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**"
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
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

Final Game:
NimbRo vs CIT Brains (Japan)
Capture Step Framework

LIP model

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

Velocity input: \( V \)

Balance Control

State Estimation

Motion Generator

Robot

Step parameters

Sensor data

Motor targets

Velocity input: \( V \)

\((x, \dot{x}, y, \dot{y})\)

[Missura, Behnke: Humanoids 2013, RoboCup 2014]
Balance Control

- Adapt ZMP, timing, and foot placement

Desired CoM state

CoM

Zero Moment Point

Footstep vector

Predicted CoM state

[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

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

[Missura and Behnke: IROS 2015]
Online Learning of Foot Placement

[Missura and Behnke: IROS 2015]
Visual Perception of Soccer Scene

Object detection

[Farazi & Behnke, RoboCup 2016]
Fused Angles

[Allgeuer and Behnke, IROS 2016]
Feedback Mechanisms

- CoM Shifting
- Continuous Foot Angle
- Support Foot Angle
- Arm Angle
- Hip Angle
- Virtual Slope
- Timing

[Allgeuer and Behnke: Humanoids 2016]
PD Feedback

[Allgeuer and Behnke: Humanoids 2016]
Landing Motion Backwards
Landing Motion Forwards
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

\[
\begin{align*}
v_x &= 0.6 \text{ m/s} \\
v_y &= 0.0 \text{ m/s} \\
\omega_z &= 0.0 \text{ rad/s}
\end{align*}
\]

[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

[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]
Graphical Debugging and Diagnostics

[38]

[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