Robust reference data generation and evaluation of data fusion algorithms in dimensional metrology with traceability to the SI metre

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Abstract

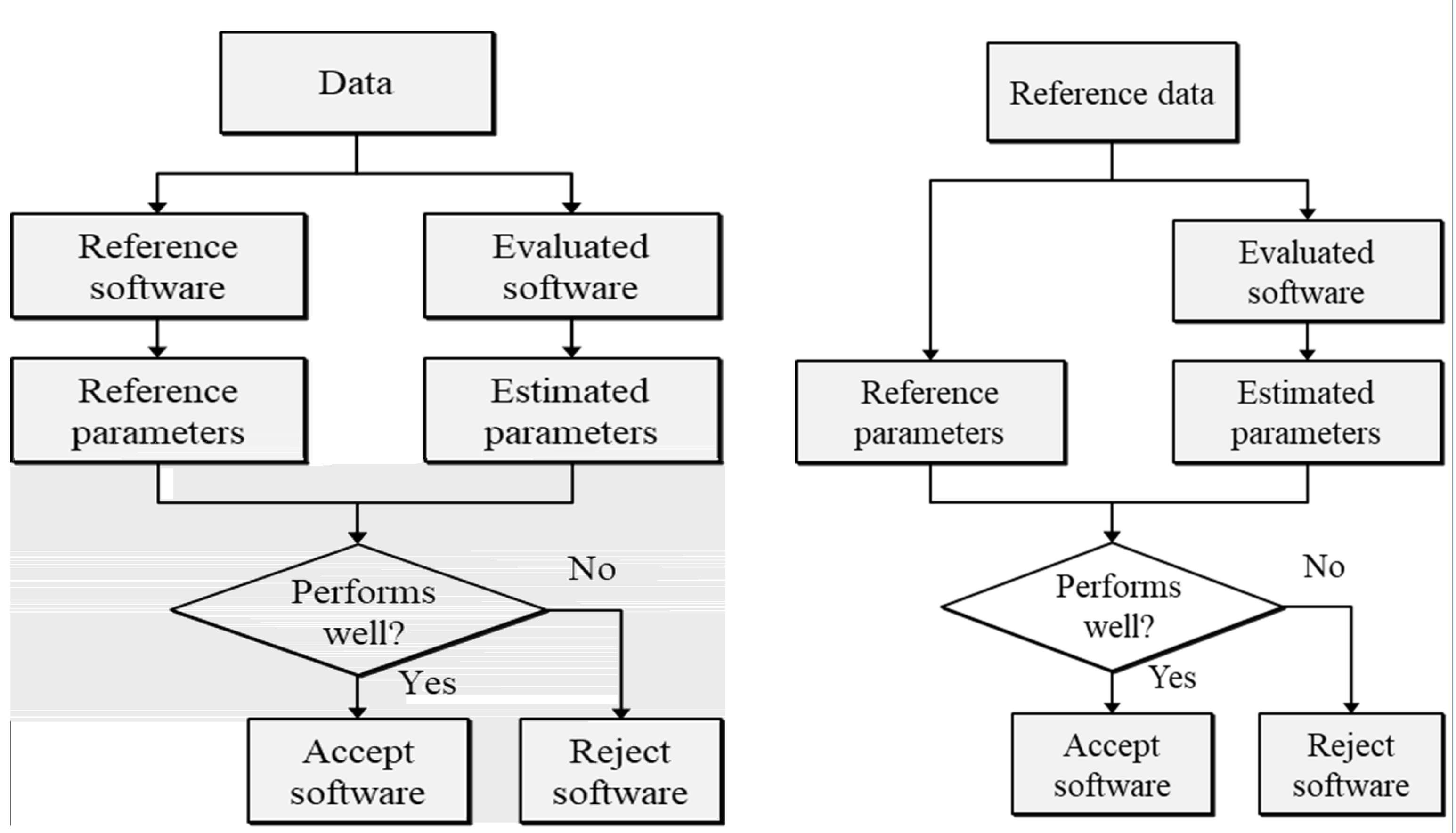
Digitalization and AI advancements introduce challenges in metrology (data fusion, uncertainty and traceability)

- **Software reliability** ensured through **reference datasets** (ISO 5436-2:2012).
- **Reference data generation** simulating **real-world conditions** (geometry, noise, transformations).
- **Evaluation framework** using **point clouds & Monte Carlo simulations** confirming minimal bias.
- **Validation process** based on **synthetic datasets** (CMM, MVS) for accuracy.
- **Impact**: Strengthens **3D measurement reliability, data fusion verification, and traceability**.

Introduction on reference data generation

Metrological software validation relies on standardized reference methods.

- **Verification & Validation:** Essential for metrological software reliability.
- **Software Measurement Standards**: Defined by **ISO 5436-2**.
- Types of Standards:
  - **Type F1**: Reference data.
  - **Type F2**: Reference software.
- **Purpose**: Ensures traceability & accuracy in measurement calculations.



(a) reference software (b) reference data

Figure 1. (a) Type F1 and (b) Type F2 software measurement standards according to ISO 5436-2 (2012)

Software evaluation ensures reliability through parameter comparison.

- **Evaluation Process**: Compares estimated vs. reference parameters.
- **Reference Source**: Derived from software or data.
- **Decision Criteria**:
  - **Acceptance**: Meets performance criteria.
  - **Rejection**: Deviates beyond acceptable limits.
- **Objective**: Ensures reliable software performance.

Methodology and material

Reference data generation is studied for rigid point cloud registration and Weighted approximation (WA) algorithms applied to different sensors and complex surfaces.

The process includes three main Steps

a. **Sampling Footpoints:** From a simulated measurement system.
b. **Adding Deviations:** Consistent with spatial data fusion algorithms.
c. **Generating Transformations:** With desired distributions.

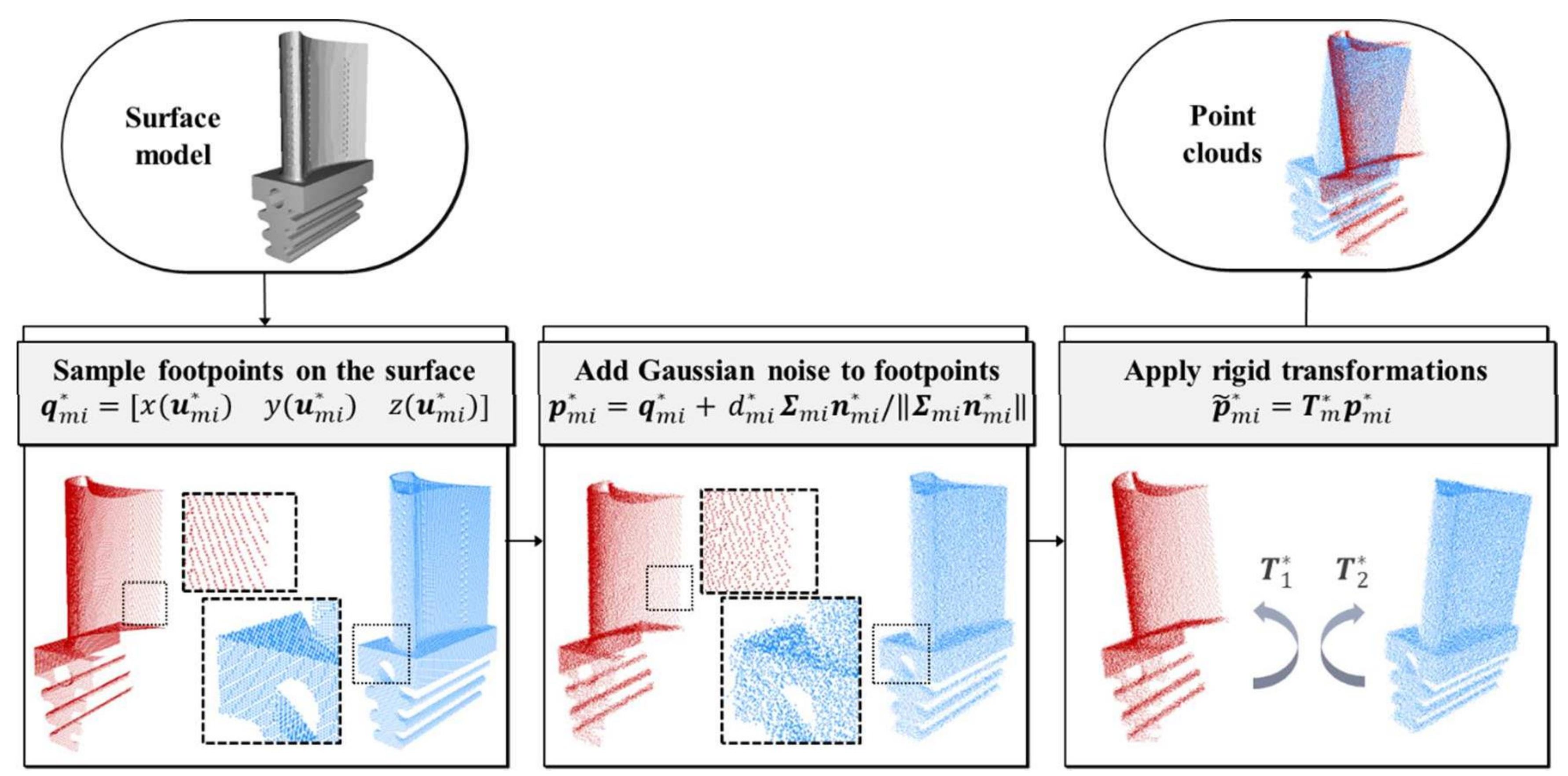


Figure 2. Point clouds generation through sampling, noise and transformation steps

Well-Defined Closest Points

✓ **Key Concept**: Reference point deviations must be collinear to the **Mahalanobis distance gradient** at the closest footpoint.

Mahalanobis Distance ensures that deviations follow the minimum variance direction:

$$d_{mi}^T \Sigma_{mi}^{-1} d_{mi}$$

Gradient Condition: The deviation gradient must be collinear with the normal

$$\nabla\left(d_{mi}^T \Sigma_{mi}^{-1} d_{mi}\right) = \Sigma_{mi}^{-1} d_{mi} \propto \tilde{n}_{mi}$$

Deviation Representation:

$$d_{mi} = \delta_{mi} \Sigma_{mi} \tilde{n}_{mi}, \delta_{mi} = \pm \| \Sigma_{mi}^{-1} d_{mi} \|$$

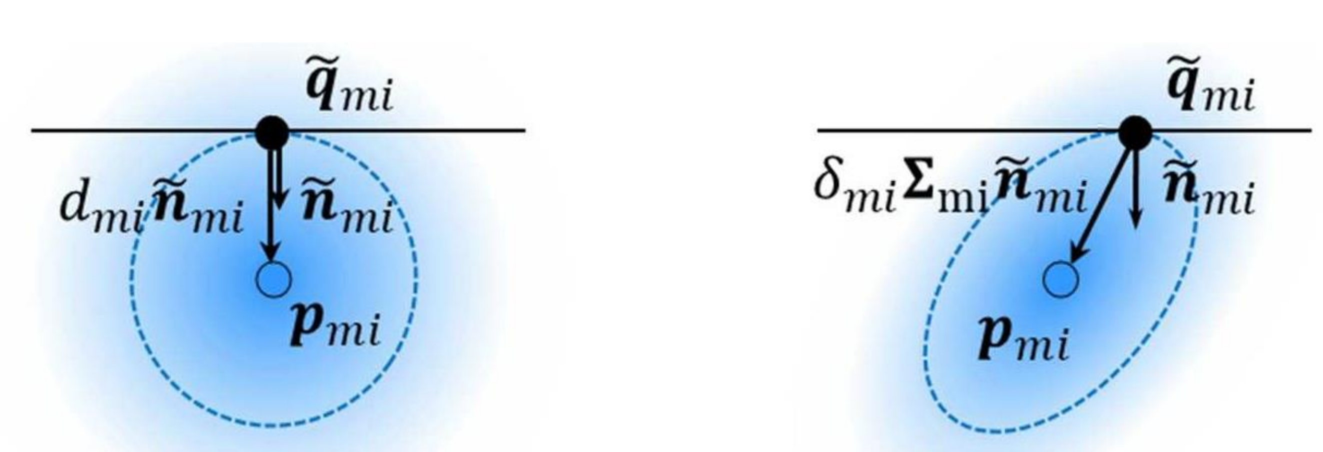


Figure 3. Probability density and Mahalanobis iso-surface (dashed blue line) for isotropic and anisotropic noise.

Results

Figure 4. Turbine Blade – CAD and CMM Sampling

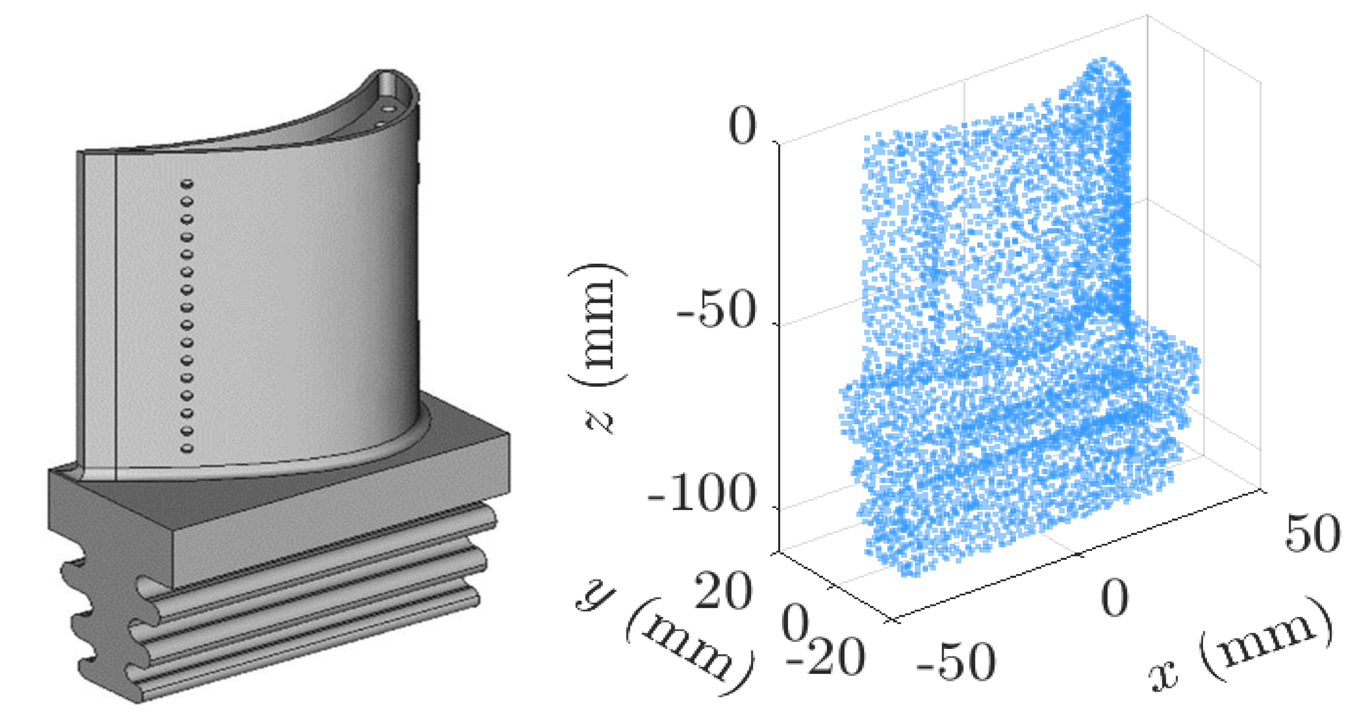


Table 1 . Mean errors and standard deviations for the turbine dataset.

Registration Algorithm	Dataset Type	$\bar{\Delta\theta} \pm u(\Delta\theta)$ (mdeg)	$\bar{\Delta t} \pm u(\Delta t)$ (µm)	$\bar{\Delta\phi} \pm u(\Delta\phi)$ (µm)
$ICP\ F_p^\sigma$ (point-to-point)	Suboptimal	55.60 ± 10.06	55.07 ± 10.19	0.86 ± 0.46
	Reference	51.90 ± 9.86	53.72 ± 9.13	0.92 ± 0.29
$ICP\ F_{pn}^\sigma$ (point-to-pan)	Suboptimal	25.57 ± 7.31	22.69 ± 7.25	0.17 ± 0.23
	Reference	22.42 ± 5.95	18.92 ± 6.30	0.14 ± 0.10
$ICP\ F_{MLS}^\Sigma$ (point-to-quadric)	Suboptimal	7.08 ± 2.71	8.03 ± 2.95	0.09 ± 0.18
	Reference	6.18 ± 2.51	6.01 ± 2.31	0.02 ± 0.02

- Suboptimal dataset: Biased, acceptable accuracy
- Reference dataset: Optimal, unbiased standard

Conclusions

✓ **Traceability assurance** through F1 softgauges quantifying F2 uncertainty.

✓ **Reference data generation** with isotropic/anisotropic noise for multi-sensor adaptability.

✓ **Bias evaluation** in data fusion confirming reliability for optimal cases and errors for suboptimal methods.

Acknowledgement

DI-VISION

https://projects.lne.eu/jrp-di-vision/

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