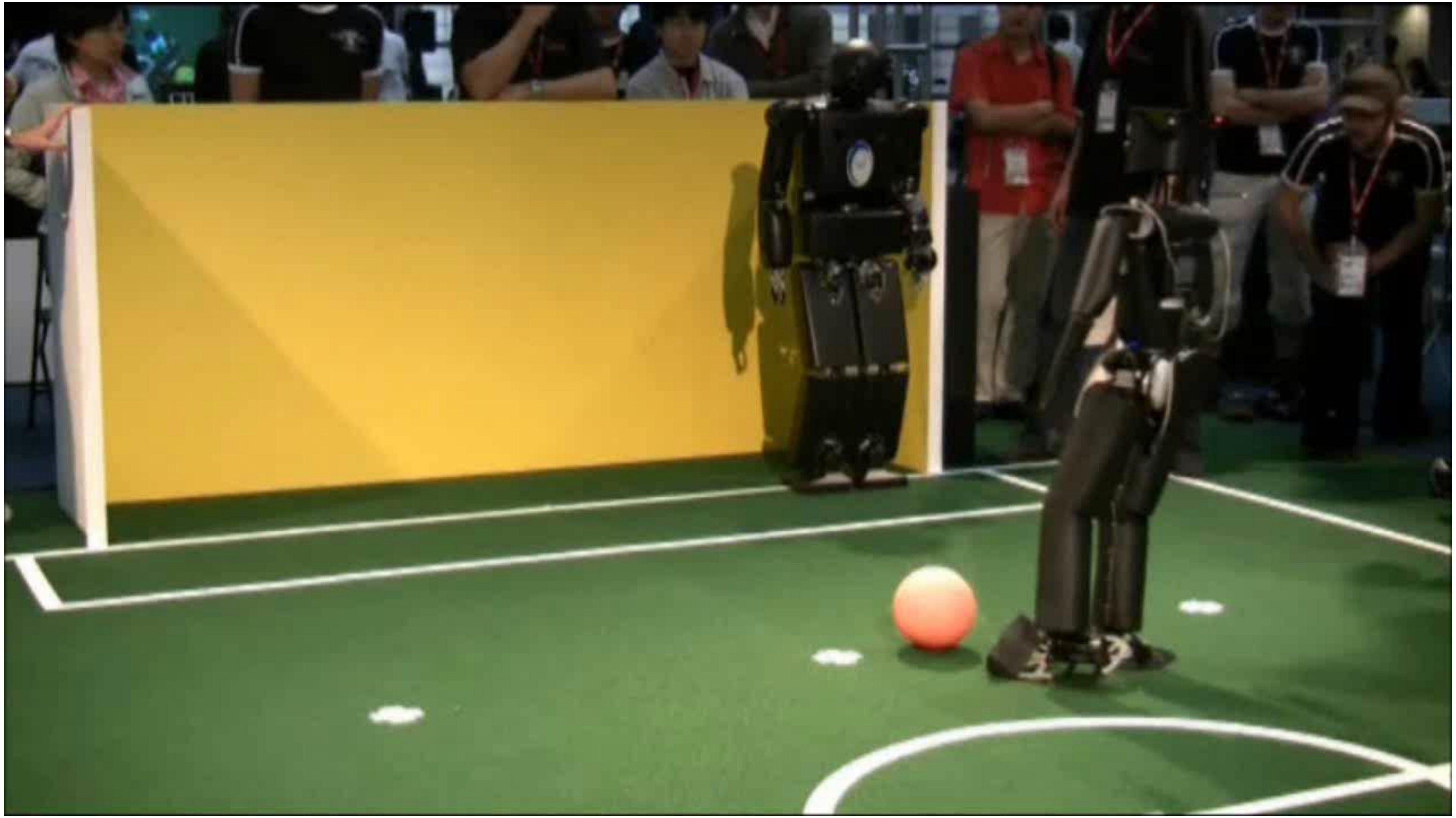
- NimbRo KidSize 2006 Robots; Bodo, Atlanta 2007




- Dynaped, Graz 2009

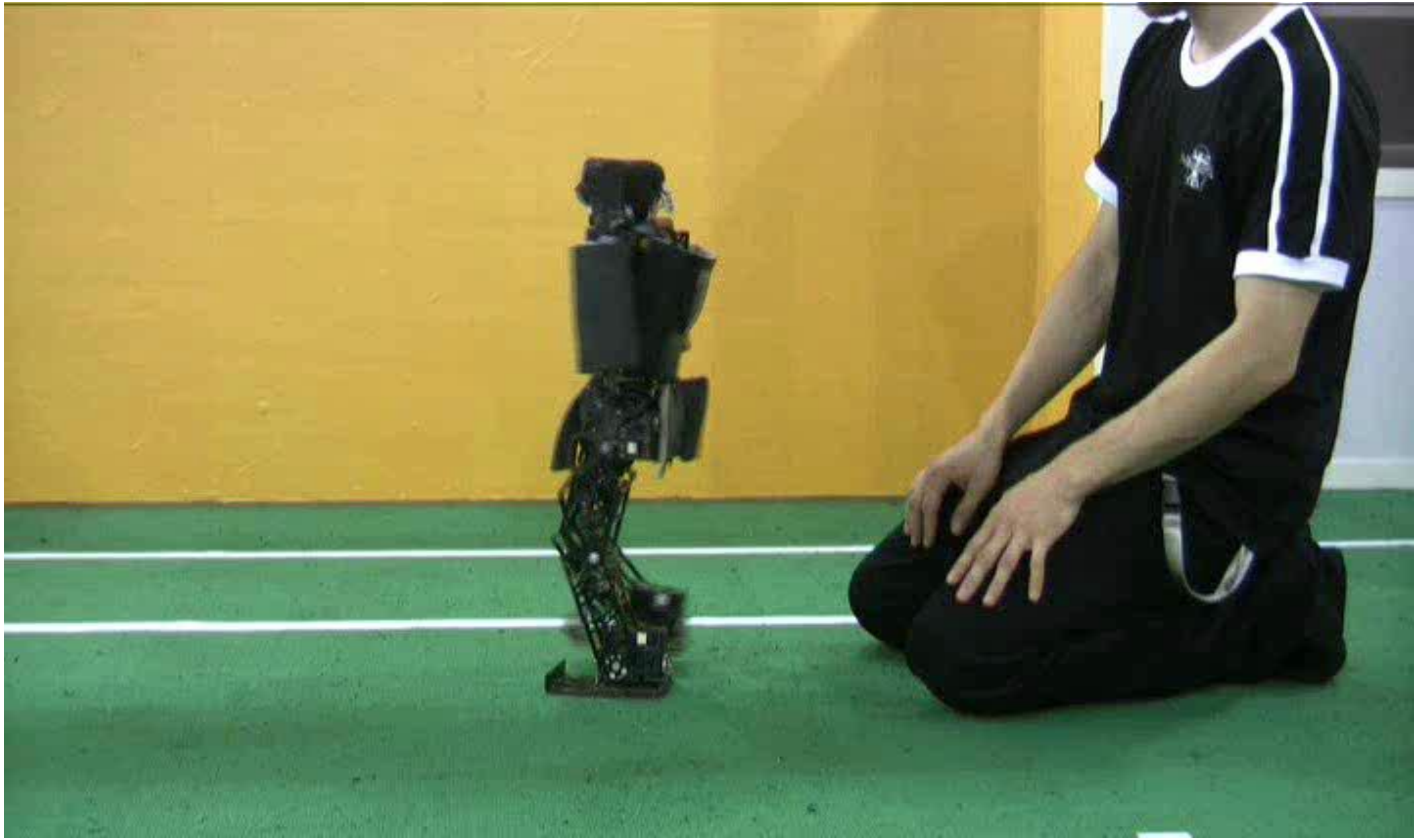
[Missura, Wilken, Behnke: RoboCup 2010]

# ROBOCUP 2007 TEENSIZE FINAL NIMBRO VS. PAL TECHNOLOGY



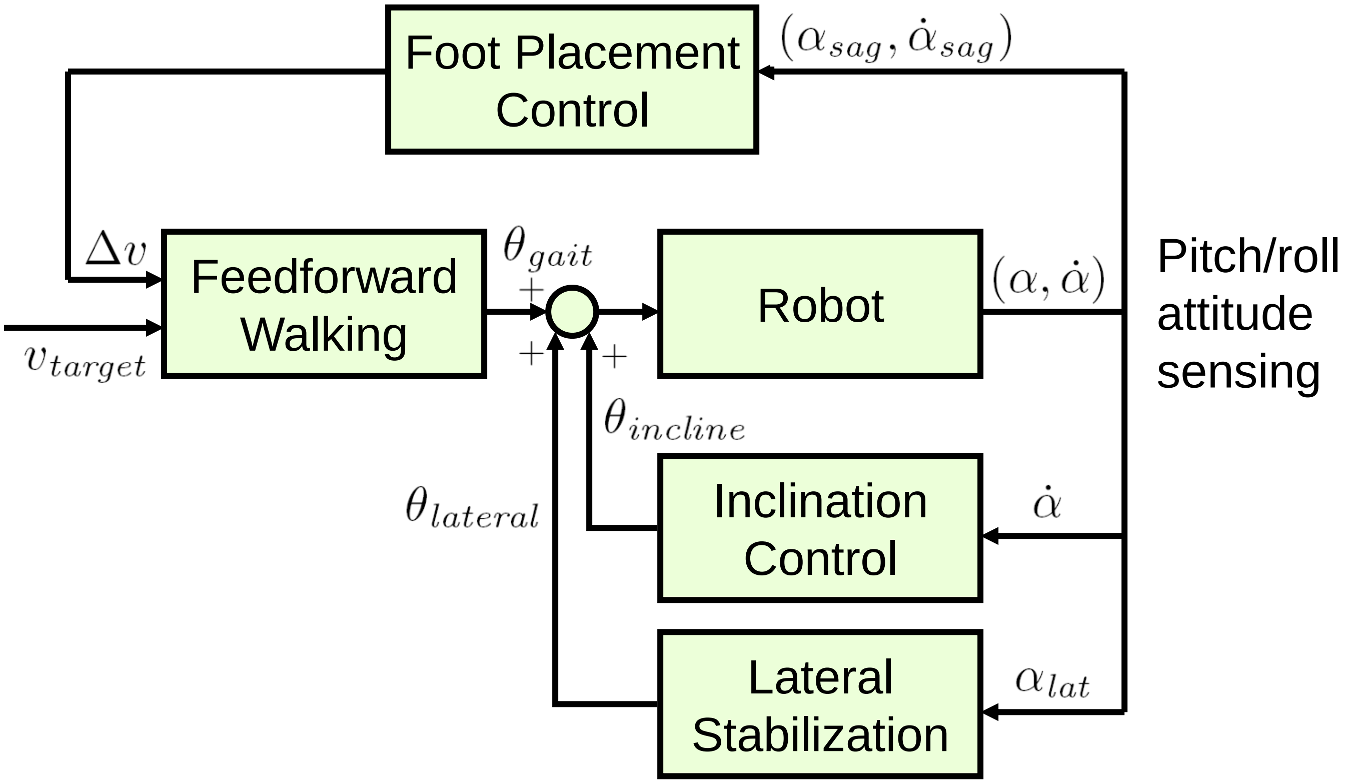
# ROBOCUP 2009 TEENSIZE DRIBBLE & KICK

# DYNAMIC WALKING STABILIZATION



[Behnke et al. RoboCup 2009]

# GAIT STABILIZATION CONTROL



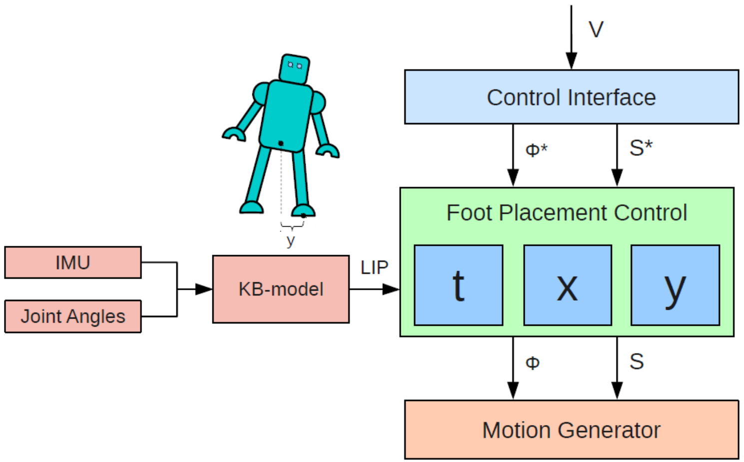

[Behnke et al. RoboCup 2009]

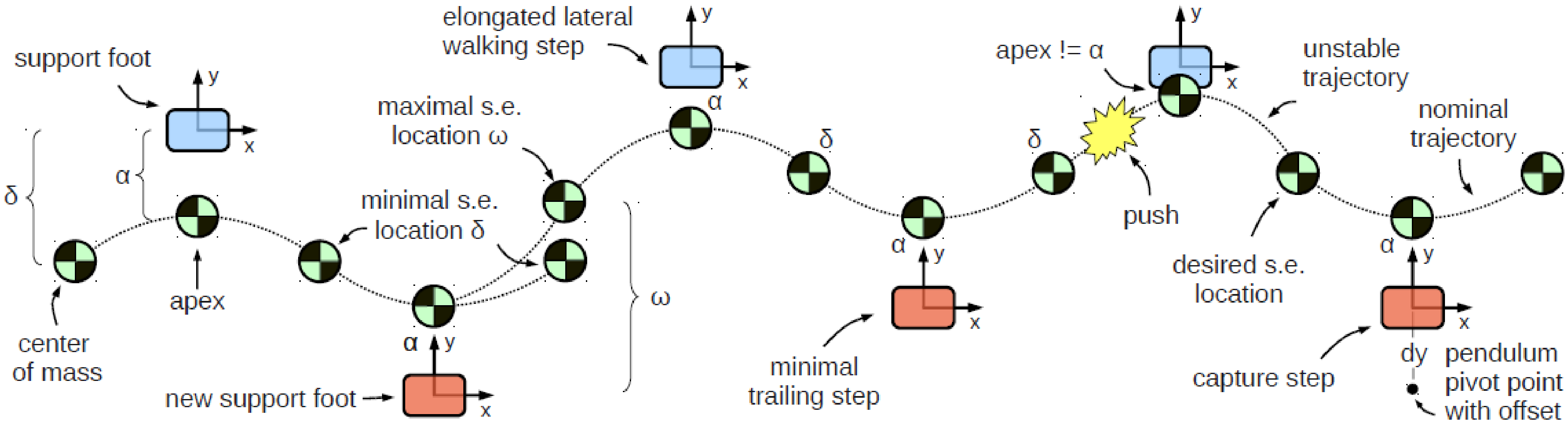
# LATERAL SENSITIVITY

[Missura, Behnke: Humanoids 2011]

# LATERAL CAPTURE STEPS

- Hierarchical control system
- Linear-inverted pendulum model $\ddot{x} = Cx$
- Offset for pendulum pivot point
- Adapt step timing and placement



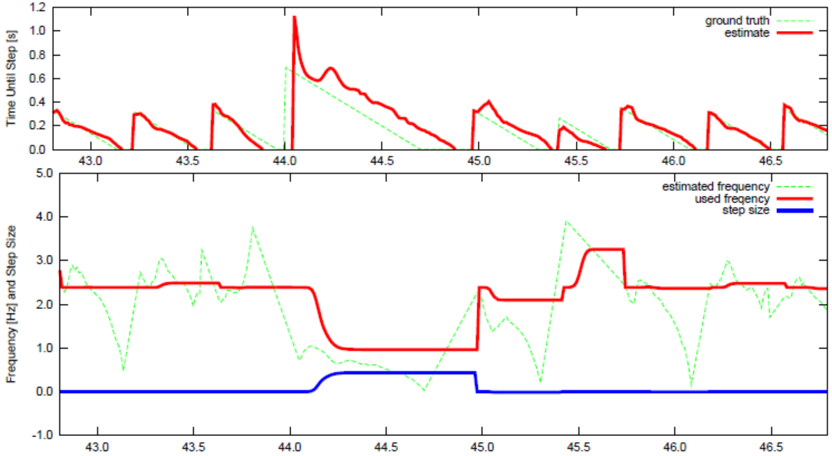

[Missura, Behnke: Humanoids 2011]

# LATERAL CAPTURE STEPS


[Missura, Behnke, Humanoids 2011]

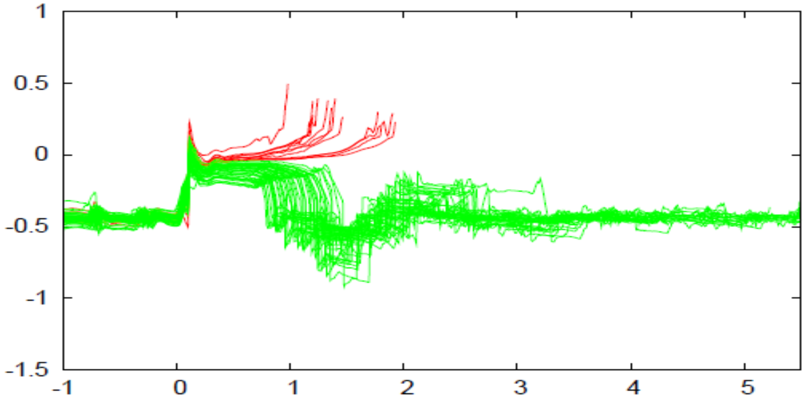
# LATERAL CAPTURE STEPS: RESULTS

- Single disturbance:

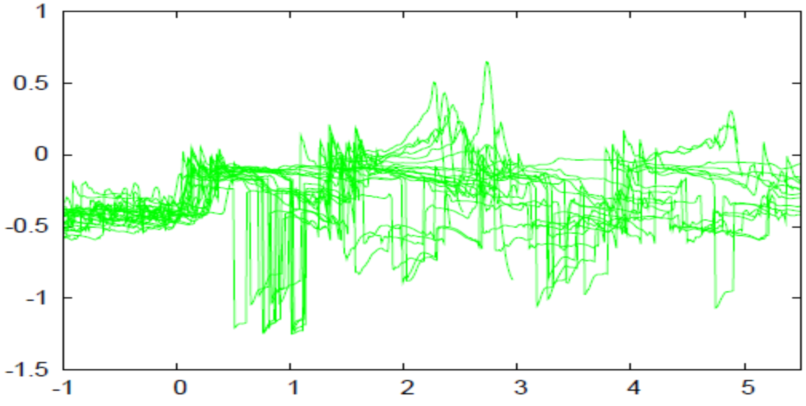



- 100 disturbances

with capture steps




without capture steps




[Missura, Behnke: Humanoids 2011]

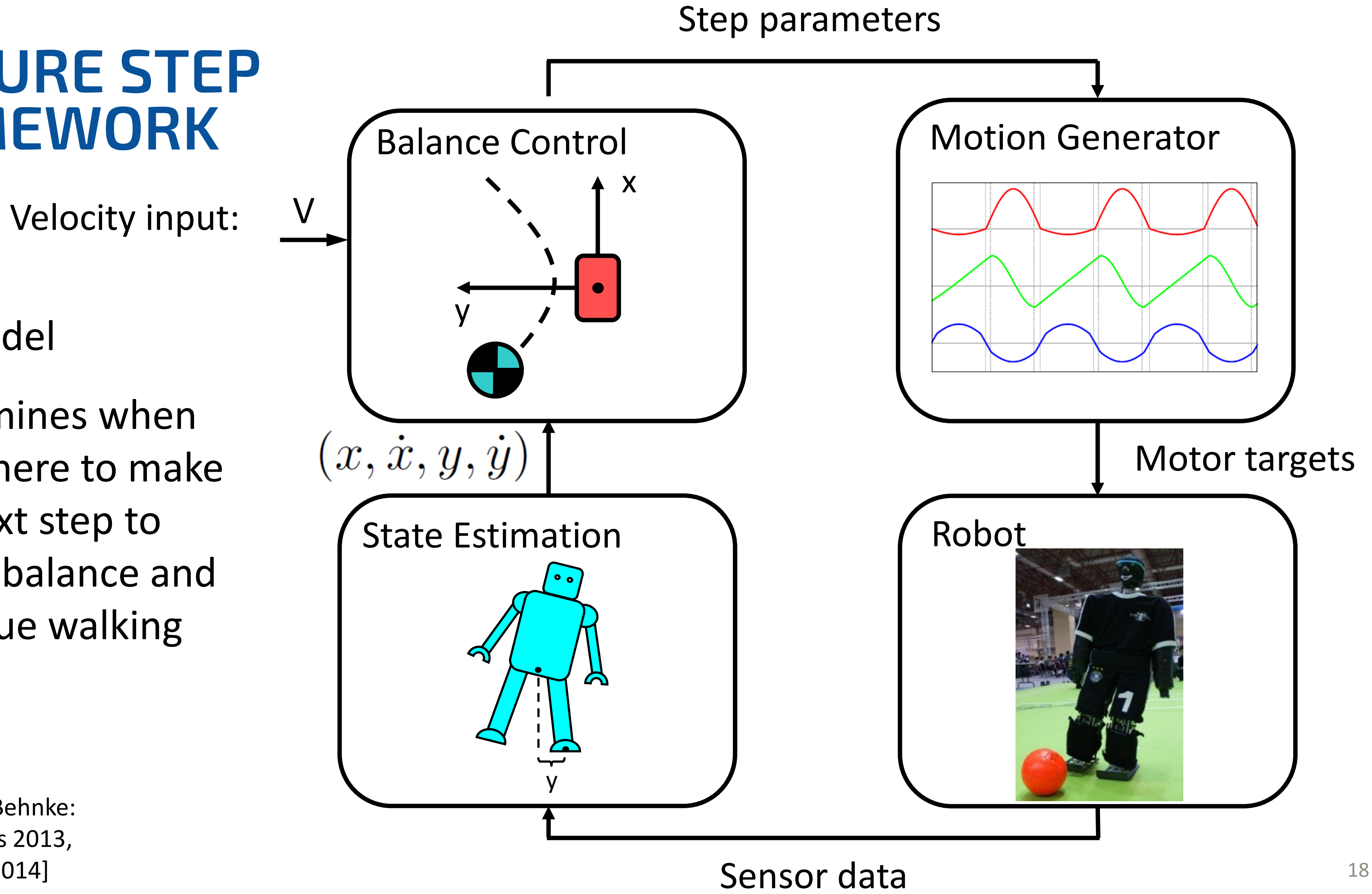
# LATERAL DISTURBANCE REJECTION

- Delay step until robot swings back

[Alcarez-Jimenez, et al. RoboCup Symposium 2012]

# CAPTURE STEP FRAMEWORK

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



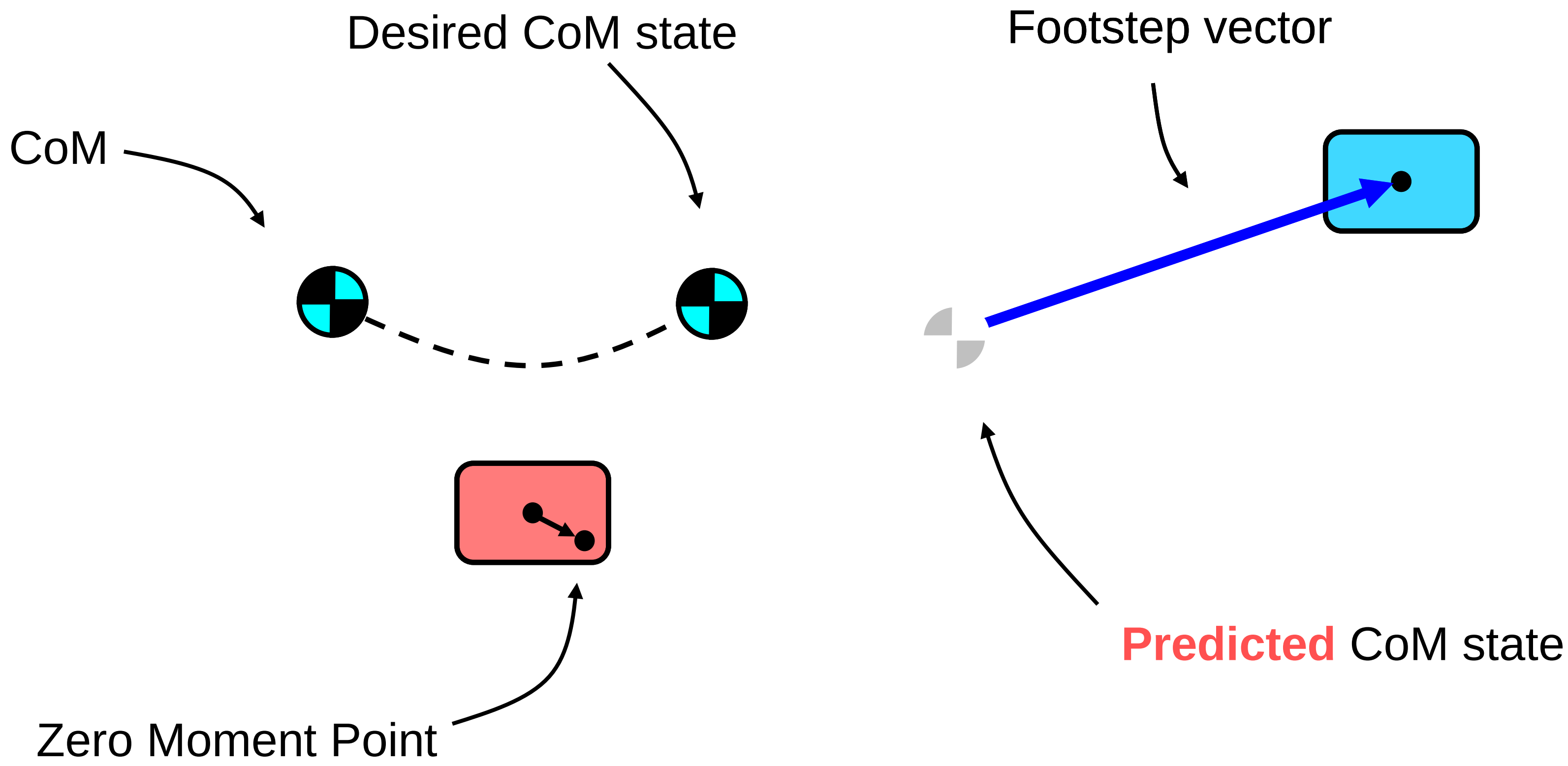

[Missura, Behnke: Humanoids 2013, RoboCup 2014]

# OMNIDIRECTIONAL CAPTURE STEPS


[Missura and Behnke: Humanoids 2013, RoboCup 2014]

# BALANCE CONTROL

- Adapt ZMP, timing, and foot placement




[Missura and Behnke: Humanoids 2013, RoboCup 2014]

# DYNAPED WITH SMALL FEET

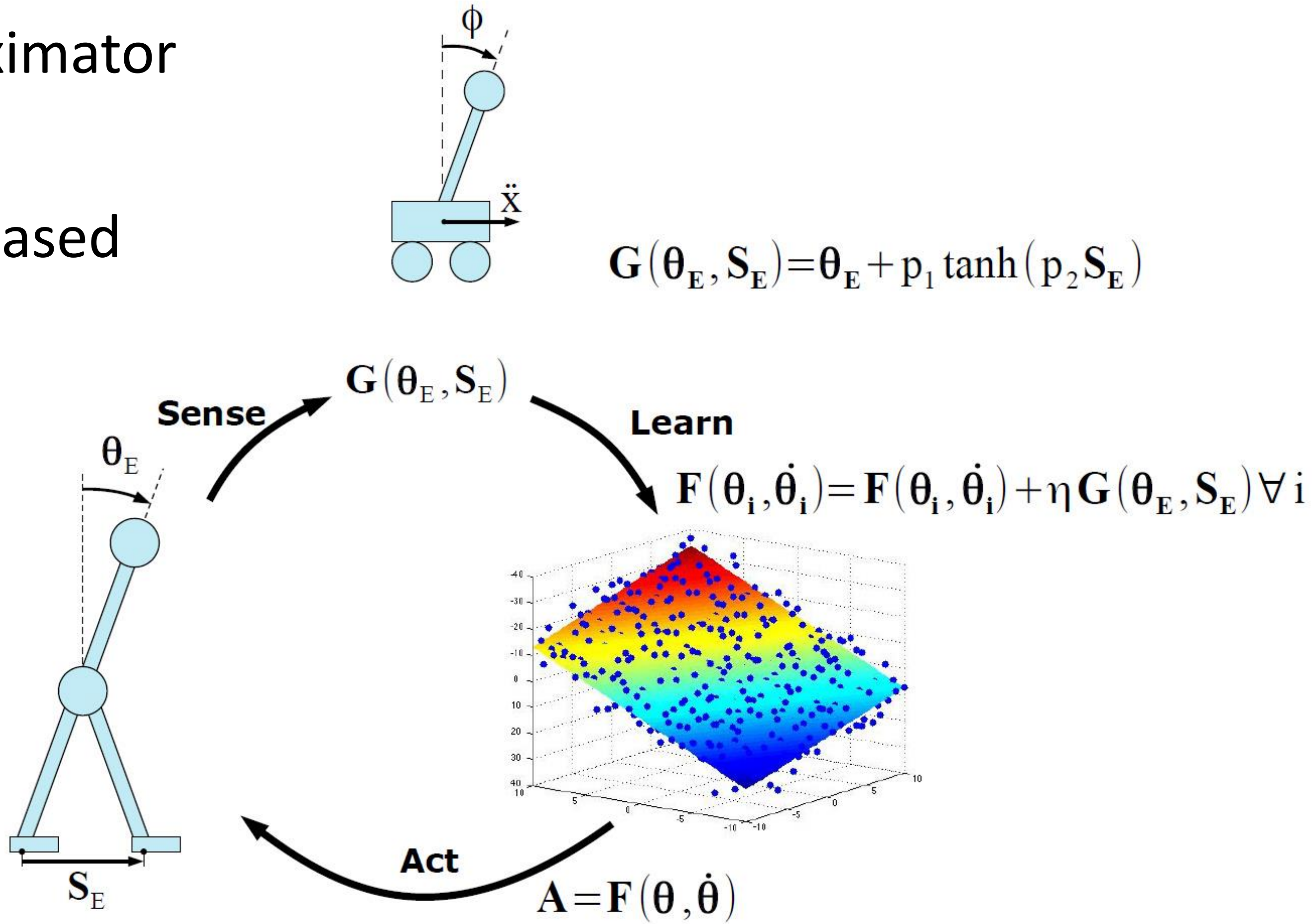

[Missura and Behnke: Humanoids 2013, RoboCup 2014]

# ONLINE LEARNING OF FOOT PLACEMENT

[Missura Behnke: IROS 2015]

# ONLINE LEARNING OF FOOT PLACEMENT

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

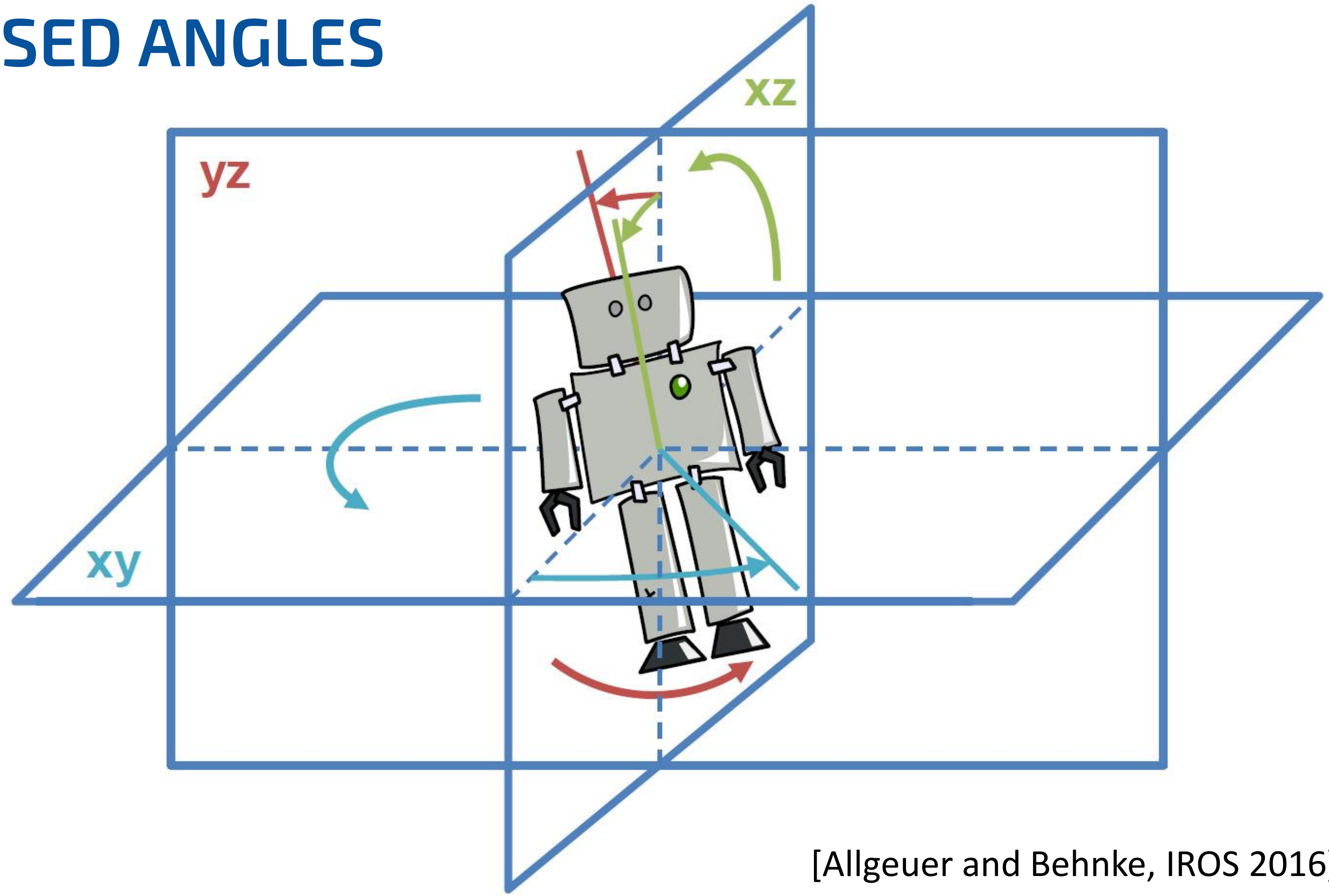



[Missura and Behnke: IROS 2015]

# ONLINE LEARNING OF FOOT PLACEMENT

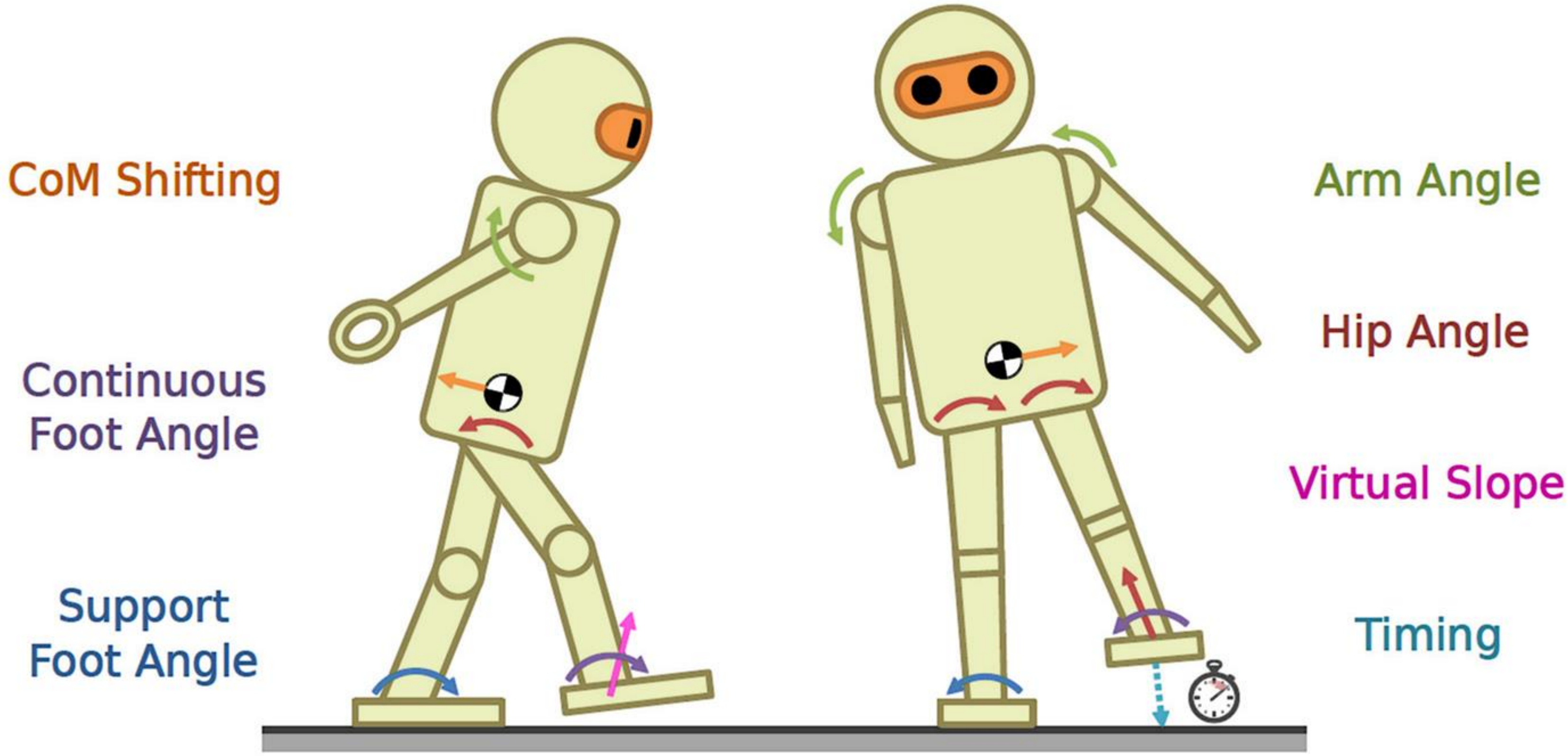
[Missura and Behnke: IROS 2015]

# FUSED ANGLES




[Allgeuer and Behnke, IROS 2016]:

# FEEDBACK MECHANISMS




[Allgeuer and Behnke: Humanoids 2016]

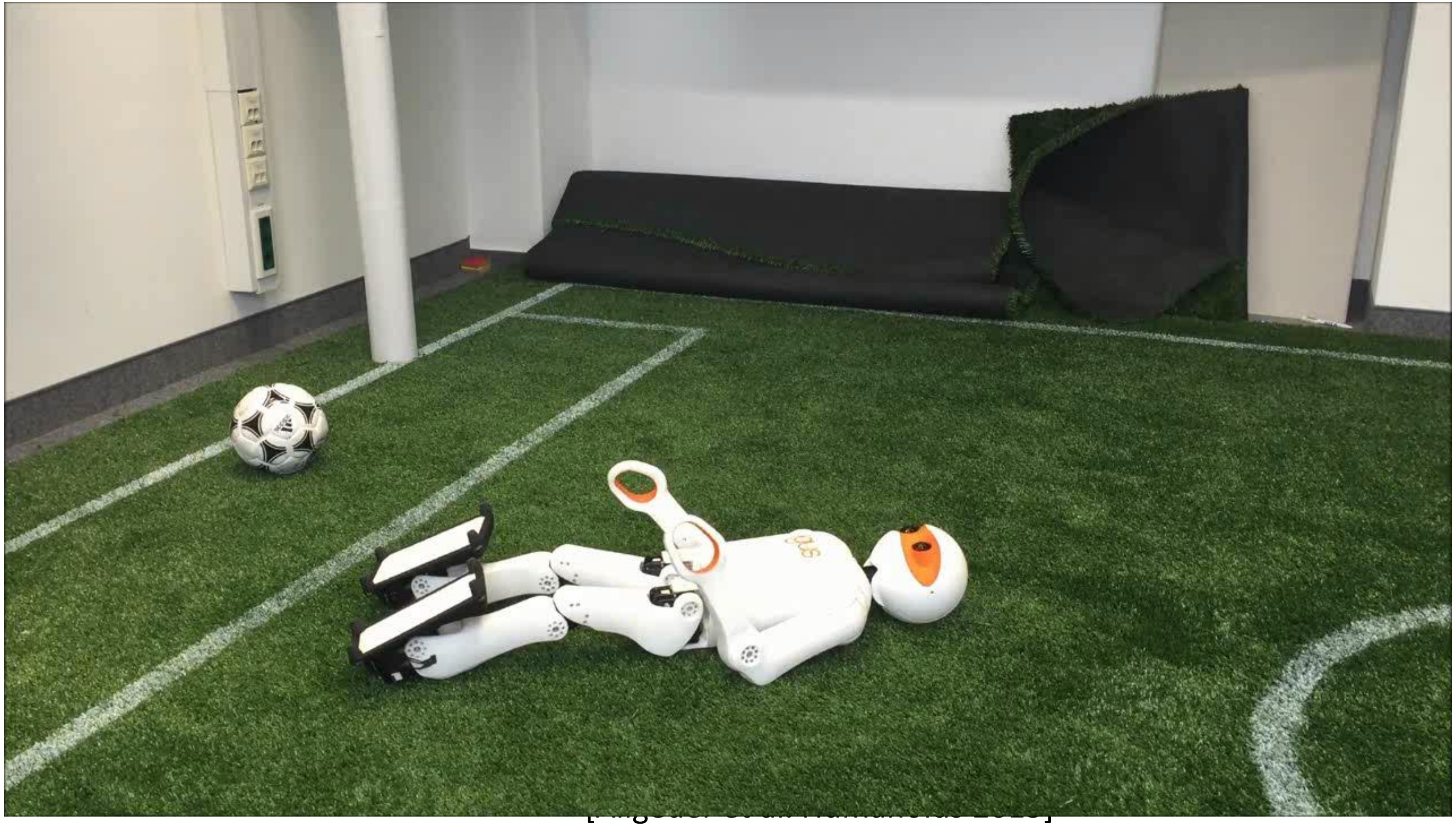
# PD FEEDBACK

[Allgeuer and Behnke: Humanoids 2016]

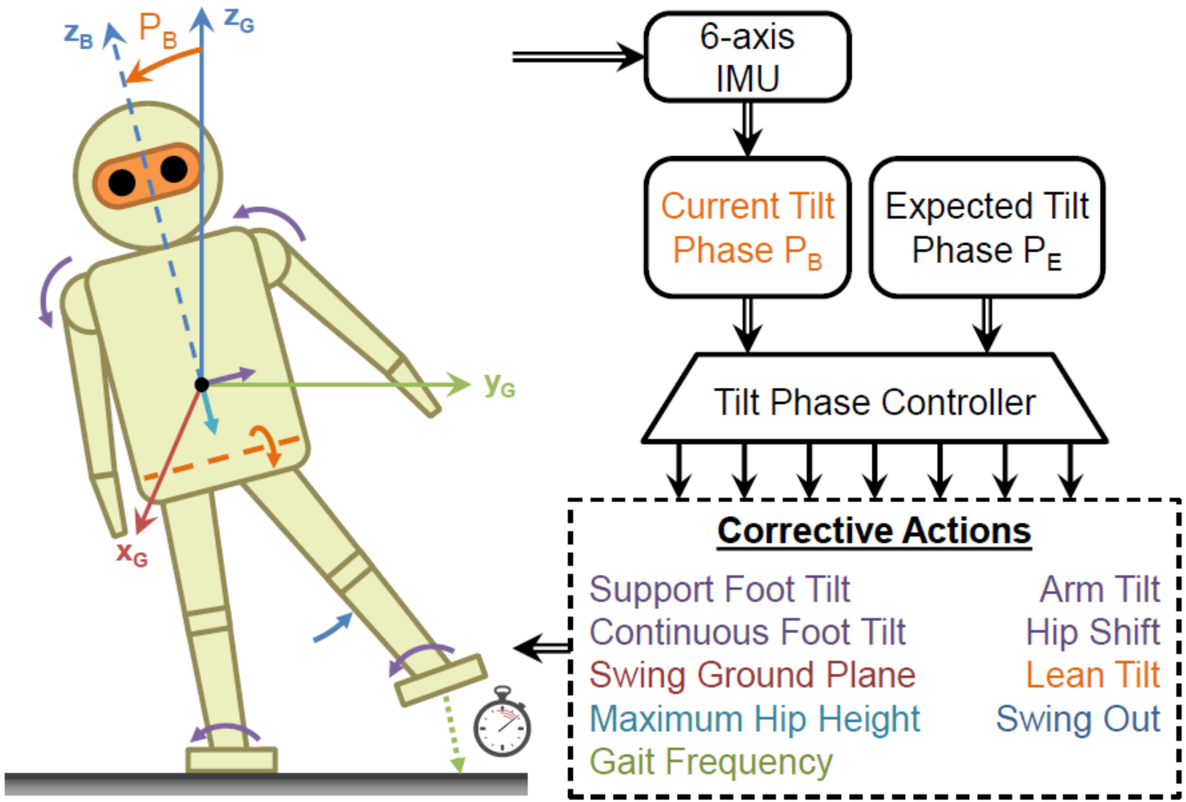
# LANDING MOTION BACKWARDS

# LANDING MOTION FORWARDS

# GETTING UP



# TILT PHASE CORRECTIVE ACTIONS




[Allgeuer and Behnke, Humanoids 2018]

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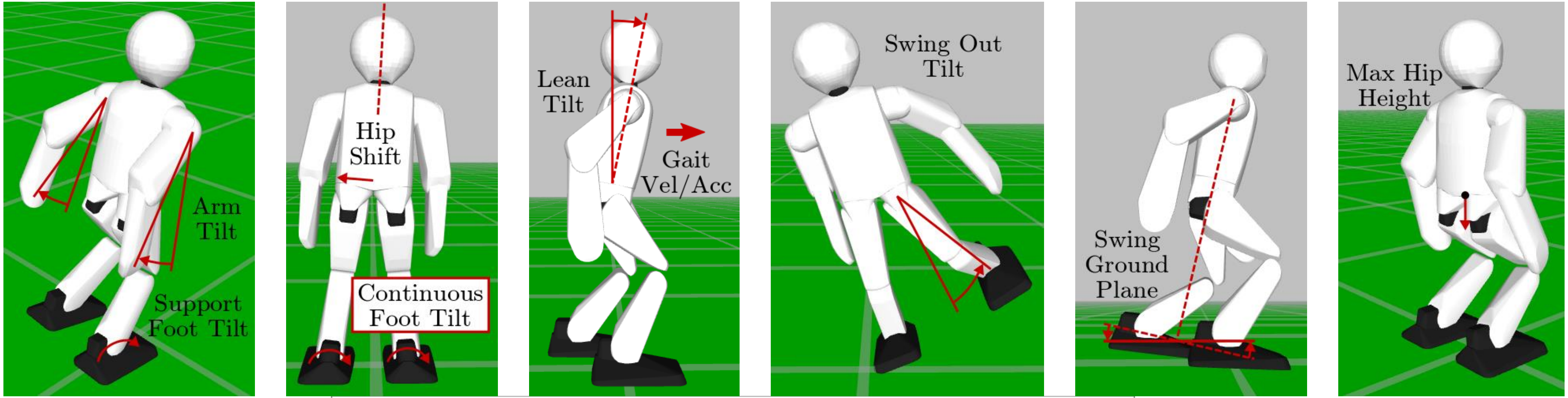
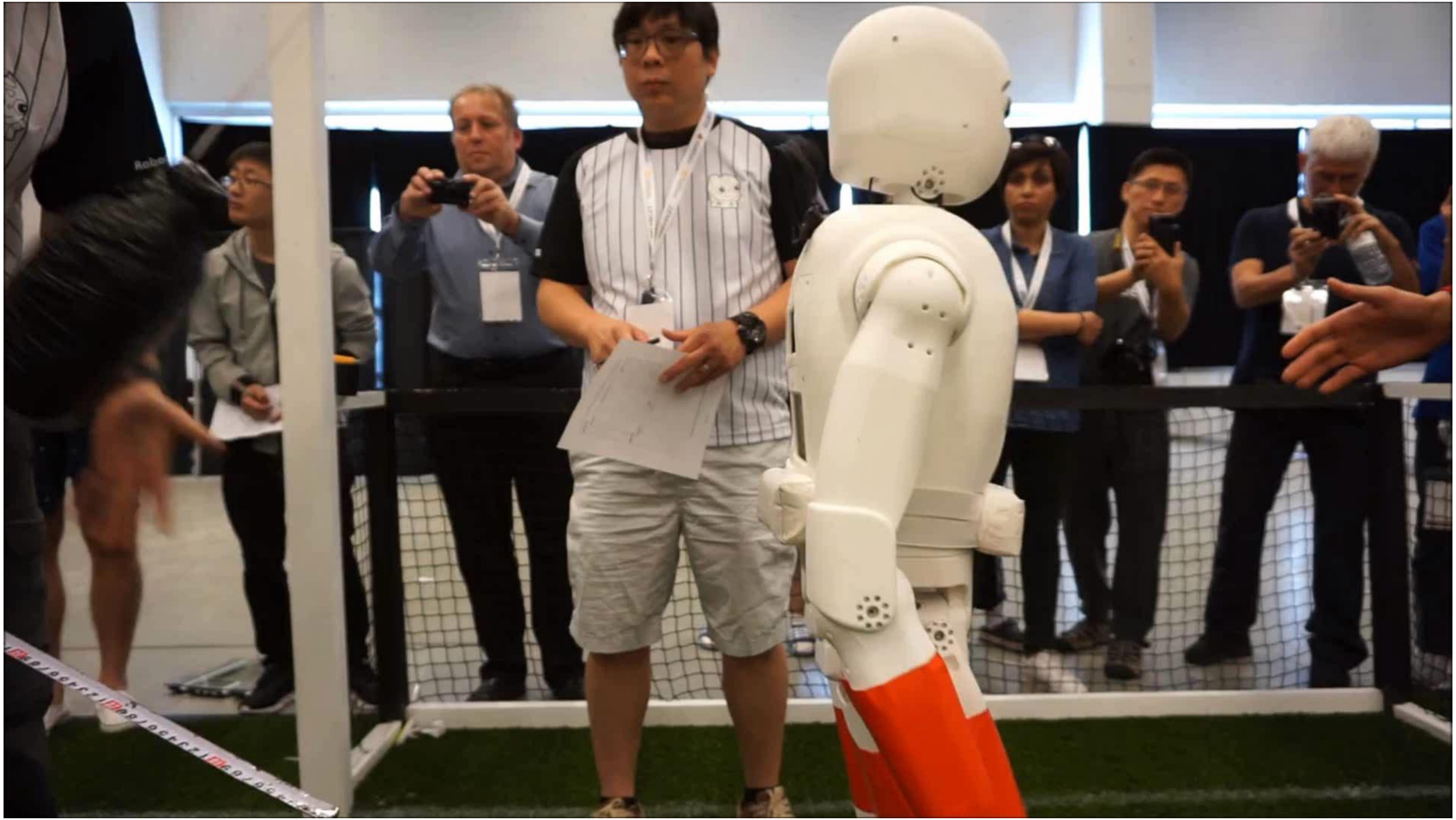



**PD Feedback: Arm and Support Foot Tilt**

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

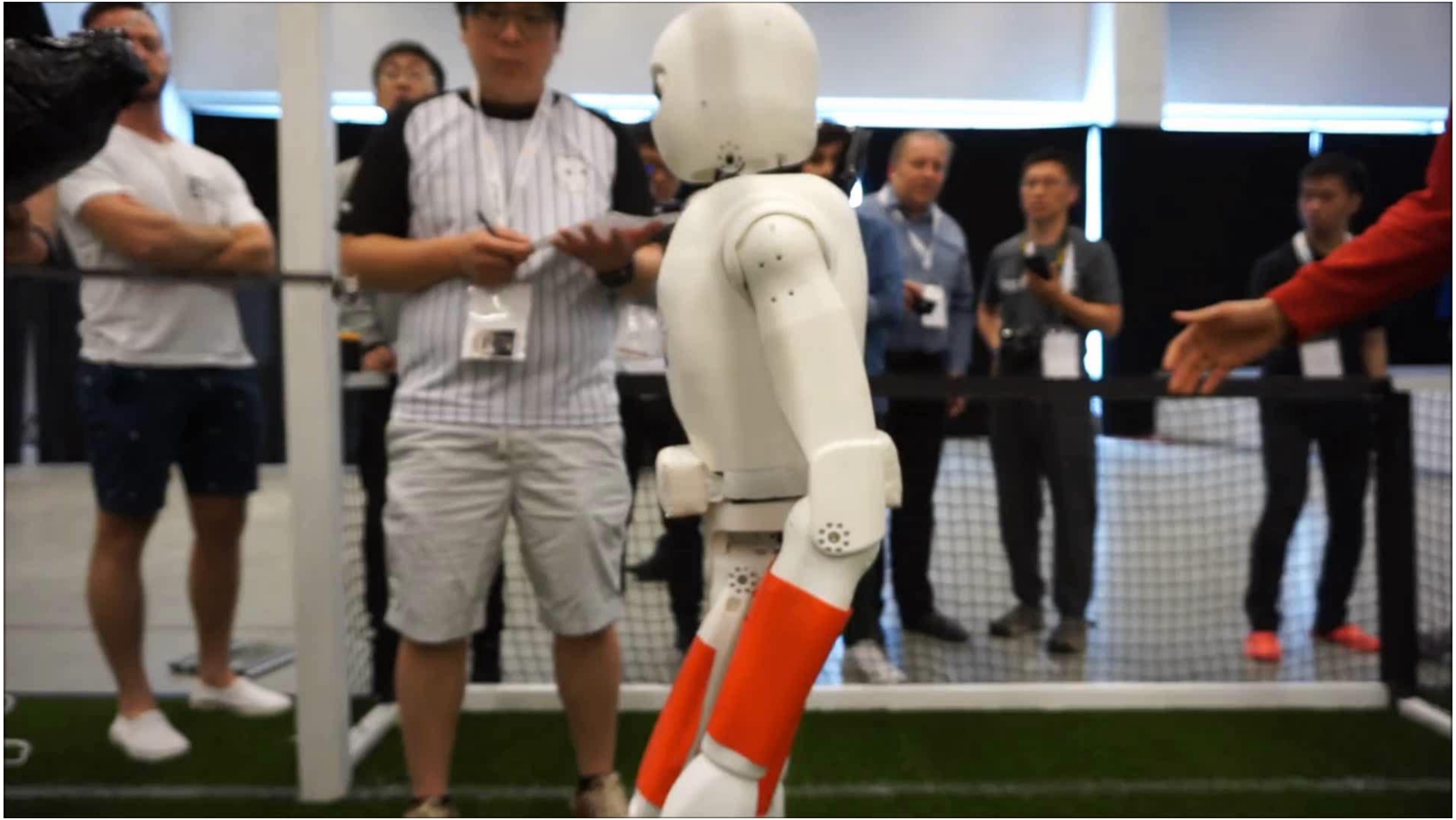
[Allgeuer and Behnke, Humanoids 2018]

# NIMBRO-OP2X PUSH RECOVERY



[Ficht et al. Humanoids 2018]

# NIMBRO-OP2X PUSH RECOVERY

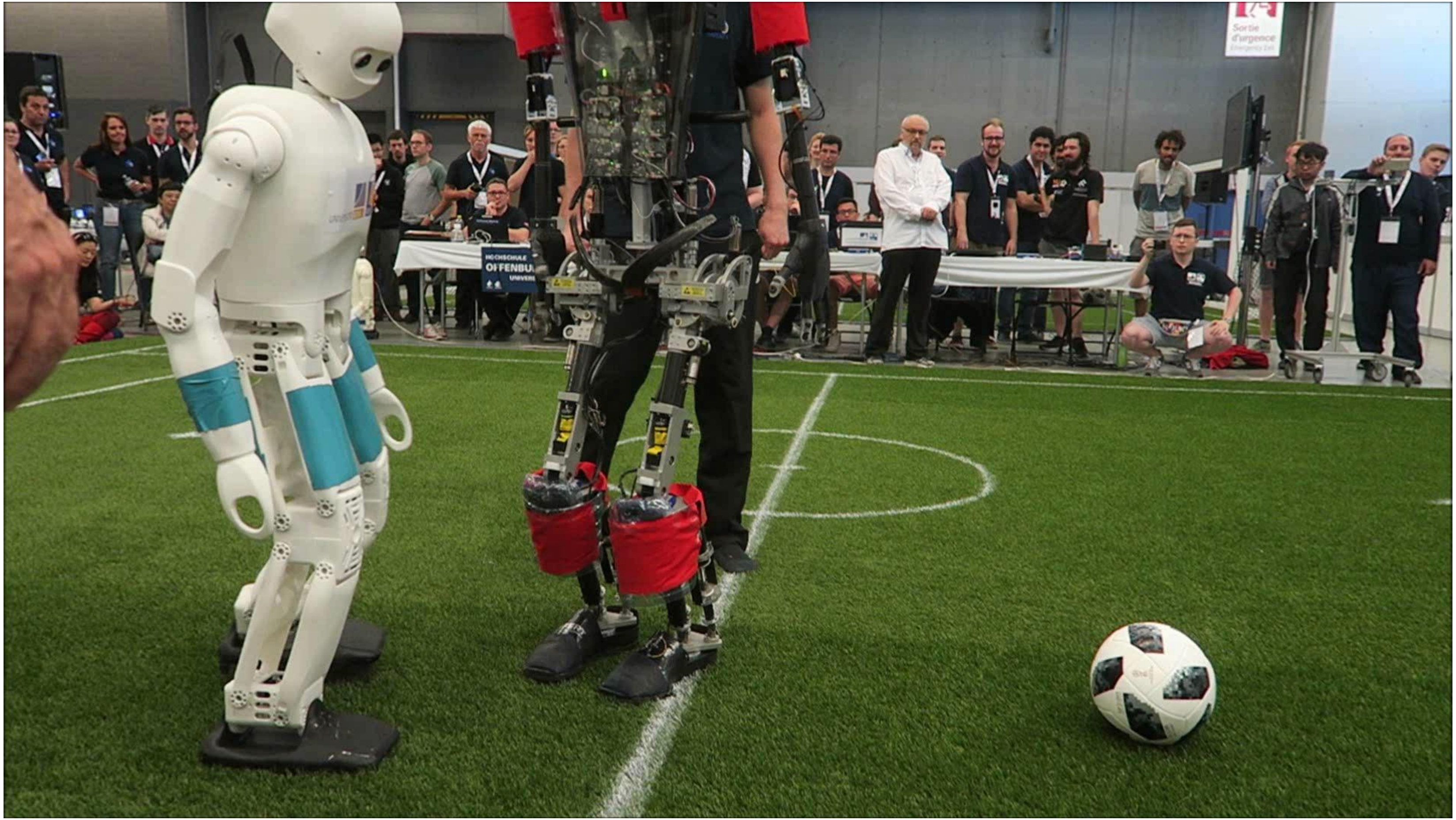


[Ficht et al. Humanoids 2018]

# ROBOCUP 2018 SEMI-FINAL

[Ficht et al. Humanoids 2018]

# ROBOCUP 2018 FINAL




[Ficht et al. Humanoids 2018]

# TEAM NIMBRO

# CONCLUSIONS

- Bipeds are inherently unstable
- Presented some techniques for disturbance rejection and landing
- Disturbances cannot always be rejected
- **Robot must survive the fall!**
- Getting up necessary to continue with task
- Advances needed in
  - Resiliant mechanics (actuators, materials)
  - Reliable state estimation (including terrain)
  - Robust control (fall avoidance, safe landing)