HSLU Hochschule Luzern

Technik & Architektur
Master Thesis

MSE - Mechatronics and Automation

Robot-World and Hand-Eye Calibration

Methods for Vision-Based Robots

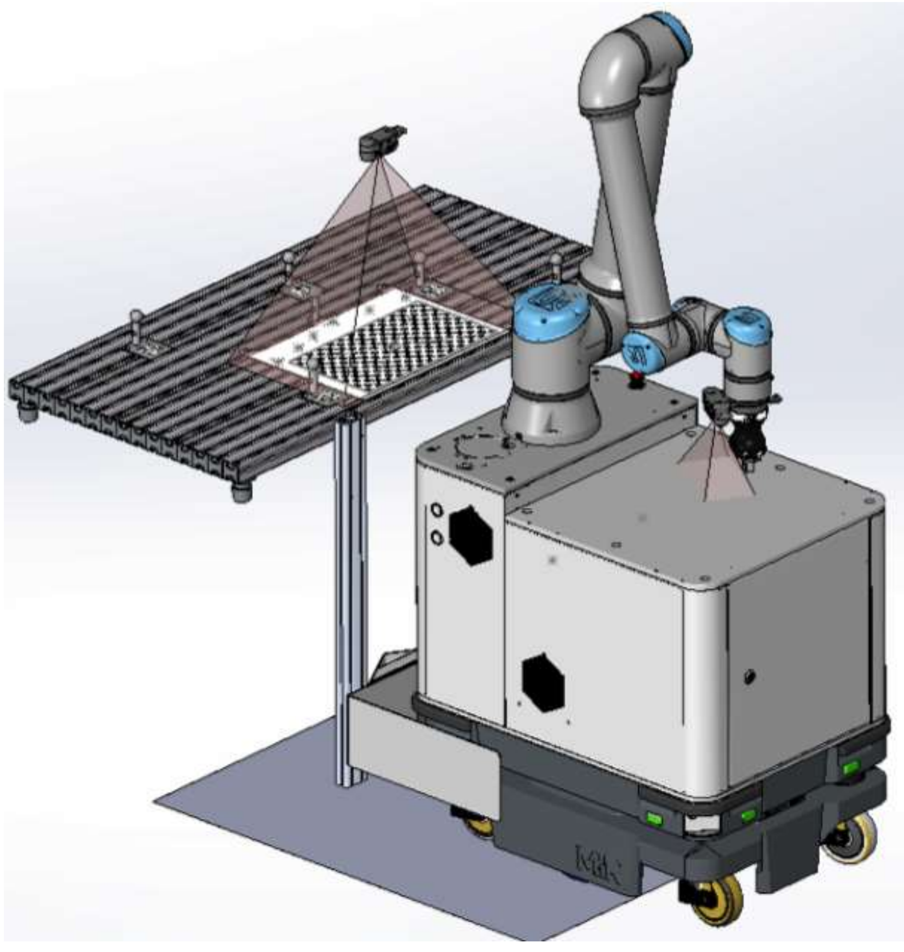

Fig. 1: Setup robot-world

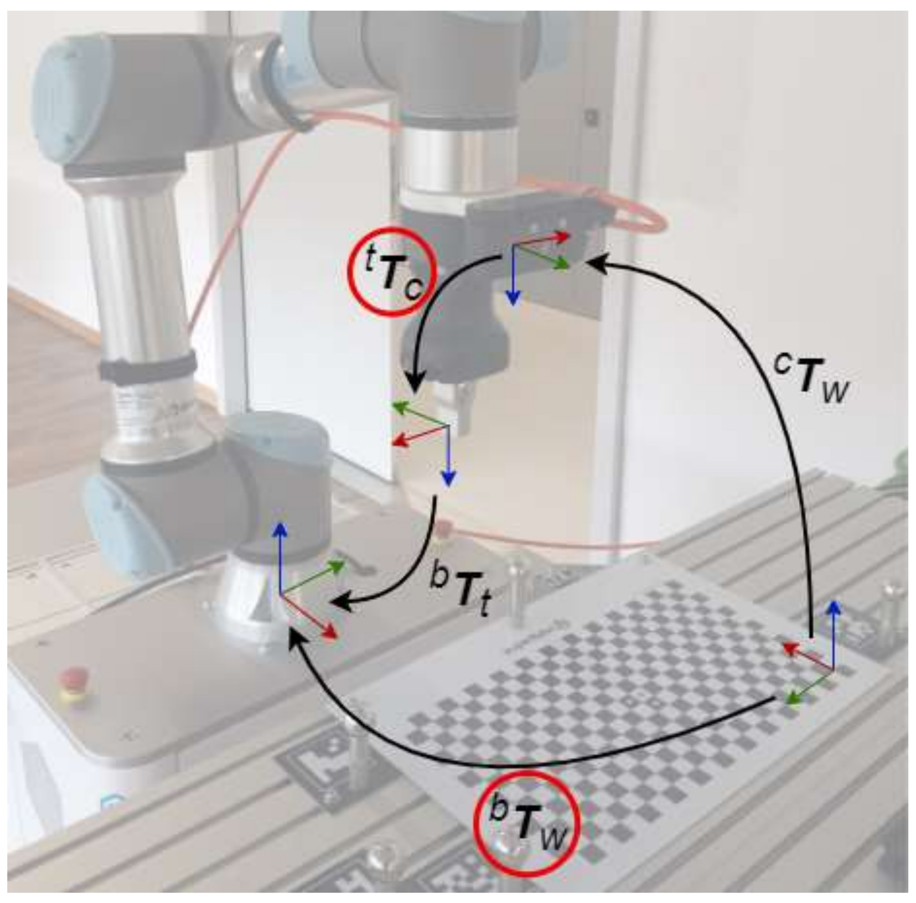

Fig. 2: Setup coordinate frames

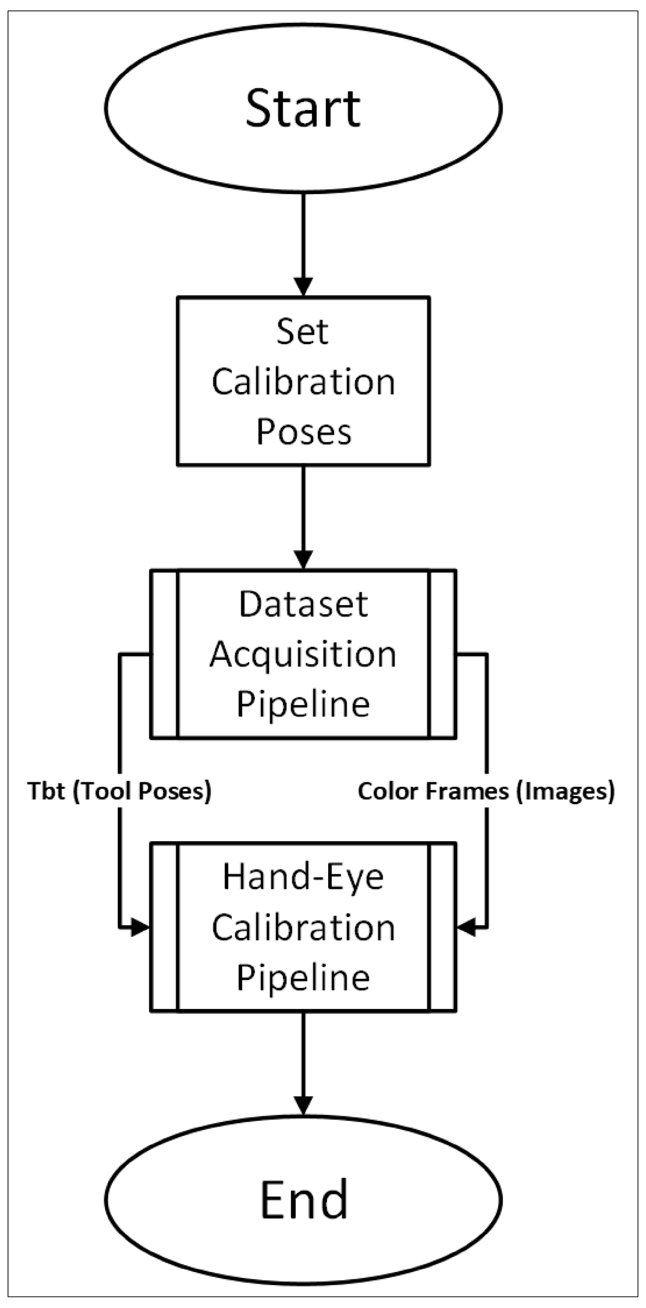

Fig.4: System workflow

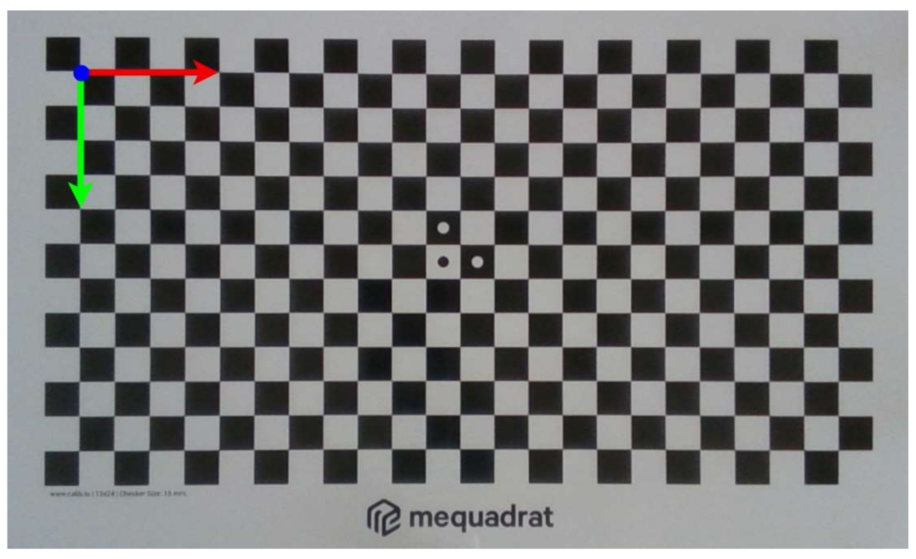

Fig. 3: Calibration object (world frame)

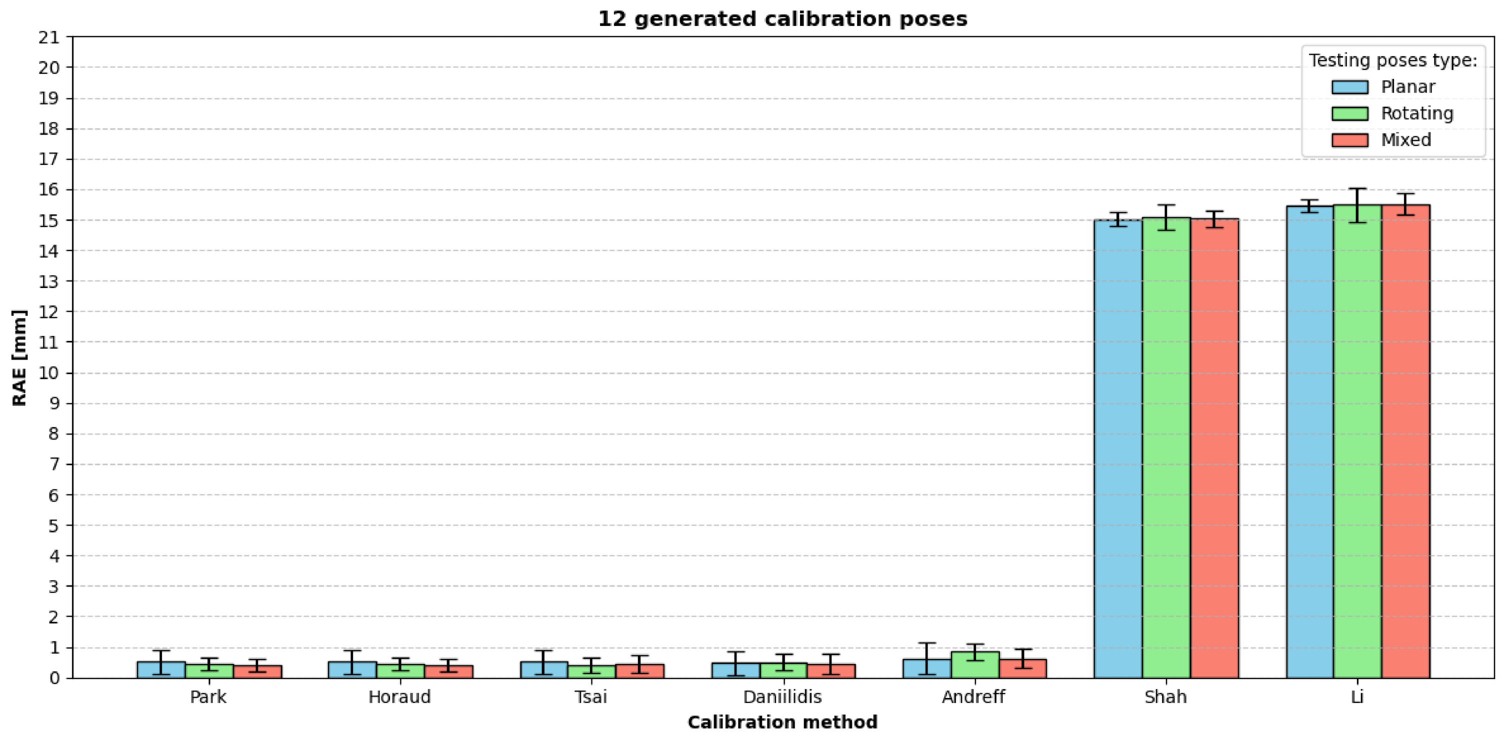

Fig. 5: **OpenCV** methods calibration **results** using of 12 calibration poses

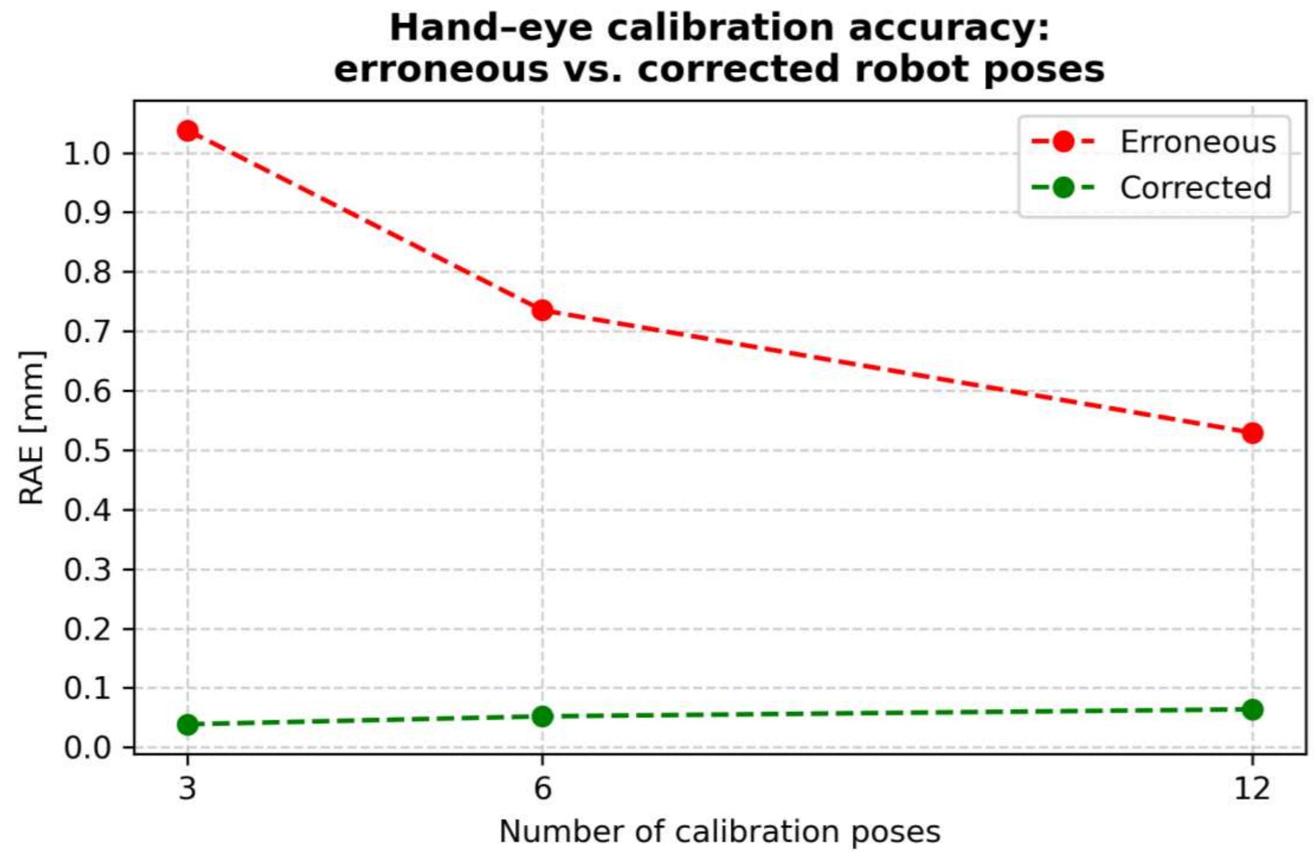

Fig. 6: **Uncertainty-aware** calibration **results** using 3, 6 and 12 calibration poses

Problem Statement

This master thesis, results from a collaborative work between HSLU and Mequadrat AG, and consisted in the development and analysis of an efficient system for robot-world and hand-eye calibration. This solution enables vision-based robots to interpret spatial data by transforming camera-acquired information into robot-readable coordinates. While the **robot-world** calibration determines the relative pose of the world in robot coordinates (Fig. 2, **Tbw**), the **hand-eye** calibration defines the camera's pose relative to the robot's tool (Fig. 2, **Ttc**).

For instance, in a pick-and-place application when a robot detects an object to grasp using its camera, the hand-eye pose allows the **conversion** of the object's **pose** from camera to tool coordinates, enabling the grasping. Similarly, the robot-world calibration allows the robot to place, relative to its base, objects in the workspace.

Methods

The calibration process begins with the **acquisition** of a **dataset** composed of images of the calibration object (e.g., a checkerboard pattern – Fig. 3) and the corresponding tool poses from predefined robot configurations. Using the known geometry of the calibration object and the intrinsic camera parameters, the camera poses with respect to the world frame are computed (Fig. 2, **Tcw**). These **camera–tool pose pairs** are then used in robot-world and hand–eye calibration algorithms to **estimate** the **spatial transformations (poses)** between the robot, world, tool, and camera frames.

To perform this calibration, **two** independent **implementations** were developed using distinct frameworks: **OpenCV** and **Halcon**. The OpenCV-based pipeline integrates and evaluates seven well-known methods from the literature (Park, Horaud, Andreff, Daniilidis, Tsai, Shah, and Li). In contrast, the Halcon implementation employs an uncertainty-aware method that explicitly accounts for errors in the robot tool poses. This approach iteratively refines the poses and provides more robust calibration results.

Results

While the **uncertainty-aware method** proved to be the **most accurate**—achieving accuracy errors **below 0.1 mm** when using corrected tool poses—its implementation relies on Halcon, a proprietary framework. In contrast, the **OpenCV-based methods**, which include a separate robot–world estimation step (excluding Shah's and Li's, that estimate both transformations simultaneously), delivered higher but still reliable accuracy errors, **below 1 mm**. Given its open-source nature, OpenCV offers therefore cost-effective and practical alternatives suitable for many industrial applications.

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