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Improving position sensor calibration via Bayesian inference

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1 Background

The performance of mechatronic systems is limited by the accuracy of the position sensors used for feedback. These sensors require accurate calibration, which is achieved using test beds that, in turn, require even more accurate calibration [1]. Due to this cascade of calibration steps, see Figure 1, modeling errors in individual calibration steps can compound and limit the achieved accuracy of the position sensor calibrated last. This compounding of calibration errors is especially problematic when limited data is available due to the high costs of manual calibration.

2 Problem formulation

The aim is to find an accurate mapping of a low-cost, relatively inaccurate sensor S_1, to a highly accurate manual instrument S_3. To this end, a test bed, equipped with sensor S_2, is calibrated on S_3 once. Subsequently, a large range of different products, each with its own sensor S_1, is calibrated automatically on this test bed.

3 Cascaded calibration via Bayesian inference

The key idea is to model the intermediate sensor calibration model $f_{2\to3}$ as a Gaussian Process (GP), where

$$y_3 = f_{2\to3}(y_2), \tag{1}$$

such that when the two sensors are aligned, the sensors S_2, S_3 each measure positions y_2, y_3. By collecting a data-set $\mathcal{D}$ from the sensors and modeling $f_{2\to3}$ as GPs, the posterior model variance $\text{cov}(\hat{f}_{2\to3})$ can be computed. Indeed, when readings of a low-cost sensor S_1 are then compared on the intermediate calibration model and stored as $\hat{\mathcal{D}}$, the total calibration model is affected by the model uncertainty of the intermediate calibration model:

$$\hat{y}_3 = \mathbb{E}(\hat{f}_{1\to3}(y_1)) = g(y_1, \text{cov}(\hat{f}_{2\to3}), \mathcal{D}, \hat{\mathcal{D}}). \tag{2}$$

Crucially, (2) provides an expression for the expected true position of the mechatronic system as a function of the reading of low-cost sensor S_1, and the variance of the intermediate calibration model. This expression can be evaluated online to correct for repeatable sensor inaccuracies.

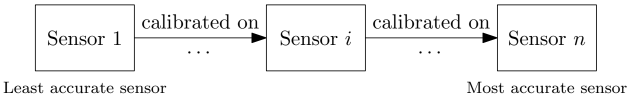

Figure 1: When multiple sensors are calibrated on each other, any calibration error is propagated down the chain.

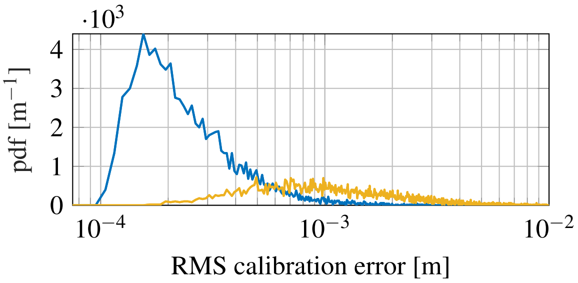

Figure 2: Normalized probability density function of the calibration error. The developed approach (—) achieves more accurate calibration than a lookup table with linear interpolation (—).

4 Simulation results

Monte Carlo simulations with 5000 scenarios are performed. In each scenario, $f_{1\to2}$ and $f_{1\to3}$ are generated randomly from a fourier basis. Figure 2 compares the resulting calibration errors $\|\hat{y}_3 - y_{\text{true}}\|_2/\sqrt{N}$ of the developed calibration approach with a lookup table with linear interpolation. The developed approach leads to significantly more accurate calibration, because (i) the chosen model structure is better suited for extrapolation, and (ii) model uncertainty of the intermediate calibration model is taken into account, such that in these regions the prior is trusted more than the model.

5 Conclusion

A cascaded calibration method is developed to accurately model position sensor inaccuracies, enabling more accurate calibration of mechatronic systems with fewer resources.

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