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Evaluation of Feature Finders for Robot Calibration

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Technical Aspects of Multimodal Systems

29. January 2019

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Motivation

- internal sensors (i. e. motor encoders) need calibration to measure the position of the robot precisely
  - repeatability across multiple robots
  - more similar behavior of across multiple kinematic chains (e.g. legs of a humanoid)
  - accurate positioning critical for balance
- external sensors (e.g. cameras) need calibration to measure the environment precisely
  - camera position and pose are not accurately known
  - angle between camera and environment is used for distance calculation

Motivation cont.

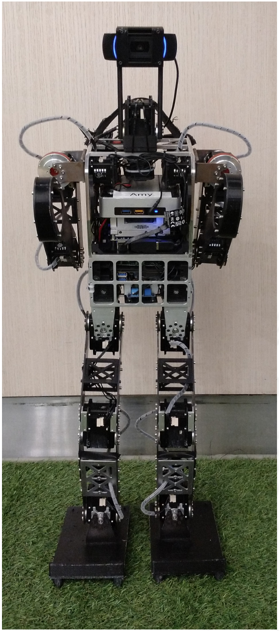
- some finders and markers are easier to set up than others
- AprilTags [1] require only a printer, some 3D printed parts and a camera
- PhaseSpace [2] requires extensive setup but provides more accuracy
- goal of my Thesis: Evaluate if AprilTags are viable for robot calibration

Related Work

- robot calibration is a standard problem in industrial robots
  - single kinematic chain
- ROS package `robot_calibration` [3]
  - not used for humanoids to my knowledge
- whole body calibration for NAO robot using checkerboards [4]
- calibration from team RHoban [5]
  - extrinsic and intrinsic camera calibration only
- calibration from team MRL-HSL [6]
  - extrinsic and intrinsic camera calibration only

Robot Platform

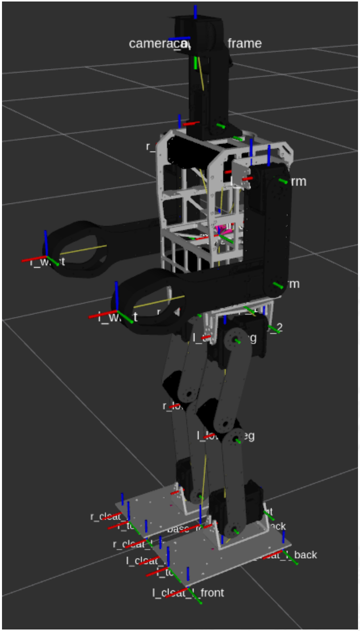
- humanoid robot with 20 DoF
  - 6 per leg, 3 per arm, 2 in the Head
  - Dynamixel MX106 and MX64 servo motors
- computation units:
  - Intel NUC
  - Nvidia Jetson TX2
  - Odroid XU4
- RHoban DXL board for Motor communication (STM32F103 + RS485 transceivers + GY85 IMU)
- Logitec C910 camera
- ROS based software
- height: 825 mm, weight: 7.1 kg



The Wolfgang robot platform

Robot Description

- robot description specifying kinematic structure of the robot was required
- Unified Robot Description Format (URDF) was chosen for compatibility with ROS
  - xml format
  - specifies links and joints (with their pose)
- only CAD models of the CNC milled parts were provided by the manufacturer
- robot assembly in Autodesk Inventor
- required measurements for robot description were taken in software
- 3D model for visualization

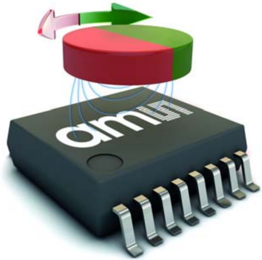


3D model of the Wolfgang robot platform

Actuators

Dynamixel MX106 from Robotis [7]

Actuators



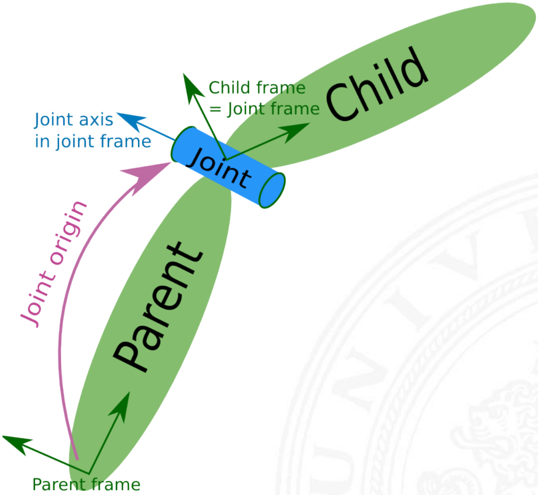
Magnetic rotary encoder using the hall effect [8]

- absolute position encoder
- calibration procedure required
- closed source, questionable accuracy and repeatability
- has to be performed on individual, partially disassembled motors

Robot Calibration

- kinematics calibration estimates geometric parameters of kinematic equations
  - position and rotation of joints relative to links
- dynamics calibration (calibration of the dynamics parameters)
  - mass, center of mass, inertia

Kinematics Calibration



kinematic structure described by a set of links and a set of joints [9]

Link Specification

```
<link name="l_upper_leg">
        <inertial>
        ...
        </inertial>
        <visual>
        ...
        </visual>
        <collision>
        ...
        </collision>
</link>
```

Joint Specification

```
<joint name="LKnee" type="revolute">
    <origin xyz=" -0.004 0 -0.1692 " rpy=" 0 0 0 " />
    <parent link="l_upper_leg" />
    <child link="l_lower_leg" />
    <axis xyz="0 -1 0" />
    <calibration rising=" 0 " />
</joint>
```

Joint Specification


```
<joint name="LKnee" type="revolute">
    <origin xyz=" -0.004 0 -0.1692 " rpy=" 0 0 0 " />
    <parent link="l_upper_leg" />
    <child link="l_lower_leg" />
    <axis xyz="0 -1 0" />
    <calibration rising=" 0 " />
</joint>

<joint name="head_to_camera" type="fixed">
    <origin xyz=" 0.02 0 0.1115 " rpy=" 0 0 0 " />
    <parent link="head" />
    <child link="camera" />
</joint>
```

Kinematic Parameters

- joint offsets

$$q = \hat{q} + off_q$$

q: real joint angle

$\hat{q}$: joint angle measured by encoder

off_q: offset of the measured value to the real joint angle

Kinematic Parameters

- frame transformation (i. e. translation and rotation) offsets

$$t = \hat{t} + off_t$$

t: real transformation between two frames (e.g. neck and camera)
$\hat{t}$: estimated transform between frames
off_q: offset from estimation to reality

Offset Measurement

- attach measurable marker to end effector at known pose
  - AprilTag [1], checkerboard, PhaseSpace LED [2]
- measure pose of marker with sensor
  - camera, depth camera

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Error function:

$$e(\theta, m_i, \hat{q}_i) = m_i - predict(\theta, \hat{q}_i)$$

m_i: measurement of marker
$predict(\theta, \hat{q}_i)$: predicted pose of marker given the joint angles, calibration parameters and kinematic structure of the robot (forward kinematics)

Parameter Estimation

$$e(\theta, m_i, \hat{q}_i) = m_i - predict(\theta, \hat{q}_i)$$

Given a set of poses, find the set of parameters θ that minimizes the error.

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measurement errors cause this to be a non-linear problem

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measurement errors cause this to be a non-linear problem

non-linear least squares optimization using a fitting solver (e.g. ceres)

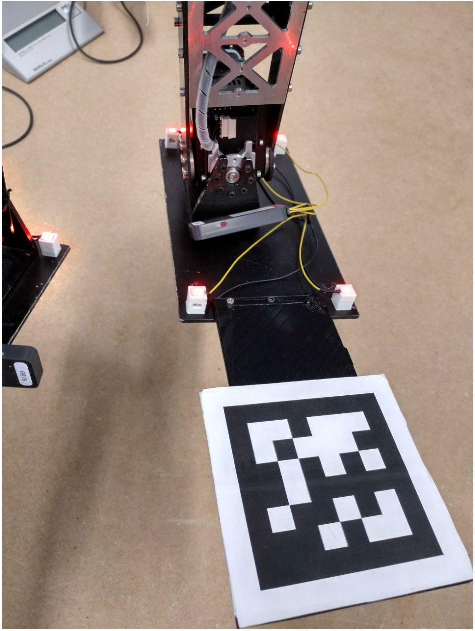
Dynamics Calibration

- dynamic parameters of the system are largely unknown
- CAD model omits multiple components of the robot
  - cables
  - computers / electronics
- highly interesting for accurate simulation
- closing the reality gap

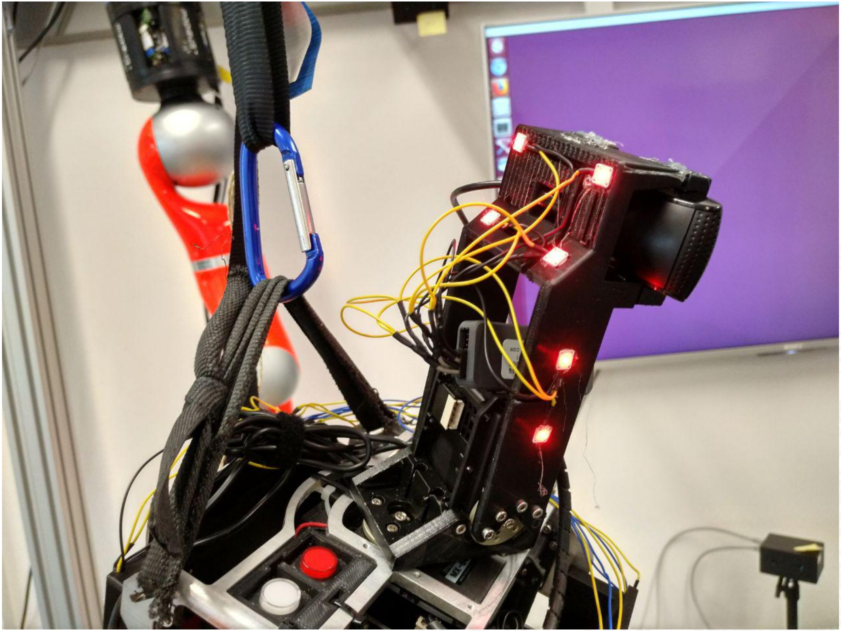
ROSdyn: Project funded by ROS Industrial [10]

Experiment Setup

- 3D printed parts for mounting PhaseSpace LEDs [2] and AprilTags [1]
- use PhaseSpace and Apriltags for calibration and compare results
- cross validation of results to identify measurement error



Robot with AprilTags and PhaseSpace LEDs



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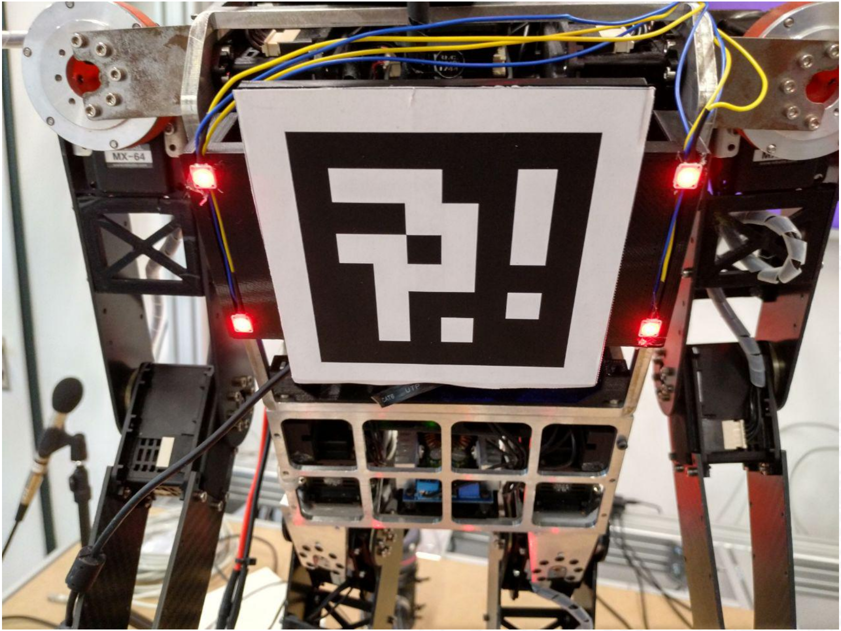

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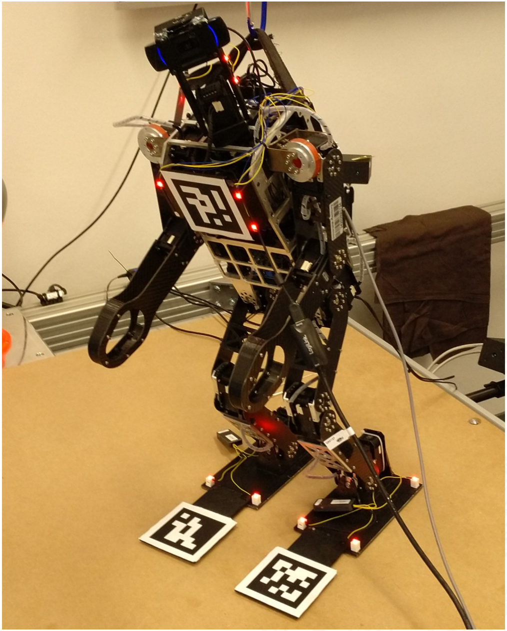
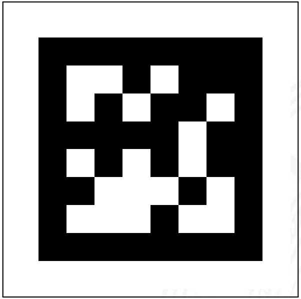


Robot with AprilTags and PhaseSpace LEDs

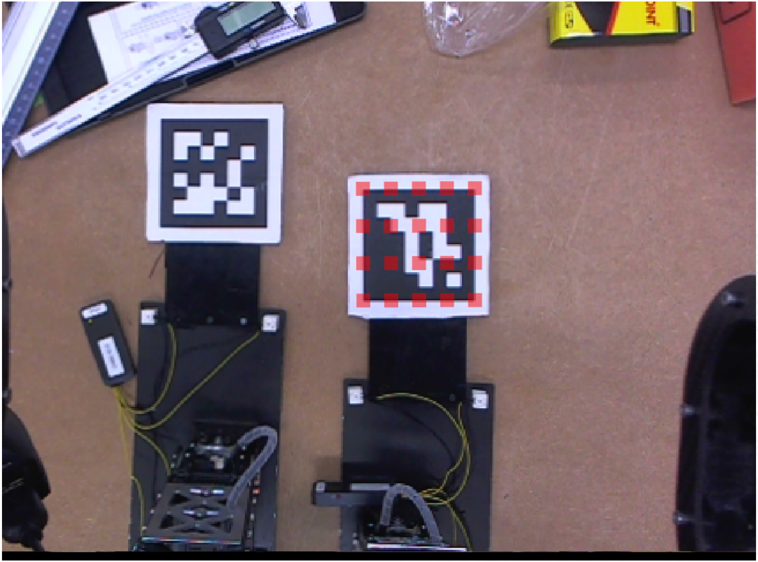
AprilTags

- visual markers
- size must be specified
- robust detection and pose estimation algorithm [11]



Example of an AprilTag [1]

Calibration using AprilTags



observation points captured by the AprilTags feature finder [12]

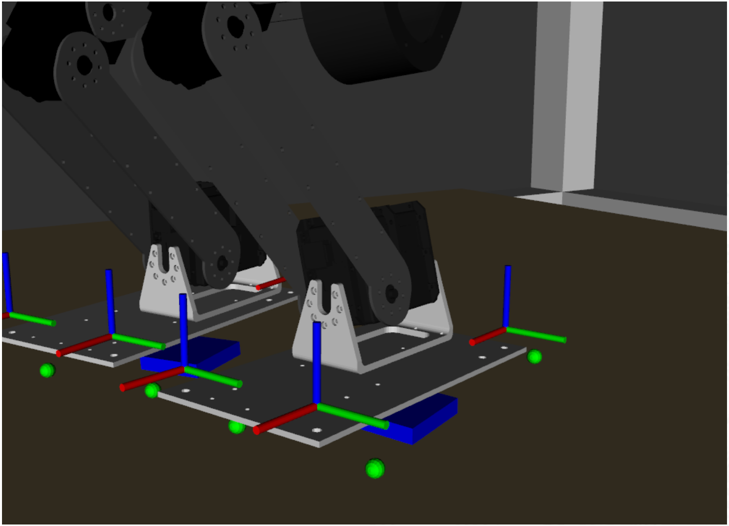
PhaseSpace

- motion capture / tracking system using uniquely identifiable LEDs by blinking frequency
- pose reconstruction using multiple LEDs
- relatively high accuracy (evaluation needed)

Calibration using PhaseSpace

- work in progress
- each LED observed by the tracking system is a measurement
- prediction is trivial using the ROS ecosystem
- `base_link` is reconstructed using markers on torso
  - accuracy improvement in pitch direction is required
  - LEDs are too close together in z-direction

Calibration using PhaseSpace

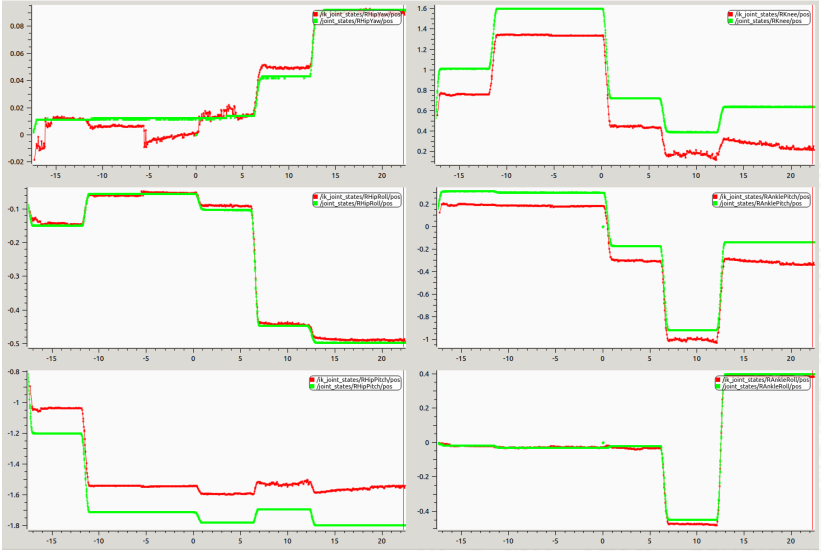


observation points captured by the PhaseSpace
Predicted points are at the origin of each coordinate system

Joint Error Measurement

- pose of end effector (i.e. foot) is measured using PhaseSpace
- pose of `base_link` is known from torso markers
- joint angles can be calculated using inverse kinematics
- only a single solution is possible given the joint constraints

Joint Error Measurement



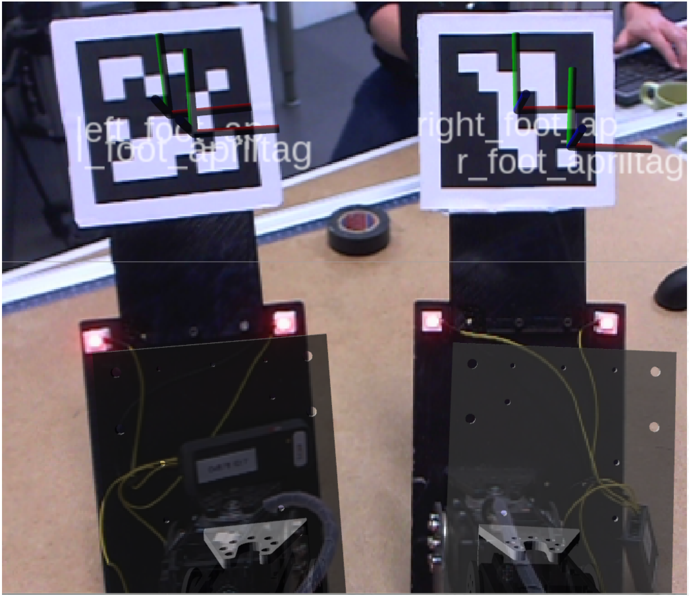
green: joint angles read by hall encoder, red: positions calculated by IK

Joint Error Measurement

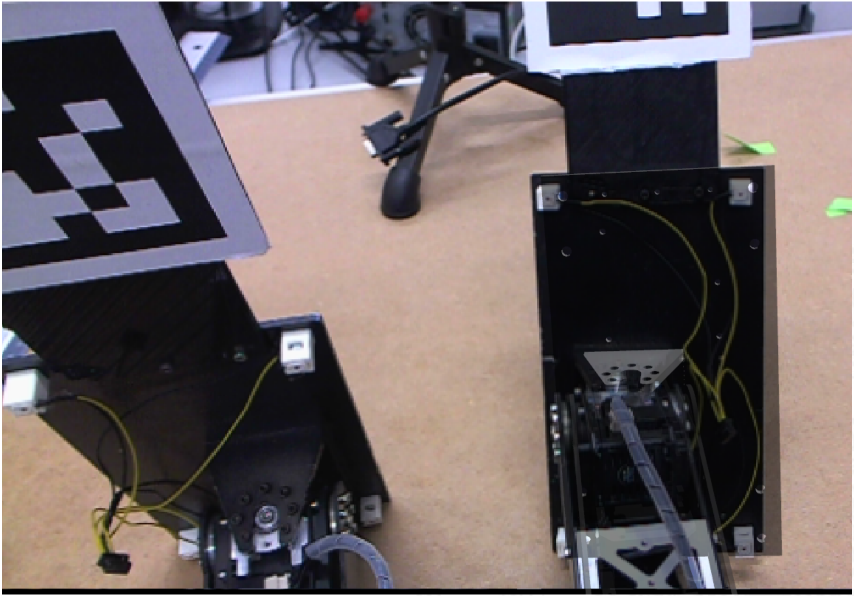
- during testing unexplained high joint errors occurred
- physical and digital measurements confirmed, that the robot was assembled wrongly

Calibration Results using AprilTags

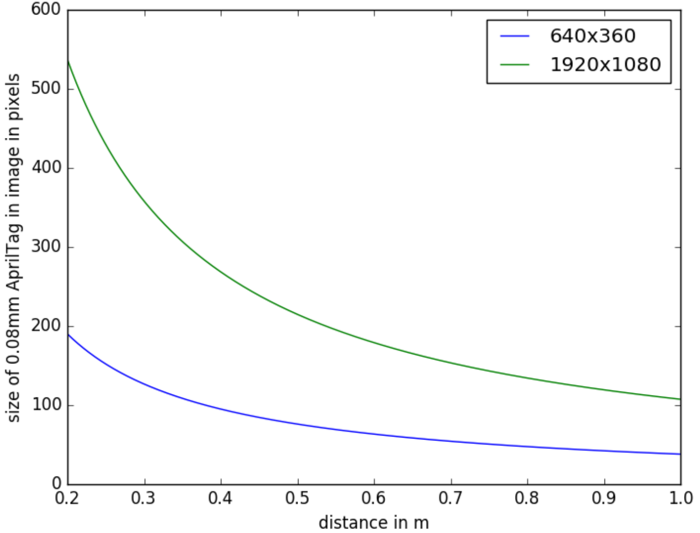
- for now: manually chosen poses
- results practically unusable since error of wrong assembly outweighs joint angles
- too low camera resolution
- camera calibration for higher resolution difficult because of motion blur



Reprojection error before calibration



Reprojection error after calibration (right foot only)



Importance of image resolution for accurate measurement

Future Work

- add LEDs to bottom of torso for better accuracy in pitch direction
- add LEDs to knee to measure intermediate joint error
- use AprilTag bundles for improved accuracy
- calibrate using phase space
- algorithm for finding a good set of poses
- calibrate arms / use arms to calibrate head
- higher resolution camera image
- finally fix URDF

Thank you for your attention.
Feel free to ask questions.

References

[1] E. Olson, “AprilTag: A robust and flexible visual fiducial system,” in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA)*. IEEE, May 2011, pp. 3400–3407.

[2] PhaseSpace motion capture – infinite possibilities. [Online]. Available: http://phasespace.com/

[3] M. Ferguson, “Generic calibration for robots. contribute to mikeferguson/robot_calibration development by creating an account on GitHub,” original-date: 2014-11-09T09:50:01Z. [Online]. Available: https://github.com/mikeferguson/robot_calibration

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[5] J. Allali, R. Fabre, L. Gondry, L. Hofer, O. Ly, S. N'Guyen, G. Passault, A. Pirrone, and Q. Rouxel, *Rhoban Football Club: RoboCup Humanoid Kid-Size 2017 Champion Team Paper*, 01 2018, pp. 423–434.

[6] M. Teimouri, A. Fatehi, H. Mahmoudi, P. S. Ha, M. H. Delavaran, F. Movafegh, G. Rahmani, and E. Fathi, "MRL team description paper for humanoid KidSize league of RoboCup 2018."

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[7] MX-106t / MX-106r. [Online]. Available: http://support.robotis.com/en/product/actuator/dynamixel/mx_series/mx-106.htm

[8] AS5040 - 10-bit rotary position sensor with absolute and incremental outputs - ams | ams. [Online]. Available: https://ams.com/as5040#tab/documents

[9] urdf/XML/joint - ROS wiki. [Online]. Available: http://wiki.ros.org/urdf/XML/joint

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[11] J. Wang and E. Olson, "AprilTag 2: Efficient and robust fiducial detection," in *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*. IEEE, pp. 4193–4198.

[12] Y. Jonetzko, "Generic calibration for robots. contribute to jntzko/robot_calibration development by creating an account on GitHub." [Online]. Available: https://github.com/Jntzko/robot_calibration