

# Winning Humanoid Soccer Robots of Team NimbRo: Mechatronics, Perception, Control, and Learning

**Sven Behnke**

Autonomous Intelligent Systems



# RoboCup German Open 2005



# Humanoid Soccer Final RoboCup 2005

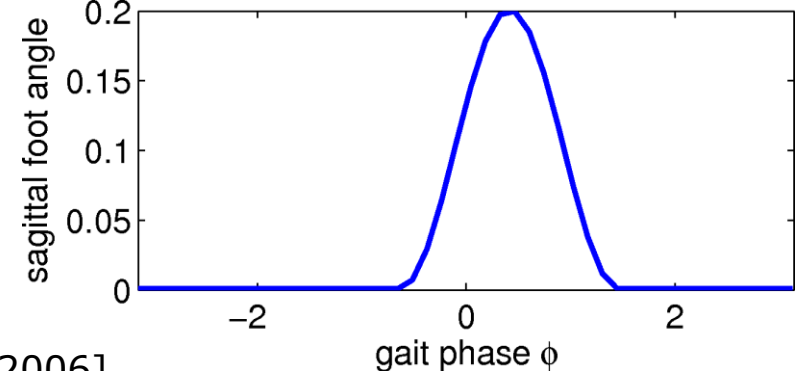
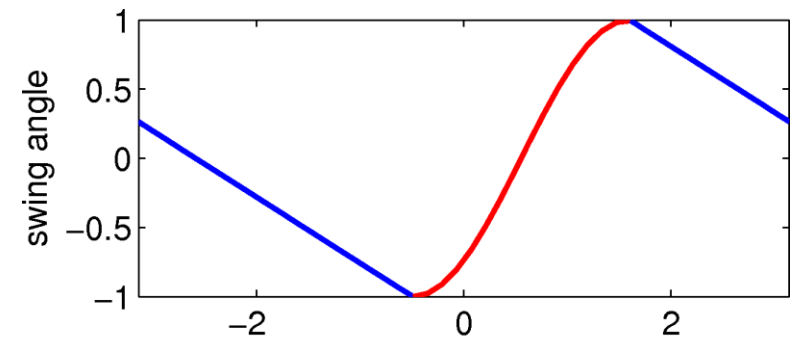
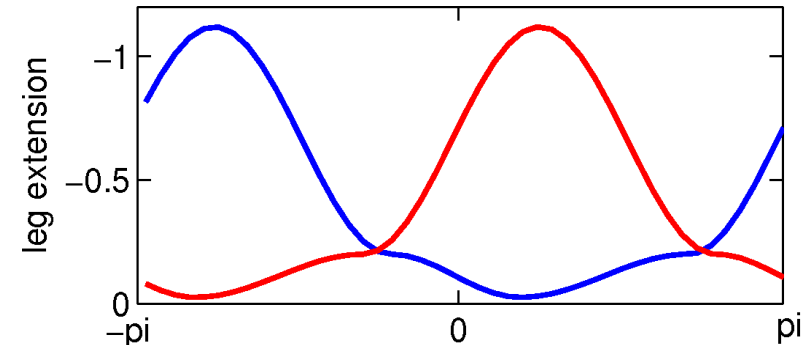
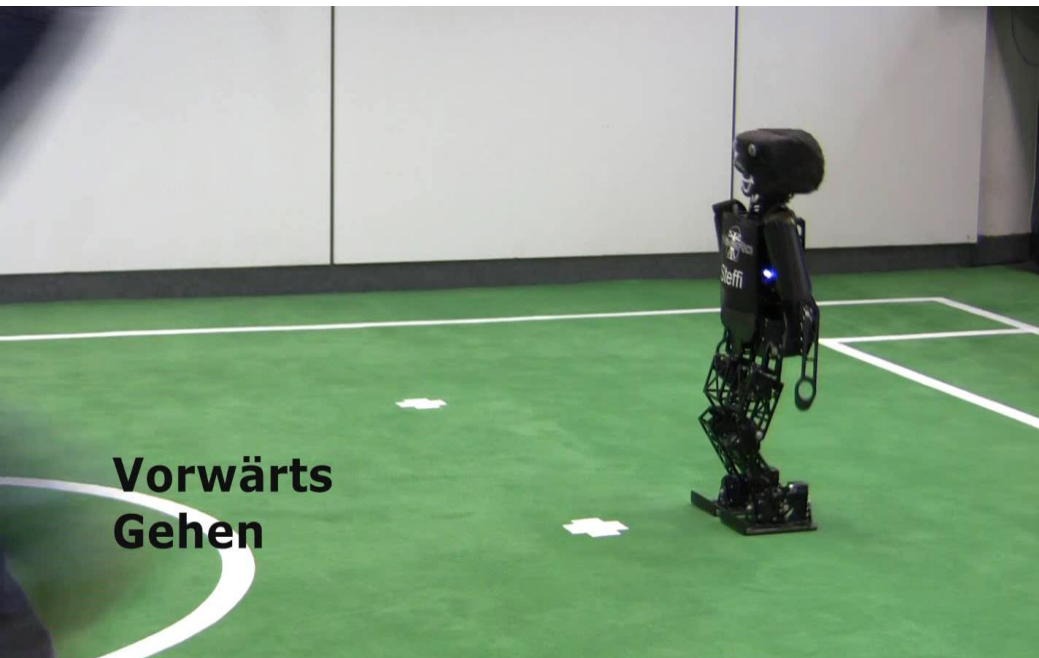


# RoboCup 2008 KidSize Final NimbRo vs. Team Osaka



# Omnidirectional Walking

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



[Behnke: ICRA 2006]

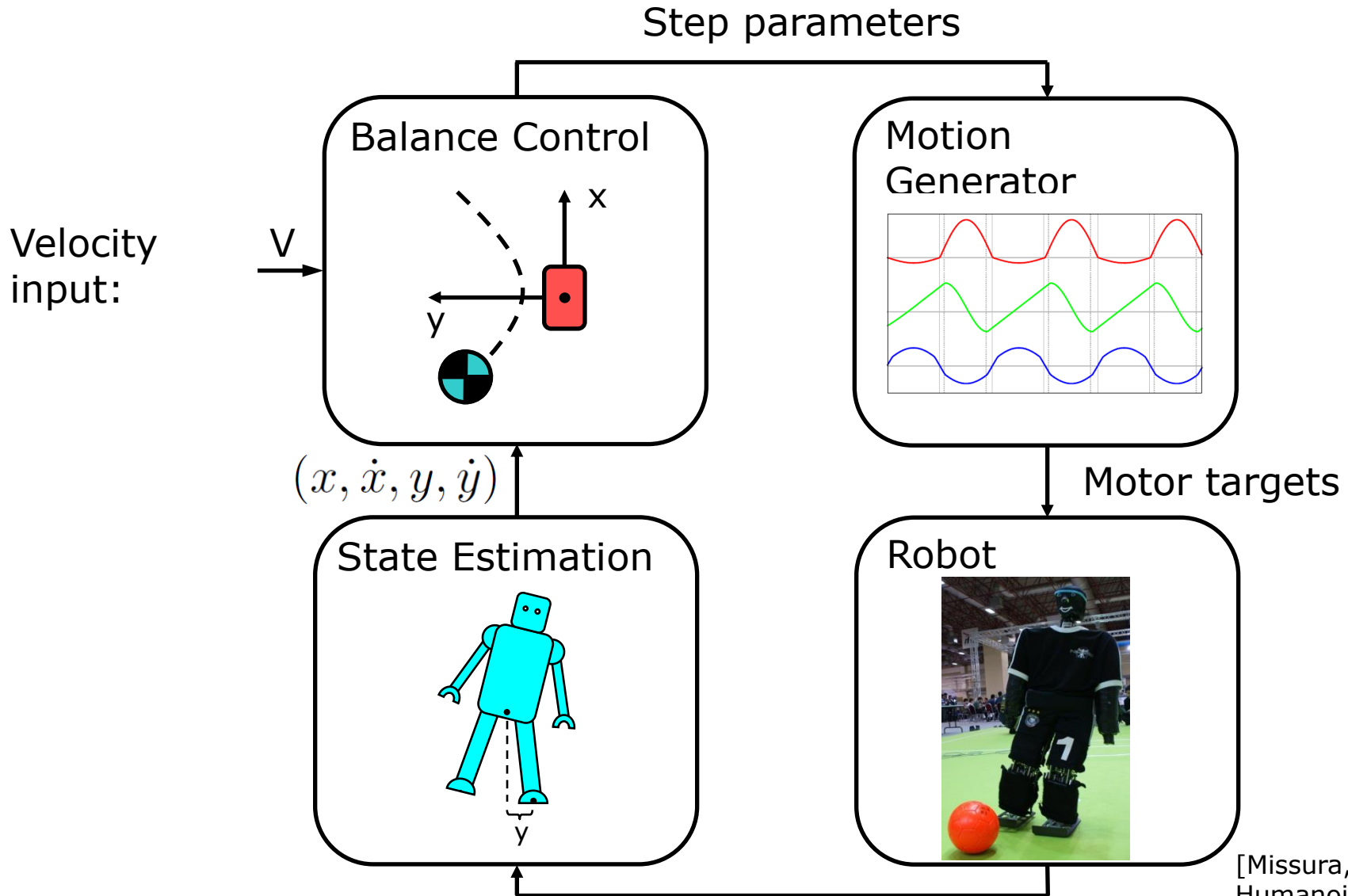
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# RoboCup 2013 Final



*Final Game:  
NimbRo vs CIT Brains (Japan)*

# Capture Step Framework



[Missura, Behnke:  
Humanoids 2013,  
RoboCup 2014]

# Omnidirectional Capture Steps

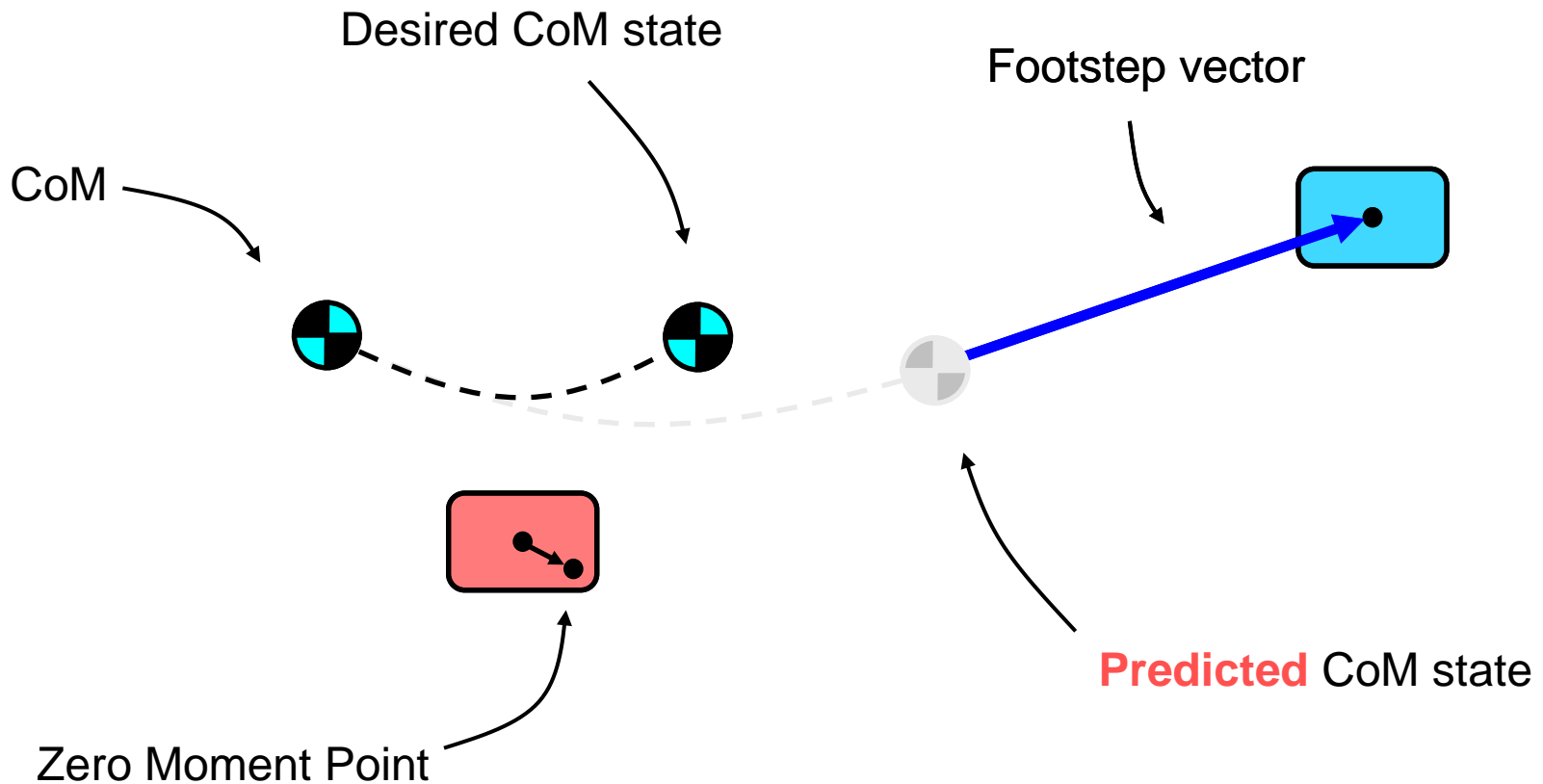


[Missura and Behnke: Humanoids 2013, RoboCup 2014]



# Balance Control

- Adapt ZMP, timing, and foot placement



[Missura and Behnke: Humanoids 2013, RoboCup 2014]

# Dynaped with Small Feet



## Dynaped with Small Feet

August 2014, Bonn



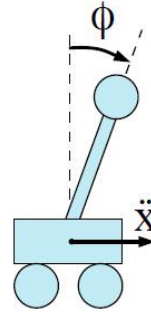
[Missura and Behnke: Humanoids 2013, RoboCup 2014]



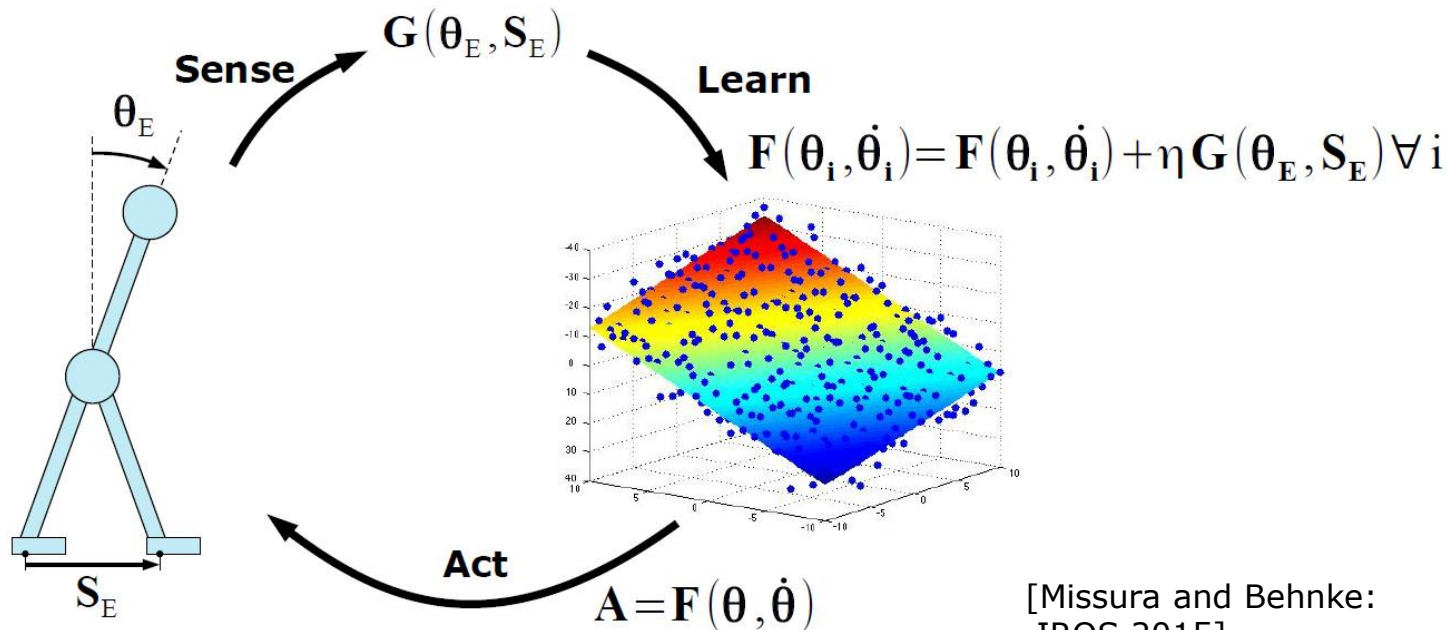
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# Online Learning of Foot Placement

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



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



[Missura and Behnke:  
IROS 2015]

# Online Learning of Foot Placement



[Missura and Behnke: IROS 2015]

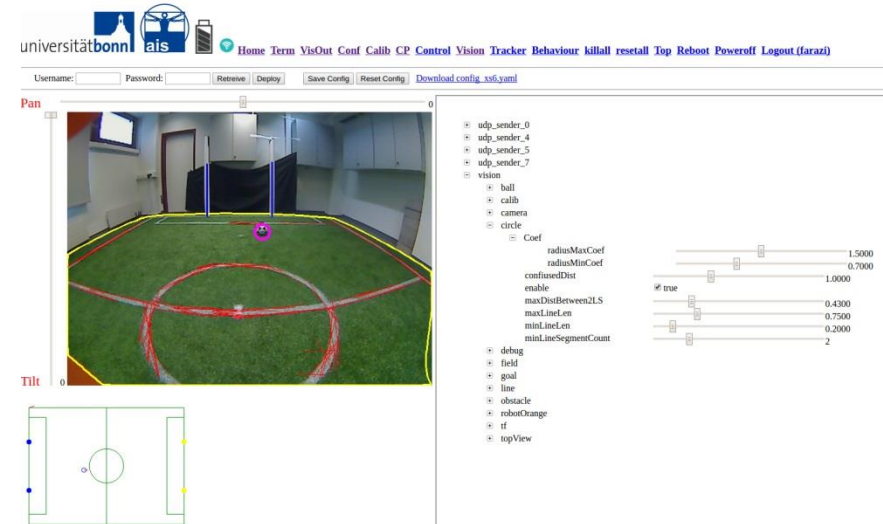
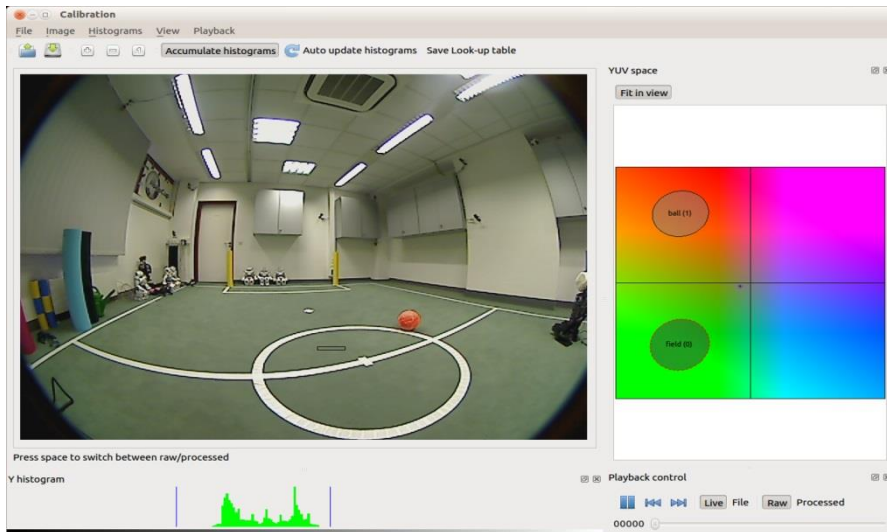
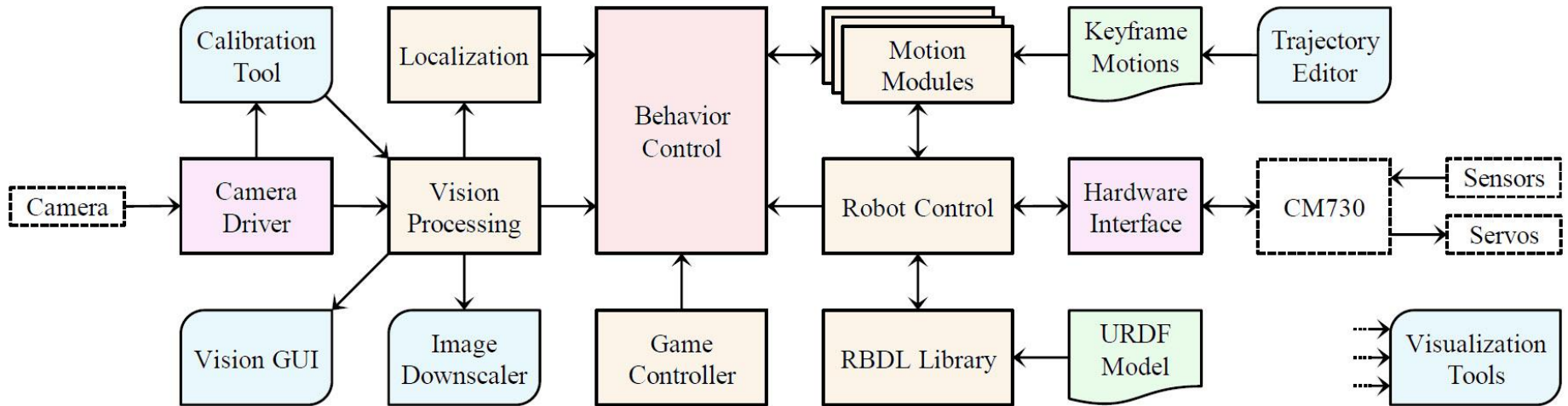
# igus Humanoid Open Platform

- 90 cm, 6.6 kg
- 3D printed structure
- 20 DoF
- Dual-core PC
- Wide-angle camera(s)
- IMU
- ROS-based software
- Hard- and software released: [nimbro.net/OP](http://nimbro.net/OP)

[Allgeuer et al. Humanoids 2015]

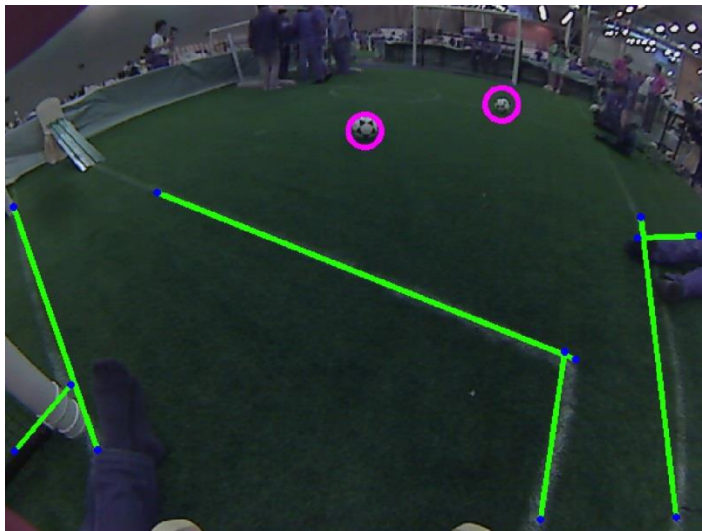


# ROS-based Software



# Perception of the Game Situation

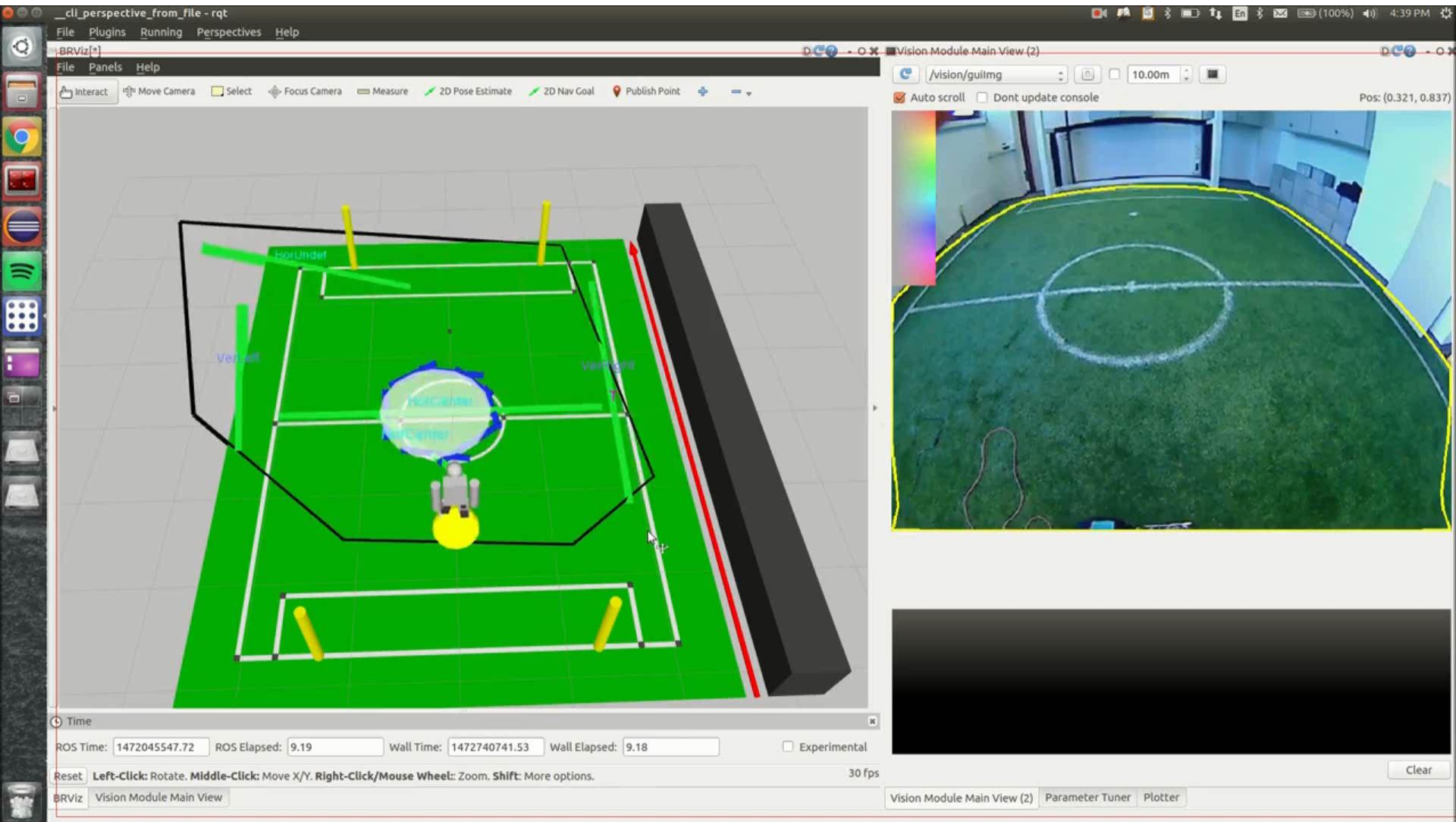
- Less relying on color
- Learned ball detection
- Goal detection



[Farazi et al. Humanoid Soccer Workshop 2015]

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# Localization



[Farazi et al. Humanoid Soccer Workshop 2015]

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# Rviz 3D Visualization

The screenshot displays the Rviz 3D visualization interface, which is used for monitoring and controlling a humanoid robot. The interface is divided into several panels:

- Parameter Tuner:** A panel on the left side of the interface, showing a tree view of parameters. The 'gait' parameter is expanded, revealing sub-parameters such as 'ankle\_effort' (0.3500), 'captureStep', 'damping', 'dynamicGait', 'GCVNormP' (2.4000), 'accelerationBackward' (0.5000), 'accelerationForward' (0.5000), 'accelerationRotational' (0.5000), 'accelerationSideward' (0.1000), 'armSwing' (0.0000), 'armSwingSlope' (0.2500), 'decelerationFactor' (2.0000), and 'firstStepDuration' (0.5000). Each parameter has a corresponding slider and a numerical value field.
- Form:** A panel on the right side of the interface, showing a 'reset' button and a 'halt' button. It displays numerical values for 'torque : 46.9848', 'angle : 0', and 'ω'. Below these, there are input fields for 'X', 'Y', and 'ω', all set to 0.00.
- Plotter:** A panel at the bottom left of the interface, showing a 'Pause' button and a 'Tree' button. It displays a graph with several colored lines representing joint states and goals. The legend includes: 'Joint states/Goals/right\_knee\_pitch' (green), 'Joint states/Positions/left\_hip\_pitch' (yellow), 'Joint states/Positions/left\_knee\_pitch' (purple), 'Joint states/Positions/right\_hip\_pitch' (blue), 'Joint states/Positions/right\_hip\_roll' (red), and 'Joint states/Positions/right\_knee\_pitch' (brown). The graph shows oscillating signals for the knee pitch and hip pitch parameters.
- 3D View:** A large 3D view on the right side of the interface, showing a humanoid robot model standing on a green field. The robot is black with a white head. Red and green arrows are visible, indicating joint positions and velocities. The field has a grid pattern and a circular path.

[Allgeuer et al. Humanoid Soccer Workshop 2013]

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# Trajectory Editor

kick\_right.yaml

Joint Space Abstract Space Inverse Space

Effort	Velocity	Position	Joint	Position	Velocity	Effort
0,20	0,00	-0,18	Head Pitch			
0,20	0,00	0,00	Head Yaw			
0,20	0,00	2,17	Shoulder Pitch	0,69	0,00	0,20
0,20	0,00	1,89	Shoulder Roll	-0,65	0,00	0,20
0,20	0,00	1,66	Elbow Pitch	-1,25	0,00	0,20
0,50	0,00	0,00	Hip Yaw	0,00	0,00	0,50
0,80	0,00	-0,20	Hip Roll	-0,48	0,00	0,80
0,80	0,00	-0,30	Hip Pitch	-0,37	0,00	0,80
0,80	0,00	0,61	Knee Pitch	0,81	0,00	0,80
0,80	0,00	-0,40	Ankle Pitch	-0,48	0,00	0,80
0,80	0,00	0,26	Ankle Roll	0,44	0,00	0,80

Header Frame

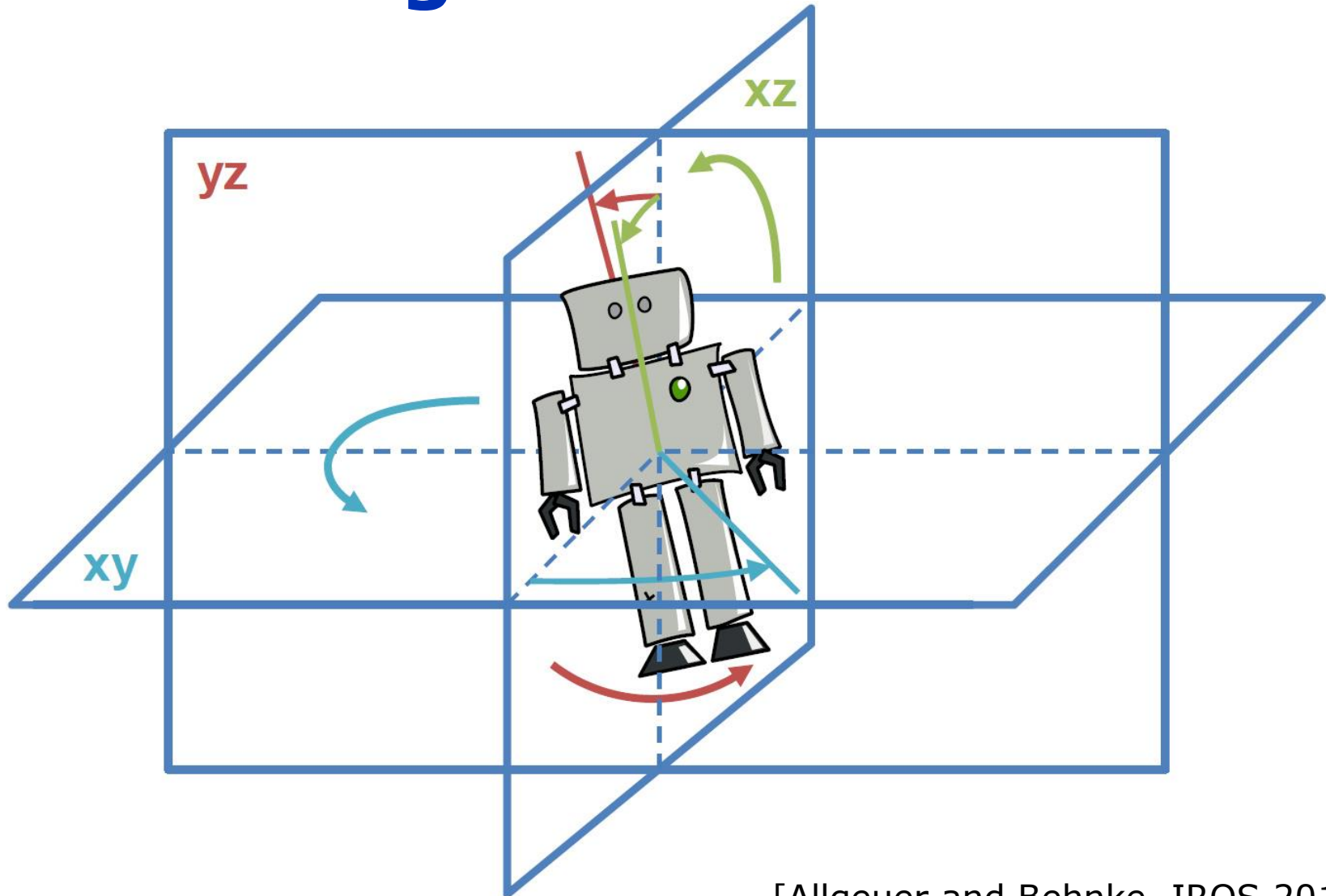
Name: kick\_right  
PreState: standing  
PlayState: kicking  
PostState: standing

On file: /home/mark/Nimbro-OP/src/nimbro/launch/motions/P1/kick\_right.yaml

[Allgeuer et al. Humanoid Soccer Workshop 2013]

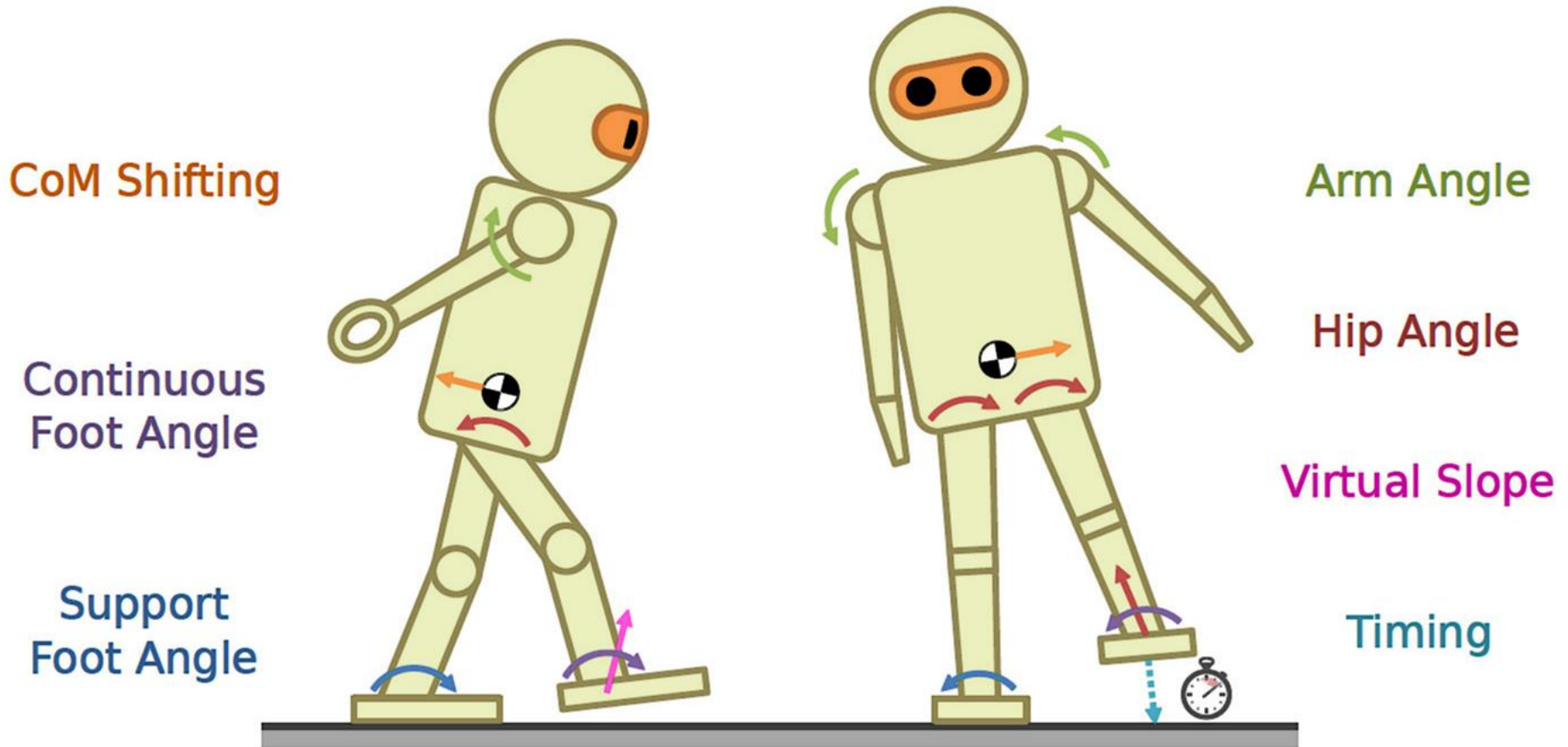
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# Fused Angles



[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



[Allgeuer et al. Humanoids 2015]



# Visual Perception



[Farazi & Behnke: Humanoid Soccer Workshop 2015]

# RoboCup 2016 TeenSize Final



Farazi et al. RoboCup 2016, Robot World Cup XX, 2017.

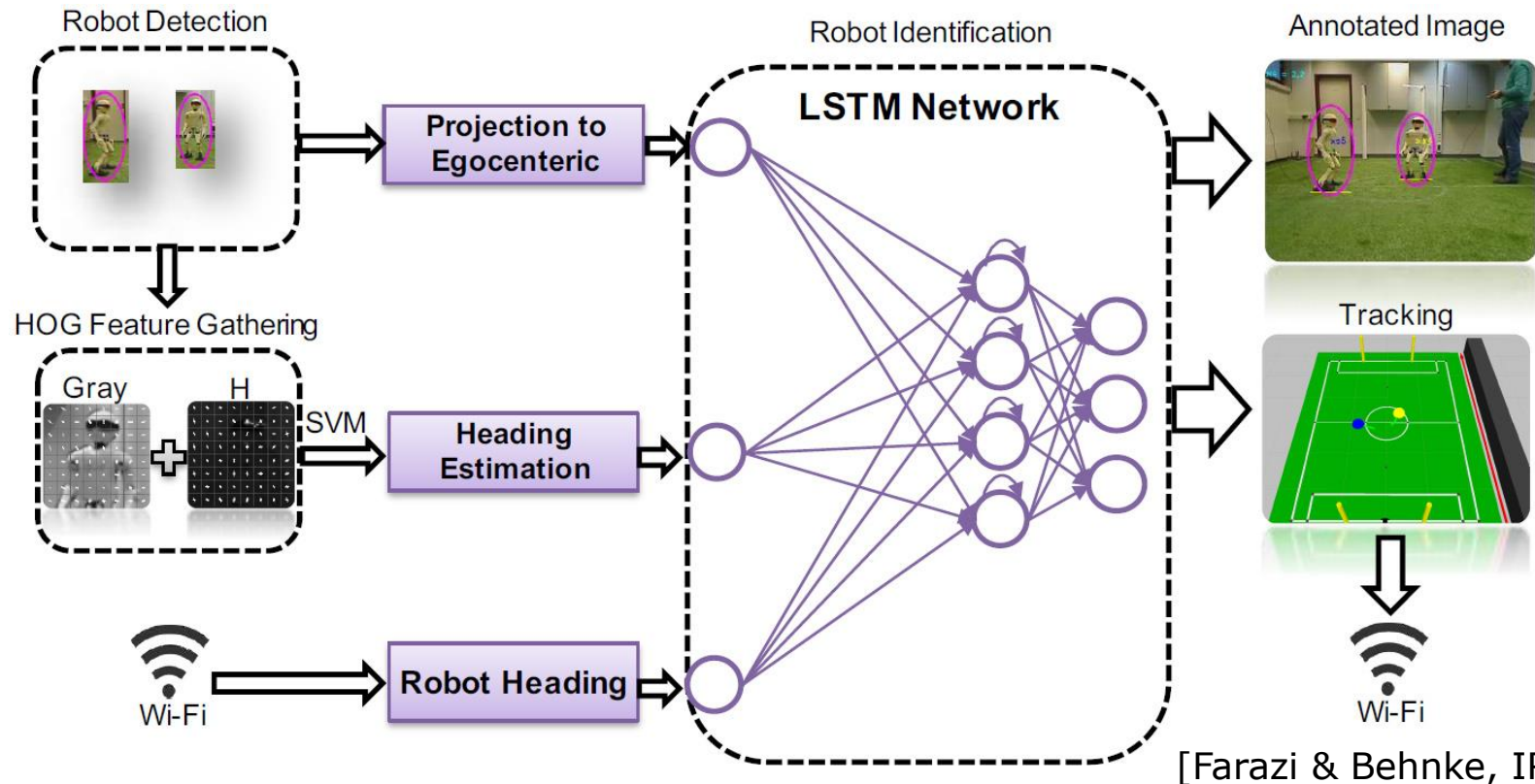
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# Team NimbRo TeenSize 2016



# Robot Detection, Tracking & Identification

- Based on visual detections and compass
- Learning data association

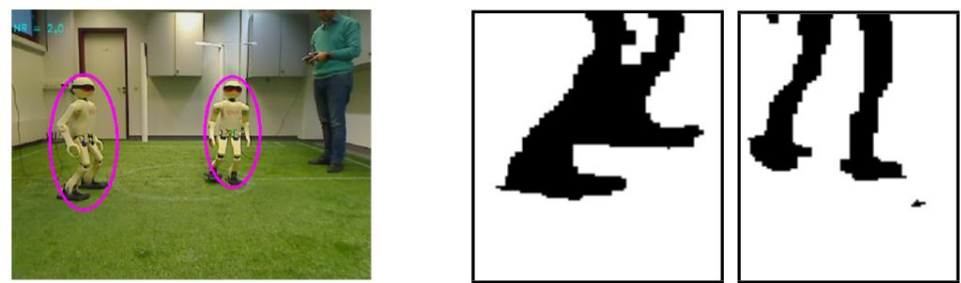


# Robot Detection & Pose Estimation

- Based on HoG features

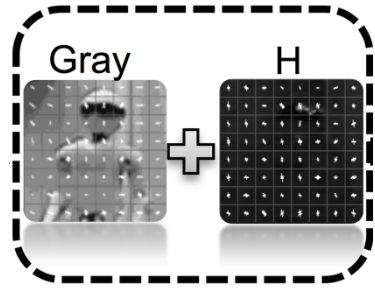


- Scan line feet estimation



- Heading estimation

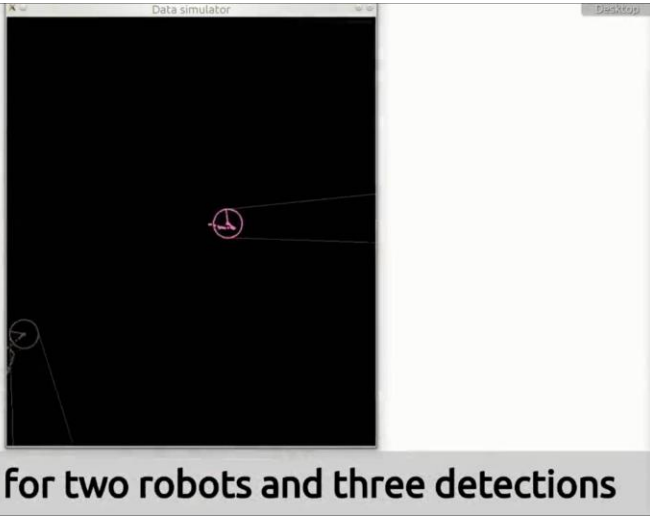
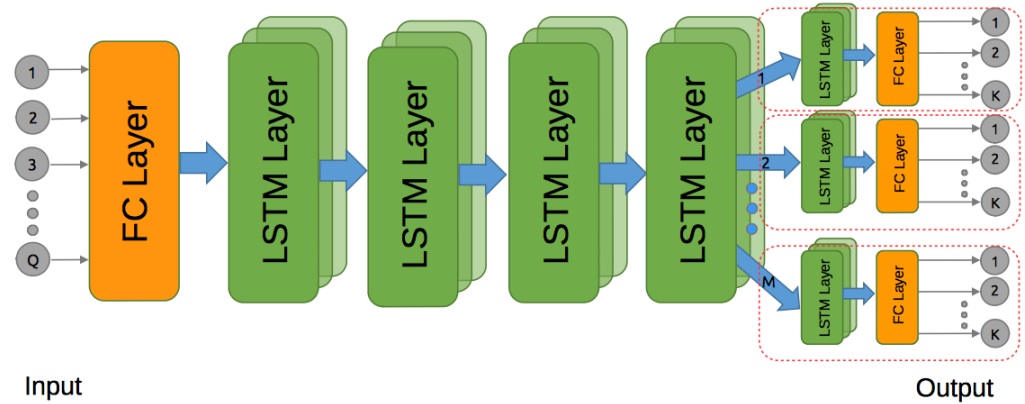
- Dense HoG
- SVM multiclass classifier



[Farazi & Behnke, IROS 2017]

# Learning Data Association

- Recurrent neural network
- Training with simulated data



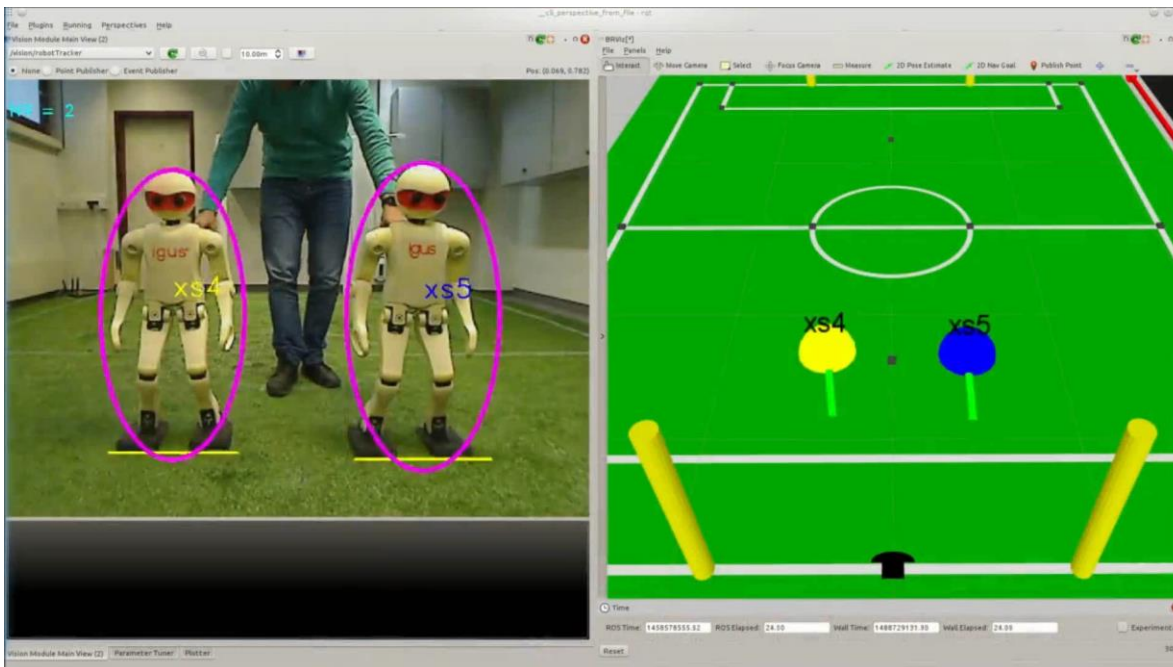
Setup	$M=3, N=2$	$M=5, N=3$	$M=10, N=7$
Human	94.3%	86.3%	<b>67.3%</b>
Kalman-HA	75.6%	72.2%	53.1%
<b>ours</b>	<b>96.2%</b>	<b>87.1%</b>	66.5%

- Fine-tuning on real data

[Farazi & Behnke, IROS 2017]

# Real-Robot Experiment

- Three Igus humanoid robots, observer in goal area
- Randomly chosen sequences, 3140 frames in total
- Partial, short term and long term occlusions, Single forward pass 4ms ( $\approx 250\text{Hz}$ )



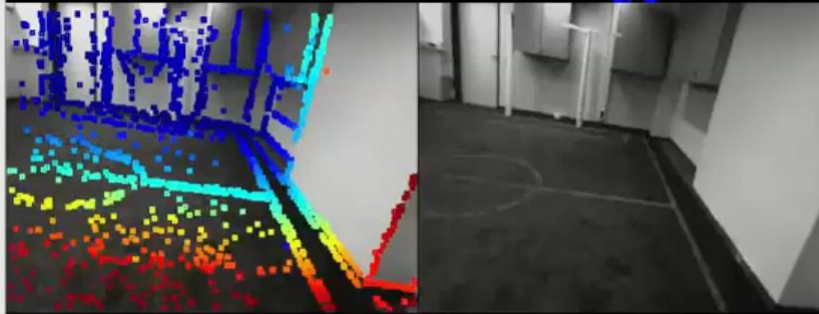
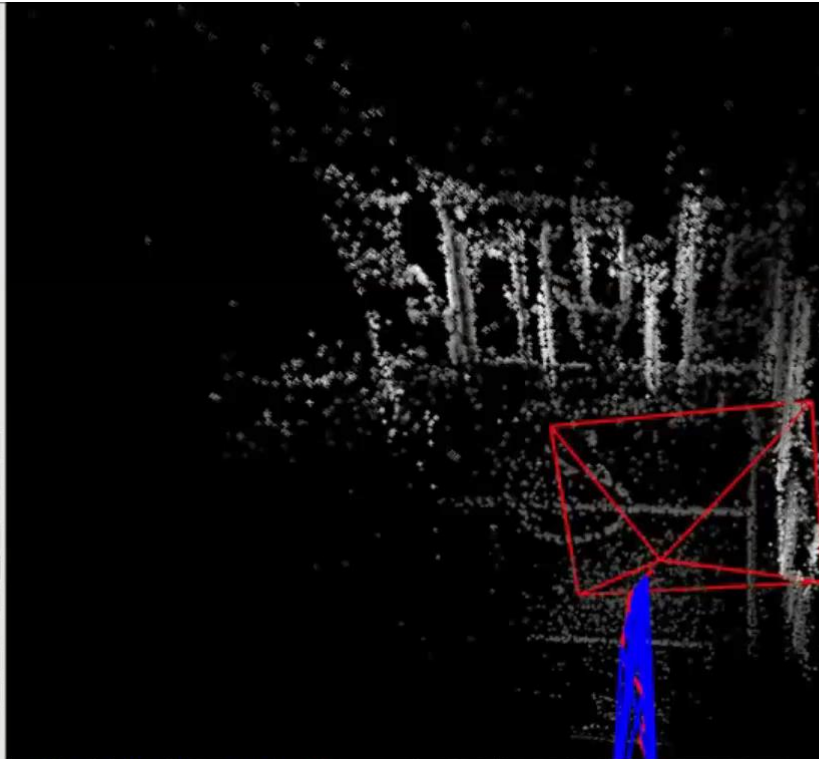
Baseline	Kalman-HA	Kalman-HA2	JPDA	Ours
Average error	0.67 m	0.30 m	0.29 m	<b>0.22 m</b>

Frames	200	400	800	Total
Kalman-HA	73.2%	75.5%	72.1%	73.8%
Kalman-HA2	87.2%	84.0%	86.3%	85.5%
JPDA	87.1%	84.6%	85.6%	86.3%
<b>Deep LSTM (ours)</b>	<b>89.8%</b>	<b>90.3%</b>	<b>92.4%</b>	<b>91.1%</b>

[Farazi & Behnke, IROS 2017]

# Direct Sparse Visual Odometry

PC\_mode 1  
 KFCam  
 CurrCam  
 Trajectory  
 FullTrajectory  
 ActiveConst  
 AllConst  
 show3D  
 showDepth  
 showVideo  
 showResidual  
 showFramesWindow  
 showFullTracking  
 showCoarseTracking  
sparsity 1  
relVarTH 0.001  
absVarTH 0.001  
minRelativeBS 0.1  
Reset  
activePoints 1200  
pointCandidates 1000  
maxFrames 7  
kfFrequency 1.3  
minGradAdd 7  
Track fps 48.31  
KF fps 4.889





# AlexNet Robot Recognition



# NimbRo-OP2

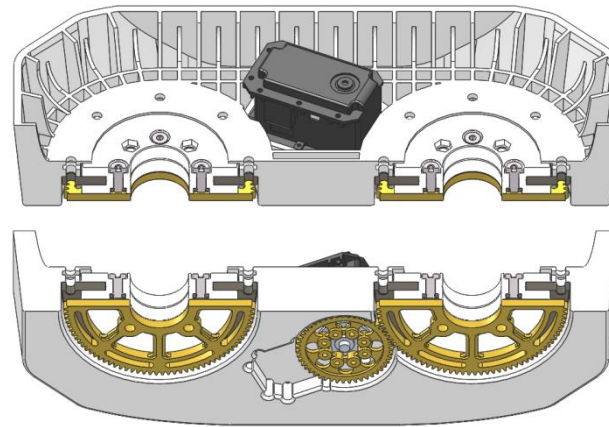
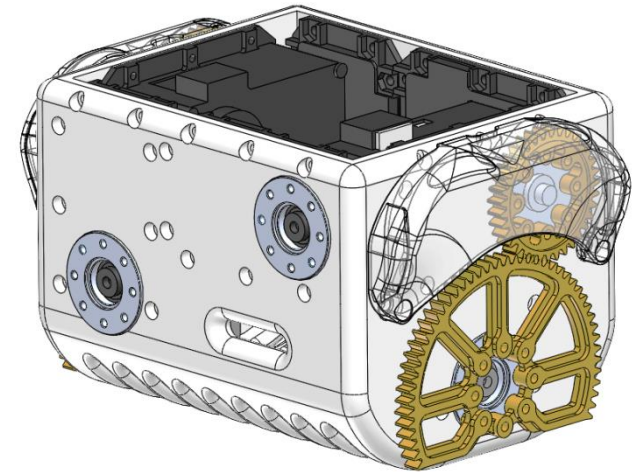


- Height: 135 cm
- Weight: 18.0 kg
- SLS printed exoskeleton
- 18 Degrees of Freedom
  - 5 DoF per leg
    - Parallel kinematics
    - 13 MX-106 actuators
    - Additional spur gears
  - 3 DoF per arm
  - 2 DoF in the neck
- SFF PC i7-7567U 3.5 GHz
- Wide-angle camera
- CM-740 with IMU
- LiPo 14.8 V, 6.6 Ah battery

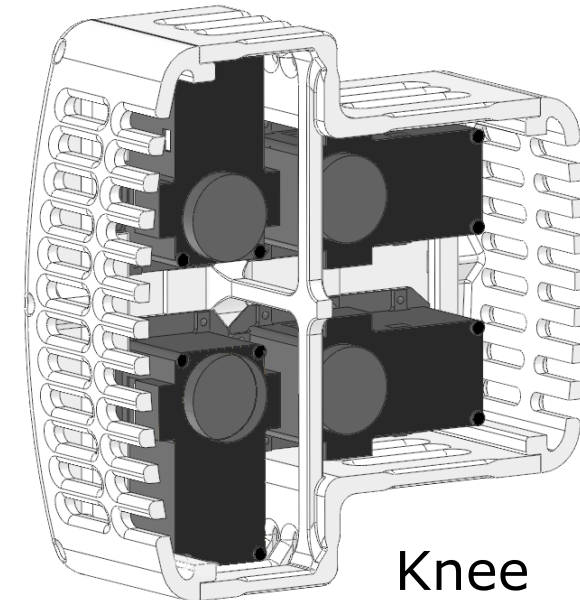
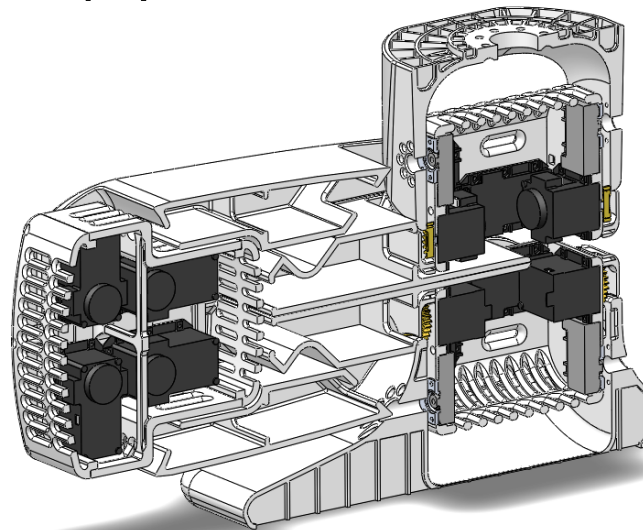
[Ficht et al. Humanoids 2017]

# Construction Details

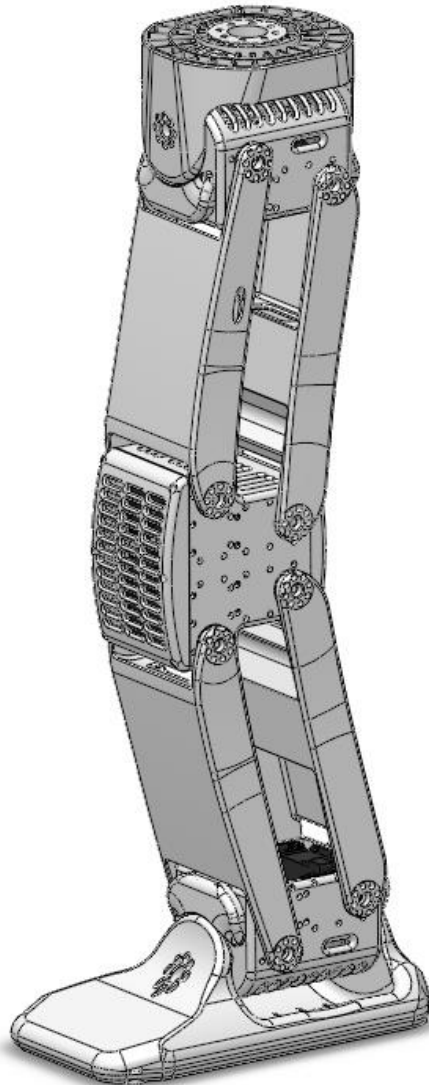
Hip pitch & roll



Hip yaw



Knee



[Ficht et al. Humanoids 2017]

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# RoboCup 2017 AdultSize Final



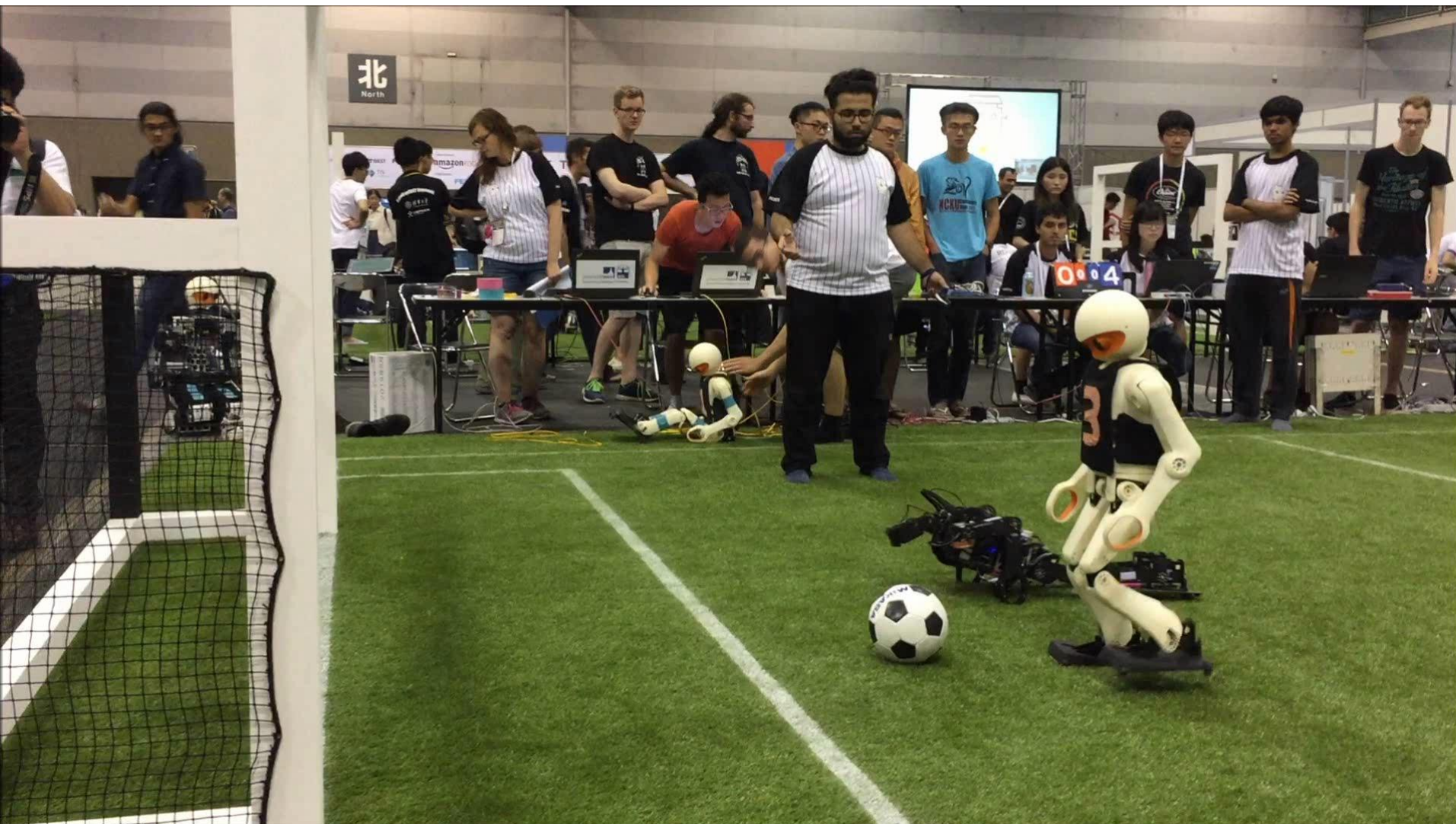
[Ficht et al. Humanoids 2017]

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# RoboCup 2017 AdultSize Technical Challenge



# RoboCup 2017 TeenSize



# NimbRo RoboCup 2017 Trophies



# Conclusions

- Capable robots for Humanoid TeenSize and AdultSize class
- Hard- and Software released
- Many challenges
  - Articulated perception
  - Dynamic full-body motions



[ais.uni-bonn.de/nimbro/OP](http://ais.uni-bonn.de/nimbro/OP)

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# Questions?