About the importance of stochastic information in deformation analysis

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Correlations in TLS point clouds: Should we care about them?

High-end Terrestrial Laser Scanners (TLSs) are used for many applications that require precise geometry of the captured object. Dimensions are frequently extracted directly from the point cloud or from estimated primitives. However, the uncertainty information attributed to each point and correlations between points are often neglected. Generally, TLS observations may be highly correlated for reasons such as similarities in the surface properties, instrument optical-mechanical misalignments, overlap of laser footprints, or similarities in the measurement environment. The current contribution demonstrates the relevance of correlations in tasks usually performed directly with the point cloud, such as distance measurements between two points, target segmentation based on point clouds (e.g., spheres), and registration. Tests were conducted using the variance-covariance propagation law and elementary error theory for simple distance measurements between highly correlated points (e.g., ρ=0.8). Firstly, simulation results are used to show that precision estimations for measured distances are up to 55% better with correlations than without. The same analysis is done with real data, and an improvement of the precision estimate of 20% was reached; however, degradation is also possible if negative correlations occur. Additionally, the impact of correlations on the sphere-based registration between two TLS station points is shown. The spheres were segmented, and center coordinates were estimated using different versions of a stochastic model. Finally, they were used in the registration. Conclusions about correlations in TLS point clouds are drawn based on these tasks encountered in almost all TLS applications.

Keywords: Uncertainty propagation, Statistical testing, Quality control, Registration, Primitive estimation

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Impact of Mathematical Correlations

Close-range photogrammetry offers a wide range of industrial applications in the field of large volume metrology. The object coordinates are derived from captured images using a bundle adjustment. Even if the observations are assumed to be stochastically independent within the adjustment procedure, the estimated object coordinates are correlated. In subsequent applications such as surface fitting or deformation analysis, these estimated object coordinates are usually treated as independent and even identically distributed observations, neglecting stochastic information of the prior bundle adjustment. However, simplifications in stochastic modelling lead to misinterpretations of the adjustment results in terms of precision and reliability. Based on the estimates of a bundle adjustment, the impact of neglected correlations in subsequent applications is investigated. It is demonstrated that the chosen stochastic model affects the resulting standard deviations significantly. In surface fitting the derived standard deviations of datum-independent form parameters are two to five times overestimated when neglecting stochastic dependencies. Applying hypothesis tests to the estimates as part of quality assurance, for instance, lead to incorrect decisions, because the test statistics are biased. Analogously, in deformation analysis the risk of type I decision errors increases when in fact stable networks are falsely detected as deformed. This contribution indicates the advantage of the fully-populated dispersion matrix because the identified discrepancies can not be compensated by introducing simple stochastic models, such as a diagonal variance matrix or a point-based block-diagonal matrix.

Keywords: Correlation, Dispersion matrix, Surface fitting, Hypothesis test, Deformation analysis, Close-range photogrammetry, Industrial metrology

J. A. Butt

Building and Solving Probabilistic Instrument Models with CaliPy

Probabilistic models of geodetic measurement instruments are essential ingredients for uncertainty quantification and optimal estimation. Traditionally, these models are formulated and analyzed manually with inference relying on classical maximum-likelihood-based parameter estimation. However, this approach typically falls short when dealing with nonlinear models, non-Gaussian distributions, or latent random variables. To overcome these limitations, we developed CaliPy (Calibration library Python), a Python library built on top of Pyro and PyTorch. CaliPy is designed to facilitate the construction, solution, and exchange of probabilistic instrument models by chaining together pre-built stochastic effects. It leverages advances in deep probabilistic programming and automatic differentiation to perform automated Bayesian inference. In this paper we demonstrate CaliPy's architecture and practical application through examples involving instrument models featuring drifts and noise. Our results highlight CaliPy's ability to handle complex probabilistic models in a unified framework, thereby offering significant benefits to the users of measurement instruments by streamlining model formulation, solution, and exchange while also providing a framework for implementing chainable stochastic effects in a Python-friendly ecosystem.

Keywords: Probabilistic programming, Instrument models, Calibration, Stochastic models, Machine learning

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K. Snow, B. Schaffrin

Total Least-Squares Collocation for Deformation Analysis

For many situations in deformation analysis, data are collected that not only enter the usual observation vector $\mathbf{y}$, but also the coefficient matrix A after linearization. Such models fall into the category of Errors-In-Variables (EIV) Models and may be treated by Total Least-Squares (TLS) adjustment. Moreover, if the deformation as described by the parameters $\boldsymbol{\xi}$ follows certain "expectations" that can be quantified, the normally non-random parameters will turn into "random effects" $\mathbf{x}$, in which case the standard estimation procedure needs to be replaced by one that resembles collocation, but is here obviously based on the TLS principle. Earlier studies involved only a non-singular combination of the observation covariance matrices; these include Schaffrin (2009), Snow and Schaffrin (2012), and Schaffrin (2020). A more general treatment was developed by Snow (2012) in his PhD dissertation and has been further extended in Snow and Schaffrin (2025) for the case where the combination of covariance matrices turns out to be singular. Here, an algorithm is presented and applied to a problem in deformation analysis.

Keywords: Errors-in-variables (EIV) model, Random effects model, Prior information, Total least-squares adjustment, TLS collocation, Singular covariance matrices, Deformation analysis