Humanoid Robotics

Whole-Body Self-Calibration

Maren Bennewitz
Motivation

- Navigation and manipulation require an accurate model of the robot, e.g., for forward/inverse kinematics, sensor pose
- Kinematic structure typically known
- But often error-prone or not exactly known:
  - Joint offsets
  - Camera extrinsics and intrinsics
- Idea: Automatic optimization of the parameters using self-observations
Example

before calibration

actual arm of the robot

projection of the arm based on current model estimate

after calibration
Data Acquisition
Nao’s Kinematic Structure
Parameters to Estimate (1)

- True position of a joint: \( q = \hat{q} + q^{\text{off}} \)

- Estimate joint offsets:
  \[
  q^{\text{off}} = \begin{pmatrix}
  q_1^{\text{off}} \\
  q_2^{\text{off}} \\
  \vdots \\
  q_n^{\text{off}}
  \end{pmatrix}
  \]
  
- Camera extrinsics (relative to the reference frame neck joint): \( R, C \)

- Camera intrinsics: \( f_x, f_y, x_H, y_H, \kappa \)
Parameters to Estimate (2)

- One marker location for each of the four end-effectors, relative to the end-effector frame

\[ \mathbf{m}_{EEFi} = [x_i, y_i, z_i]^T \]
Parameters to Estimate (3)

- 23 joints, 5 redundant joints wrt. camera pose and markers: **18 joint offsets**
- **6 extrinsic** camera parameters
- **5 intrinsic** camera parameters
- 4 end-effector marker poses: **12 values**
- Thus, **41 parameters** need to be estimated
- Stack all parameters in a vector $\theta \in \mathbb{R}^{41}$
Formulation as Least-Squares Optimization

- Consider a set of $n$ different robot configurations with encoder readings $\hat{q}_i$
- The error function is

$$e_i(\theta, z_i, \hat{q}_i) = z_i - \text{predictmarker}_{M_{EEF}}(\theta, \hat{q}_i)$$

measurement: observed marker in the image
Formulation as Least-Squares Optimization

- Consider a set of \( n \) different robot configurations with encoder readings \( \hat{q}_i \).
- The error function is

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e_i(\theta, z_i, \hat{q}_i) = z_i - \text{predictmarker}_{M_{EeF}}(\theta, \hat{q}_i)
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measurement: observed marker in the image

predicted marker location in the image given the kinematic structure
Formulation as Least-Squares Optimization

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- The error function is

$$e_i(\theta, z_i, \hat{q}_i) = z_i - \text{predictmarker}_{M_{EEF}}(\theta, \hat{q}_i)$$

- Measurement: observed marker in the image
- Current values of calibration parameters
- Predicted marker location in the image given the kinematic structure
- Joint readings
Predicted Marker Location

- The predicted location of a marker $M_{EEF}$ attached to the end-effector $EEF$ is given by

$$predictmarker_{M_{EEF}}(\theta, \hat{q}_i) = K_\theta [R_\theta | - R_\theta t_\theta] F^N_{EEF}(\theta, \hat{q}_i) \tilde{m}_{EEF}$$

homogeneous coordinates of marker position
The predicted location of a marker \( M_{EEF} \) attached to the end-effector \( EEF \) is given by

\[
predictmarker_{M_{EEF}}(\theta, \hat{q}_i) = K_\theta \left[ R_\theta \mid - R_\theta t_\theta \right] \mathcal{F}^N_{EEF}(\theta, \hat{q}_i)m_{EEF}
\]
The predicted location of a marker $M_{EEF}$ attached to the end-effector $EEF$ is given by

$$\text{predict marker}_{M_{EEF}}(\theta, \hat{q}_i) = K_\theta [R_\theta | - R_\theta t_\theta] F_{EEF}^N(\theta, \hat{q}_i) \tilde{m}_{EEF}$$

- Calibration matrix with current estimates of intrinsic camera parameters
- Current estimates of extrinsic camera parameters
- Homogenous coordinates of marker position
- **Forward kinematics**: transformation from the $EEF$ frame into the neck frame from joint encoder readings and current estimates of the offsets
Forward Kinematics (1)

- Goal: Express the coordinates given in one frame of the robot with respect to another frame.
- This transform depends on the kinematic structure and the position of the joints along the kinematic chain.
- The transform between joints is called forward kinematics.
Forward Kinematics (2)

- Consider two coordinate frames $B$ and $E$ that are connected by a kinematic chain consisting of $n$ joints $(j_1, j_2, \ldots, j_n)$ and $n + 1$ links.

- The first link $L_0$ connects the robot reference frame $B$ with the first joint $j_1$ and the last link $L_n$ connects $j_n$ with the frame $E$.

- Described by constant homogenous transformation matrices $T_0^B$ and $T_n^E$. 
Forward Kinematics (3)

- The complete transform between $E$ and $B$ corresponding to forward kinematics is given by

$$\mathcal{F}^B_E(\theta, \hat{q}) = T^B_0 \left( \prod A^{-1}_i(q_i) \right) T^n_E$$

transformation depending on joint encoder readings and current estimates of the offsets
Forward Kinematics (3)

- The complete transform between $E$ and $B$ corresponding to forward kinematics is given by

$$\mathcal{F}_E^B(\theta, \hat{q}) = T_0^B \left( \prod A^{-1}_i(q_i) \right) T^n_E$$

- transformation depending on joint encoder readings and current estimates of the offsets

- position of joint $i$ according to $\hat{q}$ and $\theta$
Forward Kinematics (3)

- The complete transform between $E$ and $B$ corresponding to forward kinematics is given by

\[ \mathcal{F}^B_E(\theta, \hat{q}) = T^B_0 \left( \prod A^{i-1}_i(q_i) \right) T^n_E \]

- Transformation depending on joint encoder readings and current estimates of the offsets
- Transformation matrix for the transform between the joints $i$ and $i - 1$ given $q_i$
- Position of joint $i$ according to $\hat{q}$ and $\theta$

[see exercise for the computation of $A^{i-1}_i(q_i)$]
The predicted location of a marker $M_{EEF}$ attached to the end-effector $EEF$ is given by

$$\text{predictmarker}_{M_{EEF}}(\theta, \hat{q}_i) = K_\theta [R_\theta | - R_\theta t_\theta] \mathcal{F}^{N}_{EEF}(\theta, \hat{q}_i) \tilde{m}_{EEF}$$

- **forward kinematics**: transformation from the $EEF$ frame into the neck frame from joint encoder readings and current estimates of the offsets.
Formulation as Least-Squares Optimization

- The goal is to minimize the residuals
  \[ e_i(\theta, z_i, \hat{q}_i) = z_i - \text{predictmarker}_{M_{EEF}}(\theta, \hat{q}_i) \]

- Apply least squares to minimize the squared error function
  - Linearize the error terms around the current estimate using Taylor expansion
  - Get a quadratic from, set its derivative to zero to obtain a linear system
  - Solve the linear system, obtain the new state
  - Iterate
Automatic Selection of Robot Configurations

- The result of the optimization depends on
  - the initial linearization point and
  - the set of configurations together with their measurements

- A higher number of configurations can lead to more accurate estimation results, but it also needs more time

- **Goal:** Good trade-off between the time needed to carry out the calibration and the accuracy of the result
Generating a Pool of Configurations (1)

Idea:

- Initially, sample a large pool of configurations
- Subsequently, select a subset of configurations that optimizes a certain criterion for the calibration process
Generating a Pool of Configurations (2)

- Configurations sampled uniformly in joint space
- Check whether expected marker locations are inside the camera field of view (proj.)
- Check for self-collisions and occlusion
Selecting a Subset of Configurations (1)

- 41-dim. parameter vector, each measurement yields two constraints
- Needed: **At least 21 configurations with corresponding measurements**
- **Question:** Which subset of configurations is the best one for the calibration result?
Selecting a Subset of Configurations (2)

- **Goal**: Reduce the uncertainty in the estimate of the parameters

- This corresponds to minimizing the product of the eigenvalues of $J$ (without proof)

- Thus, compute the Jacobian + product of its eigenvalues corresponding to different subsets of configurations (>20), choose the best one

- **Perform the calibration based on this optimized set** (execute, measure, minimize error)
Calibration Results (1)

- Comparison of the proposed selection method vs randomly selected configurations
- Pool containing 750 poses per chain (=3000)
Calibration Results (2)

Initial RMSE: 43.4 px

RMSE after calibration: 5.5 px
Summary

- Automatic calibration of the complete kinematic model of a humanoid given its kinematic structure
- Least squares error minimization based on estimated and observed marker positions
- Automatic selection of robot configurations that enable an accurate calibration
- Only few observations are needed to obtain an accurate calibration result
- Can also be used for other robots with a different kinematic model
Literature

- Whole-Body Self-Calibration via Graph-Optimization and Automatic Configuration Selection
  D. Maier and M. Bennewitz,
  Proc. of the IEEE International Conference on Robotics & Automation (ICRA), 2015