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Bayesian Hierarchical Modeling for Reliable Large-Scale Sensors Deployments and Applications

Reliability of large populations of sensors is a major challenge in modern industrial production and applied functional monitoring systems. The massive deployment of low-cost Micro-Electro-Mechanical Systems (MEMS) sensors across several technological domains requires calibration strategies that ensure metrological reliability while remaining feasible at industrial scale. However, traditional laboratory calibration procedures become impractical when sensors are produced in very large quantities, motivating the development of statistical approaches for large-scale calibration.

This work develops a Bayesian statistical framework for the virtual calibration and actual applications of large sensor batches. A earlier published model exploits information from a reference, laboratory-calibrated batch to infer the calibration properties of new lots of the same production process. By calibrating only a small subset of sensors from each batch, the model estimates
key parameters that characterize the entire lot, providing robust reliability assessments while drastically reducing direct calibration effort. Building upon this formulation, a hierarchical extension of the model is developed by introducing a Beta hyperprior distribution
on the probability of detecting out-of-tolerance sensors, enabling the integration of prior industrial knowledge with explicit control of parameter variability. This approach softens prior deterministic assumptions about batch quality and enhances the flexibility and robustness of reliability estimates. The choice of hyperprior parameters therefore plays a
crucial role in ensuring that the model coherently reflects prior industrial knowledge.
The study evaluates sensor batch reliability metrics under varying model parameters and introduces alternative metrics to address identified limitations. Model validation was conducted on a case study
of 100 digital MEMS accelerometers calibrated at INRiM. Models based on weakly informative hyperpriors rely more strongly on the information conveyed by the likelihood. Consequently, when the observed data indicate a smaller percentage of defective sensors than that expected according to the prior, higher batch reliability and lower uncertainty associated with the statistically calibrated sensors are obtained. Conversely, when the data suggest a higher percentage of defective sensors, the same models produce a substantial increase in the associated uncertainty. This result highlights how the agreement between the prior assumption and the data-driven evidence plays a fundamental role in the assessment of the batch reliability and uncertainty.

Future research will extend the model by including utility and cost functions to formally represent the producer's risk in rejecting a batch and the consumer's risk in accepting it, integrating
probabilistic calibration results with decision-making criteria. These studies will be crucial for balancing the benefits of using less informative hyperpriors, which may lead to higher estimated reliability of lots, against the drawback of a larger posterior variance, that is, a reduced confidence in the estimation of the true number of defective sensors.

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