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Carlo Pellegrino · Flora Faleschini ·
Mariano Angelo Zanini · José C. Matos ·
Joan R. Casas · Alfred Strauss *Editors*

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Preface

This conference proceedings contains papers presented at the 1st Conference of the European Association on Quality Control of Bridges and Structures—EUROSTRUCT2021—took place in Padova, from August 29 to September 1, 2021. The EUROSTRUCT has been created from COST Action TU146 "Quality specifications for roadway bridges, standardization at a European level (BridgeSpec)," which aimed to achieve the European economic and societal needs by standardizing the condition assessment and maintenance level of roadway bridges. The association acts a relevant role in the development of knowledge of existing bridges and structures, and the conference is aimed at providing an international forum for promoting the worldwide exchange of knowledge and experience in quality control and improvement of bridges and structures and was thus targeted to attendees from academia and industry. The first conference of EUROSTRUCT was held in Padova, Italy, hosting more than 200 of international participants from all over the world, becoming one of the first scientific conferences again in the presence after the COVID-19 pandemic reality, and at the same time, a novel and reliable round table where all the stakeholders working in the field of bridge engineering can meet, discuss together and draw the new trends in bridge engineering.

Topics such as structural reliability, robustness, risk and resilience were discussed, new methodologies and technologies for improving quality and sustainability of existing infrastructures were proposed, and moreover, particular attention was provided to the use of advanced tools in the decision process for the stakeholders. The main topics covered in the conference can be grouped as follows:

- Testing and advanced diagnostic techniques for damage detection in existing bridges and structures;
- Structural health monitoring and AI, IoT and machine learning for data analysis of existing bridges and structures;
- Fiber optics and smart sensors for long-term SHM of existing bridges and structures;

- Structural reliability, risk, robustness, redundancy and resilience for existing bridges and structures;
- Corrosion models, fatigue analysis and impact of natural and man-made hazards on infrastructure components of existing bridges and structures;
- Bridge and asset management systems, and decision-making models of existing bridges and structures;
- Life cycle analysis, retrofit and service life extension, risk management protocols of existing bridges and structures;
- Quality control plans, sustainability, green materials.

All papers submitted to the EUROSTRUCT2021 conference were subjected to a peer-review process by identified leading experts, acting independently on the assigned manuscripts. The process significantly enhanced the quality of the proceedings, and the contribution of the referees is highly acknowledged.

Special acknowledgments are due to the following organizations:

- IABMAS—International Association for Bridge Maintenance and Safety
- IALCCE—International Association for Life-Cycle Civil Engineering
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- University of Padua
- Department of Civil, Environmental and Architectural Engineering (ICEA) of the University of Padua
- iBIMi
- Regione del Veneto
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This volume contains an up-to-date overview in the field of bridge engineering, with significant contributions in the fields of testing, assessing, monitoring, maintaining and managing existing structures and infrastructures. Special attention is paid to the most recent innovations about sustainability and technological advances for bridge engineering. The editors would like to take this opportunity to thank the keynote speakers for their inspiring lectures, specifically to:

- Paolo Gardoni, University of Illinois at Urbana-Champaign, USA, for presenting "An Overview of Regional Risk and Resilience Analysis";
- Joan R. Casas, Technical University of Catalonia, Spain, for presenting "Distributed Optical Fiber Sensors in Structural Health Monitoring";
- Dan Frangopol, Lehigh University, USA, for presenting "Risk, Resilience and Sustainability of Civil Infrastructure Systems under Lifetime Hazards in a Life-Cycle Optimization Framework";
- Walter Salvatore, University of Pisa, Italy, for presenting "Application of the new Italian Guidelines on existing bridges: first results and open problems."

All the authors are gratefully acknowledged for their effort in preparing and presenting highly qualitative papers. We are confident that the proceedings will provide a valuable reference for future work and developments for engineers, researchers, academics and students from all areas of bridge and structural engineering.

C. Pellegrino
M. A. Zanini
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Quantification of Uncertainties for Geodetic Observations in the Context of Bridge Surveillance

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Abstract. Ageing infrastructure and the pursuit of minimal life cycle costs provide a basis for a wide range of surveillance and recalculation techniques such as structural health monitoring and model updating. For many of these applications, the accompanying uncertainties in the measurement of structural reactions are key to the success of these methodologies. In this context, geodetic surveillance represents one of the most widely used methods for the measurement of deformations.

This paper will explain and quantify the uncertainties inherent to geodetic observations of bridge structures based upon measurements conducted in Roding (Bavaria) with the objective to update a Finite-Element-Model via Bayes´ theorem. In this project, both a tachymeter and a lasertracker were used for data gathering.

After providing an overview on the theoretical background on uncertainty quantification according to the GUM, the measurement uncertainties of both devices are evaluated and compared to the manufacturer's specifications.

The determination of the stochastic parameters' variances will follow from the statistical analysis of the empirical test data, e.g. by bootstrapping. Finally, this results in statistical models for the surveying uncertainties of both devices.

Keywords: Geodetic surveillance · Structural health monitoring · GUM · Uncertainty in measurement · Measurement of deformation · Model updating · Parameter identification · Bootstrapping

1 Introduction

1.1 Data Acquisition from Geodetic Observations

Geodetic surveillance enables data gathering on the status of civil engineering structures. In the context of monitoring and identification of static properties of a system, geodetic data can provide valuable information on the structure's behavior when exposed to external influences. However, knowledge about the inherent uncertainties of the observed system to specified loading is essential for the success of these methods [1].

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Hence, this paper presents the theoretical methodology according to GUM (Guide to the Expression of Uncertainty in Measurement), the subsequently conducted laboratory tests and the concluding statistical evaluations. The entire procedure focuses on the objective of quantifying the precision, by which the true values of the recorded deformations have been determined. For further information on the metrological aspects of deformation measurement and the associated quality criteria for the purpose of updating, please refer to [2].

1.2 Measurements in Roding

To gain input data for a subsequent identification of the static parameters, static load tests on the bridge, depicted in Fig. 1, have been carried out using both a dumper and a tank for prespecified loading positions.

Fig. 1. Overview screen of the trial bridge in Roding

Figure 2 illustrates the designated points of the conducted geodetic surveillance. The displacements of the entire soffit were recorded for two of the midspans (M1 and M3). For that matter, measurement points were set up at each lower edge of the exterior webs and at the centers of the bottom flange. For the observations at target 1, 3–6, a tachymeter Leica TPS 1201 was applied. The manual observation of the horizontal angle was preferred over the application of the automatic target recognition (ATR) due to the higher accuracy that can be reached. In order to avoid systematic influence from a possible axis error, the measurements have been carried out in two telescope positions. At target 2, the measurement has been carried out using a lasertracker of type Leica AT-901-LR. To minimize perturbation from traffic at an adjoining bridge, the measurements were only executed in the absence of heavy traffic. For further information on the specific project, please refer to [1, 3].

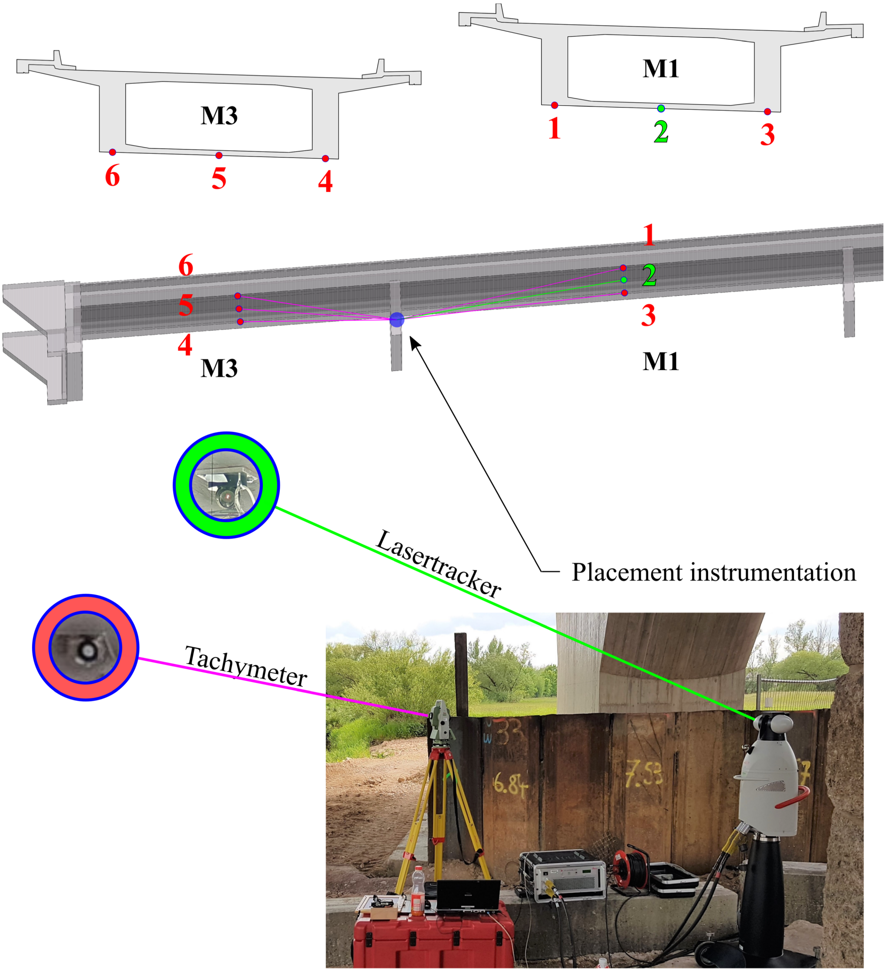

Fig. 2. View from below, denomination of the observed targets and instrumentation

2 Uncertainty in the Framework of the GUM

2.1 General Remarks

Even for a measurement carried out with the highest possible diligence, there always exists uncertainty in the determination of the true value.

Such dispersions in the observations arise from imperfections in the calibration of measuring systems, systematic influences during the measuring process, but also from unpredictable or random components within the observed measurand [4]. The observed value X of the deformation can thus be split according to Eq. (1) into the true value $\tilde{X}$, a systematic error δ and a random error ε described by a distribution function $N(0, \sigma)$ [5].

$$X = \tilde{X} + \delta + \varepsilon \tag{1}$$

To account for these uncertainties that are intrinsically tied to all forms of observations, the Guide to the Expression of Uncertainty in Measurement (GUM) was introduced by the Joint Committee for Guides in Metrology in 1995 and is currently used in a version dating from 2008 [4].

The standard of GUM allows both for an assessment based on an empirical examination and subsequent statistical evaluation of independently repeated measurements (type A-evaluation) and for a judgment based on expert knowledge (type B-evaluation) [4]. A type A-evaluation is quantified by conducting repeated and independent measurements of either the different influence quantities or the desired value itself. The statistical analysis of this series of measurements delivers the mean value as the best estimation of the true value [6] and the standard deviation as a measure of the precision of the data [4]. Based on the Central Limit Theorem, the GUM proposes the Gaussian curve as the standard choice to characterize the underlying stochastic distribution function. Figure 3 illustrates the derivation of the two estimators from the histogram of a normally distributed sample of size 31.

Systematic errors cannot be revealed in this way. However, differential measurement of small deformations justifies the assumption of only a neglectable distortion of the data due to systematic influences.

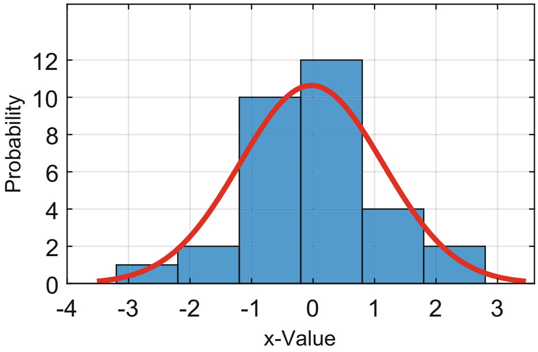

Fig. 3. Fit of a Gaussian distribution to a normally distributed sample set of size 31 for an expected value of E(x) = 0 and a standard deviation σ = 1.

In contrast to the above-mentioned experimental approach, type B-evaluation is mainly based on previous experiments or on data sheets [4]. Even though GUM mentions specifications as one of the main sources for a type B-evaluation [4], manufacturers tend to give too conservative information on their measuring systems [7]. Additionally, these cannot account for a random component introduced by the operator, as the experience and elaborateness of the geodesist must be seen as one of the main sources of uncertainty.

In the absence of empirical data, the uncertainty is often expressed by a uniform distribution, e.g. using the Maximum Permissible Error (MPE) [8]. Even though the standard deviation may also be attributed to this kind of representation, the assumption of an exact lower and upper bound and the equal probability for the full range of possible values is questionable. Figure 4 shows a rectangular distribution in comparison to a Gaussian curve of equal standard deviation.

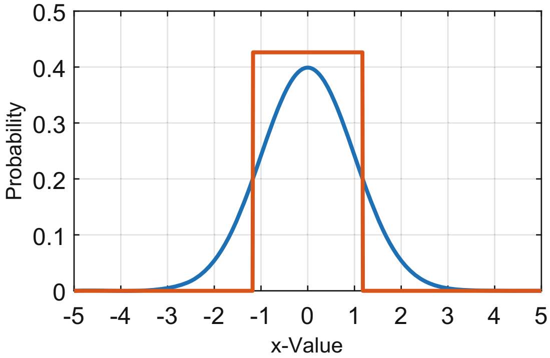

Fig. 4. Uniform distribution and a normal curve of equal standard deviation (σ = 1)

2.2 Statistical Treatment of Measurement

In order to provide a short summary on the mathematical treatment of repeated measurement, this section specifies the basic equations for investigating measurement uncertainties. For details on the statistical background, please refer to [9–11].

To assign the best possible estimate of the true value, the mean is considered as the best choice to approximate the expected value of the underlying parent distribution [6]. For the evaluation of uncertainties attributed to a single field measurement, the standard deviation of bench tests is considered as a suitable approximation for the parent distribution based on a limited number of trials. The formula for estimating the standard deviation $s(q_k)$ from a set of independent observations q_i and a mean value of $\overline{q}$ is given in Eq. (2).

$$s(q_k) = \sqrt{\frac{1}{n-1} \cdot \sum (q_i - \overline{q})^2} \tag{2}$$

For measurements carried out repeatedly in the field, e.g. a time series from lasertracking data with n-independent observations, the experimental standard deviation of the mean $s(\overline{q})$ is employed to improve the approximation of uncertainty. The value $s(\overline{q})$ from Eq. (3) is an expression for the standard deviation of the mean assuming normal distribution.

$$s(\overline{q}) = \frac{1}{\sqrt{n}} \cdot s(q_k) \tag{3}$$

For a finite number of realizations of the underlying experiments, the standard deviation $s\left(\widehat{\theta}\right)$ still contains uncertainties, collocated as ‘error in the error’. The standard uncertainty for normally distributed estimators $\widehat{\theta}$ (e.g. $E(X)$ or σ) can be approximated by Eq. (4) [4, 6, 12]. For a numerical evaluation of this quantity using bootstrapping, please refer to Sect. 4.1.

$$\sigma\left(s\left(\hat{\theta}\right)\right) \approx \frac{1}{\sqrt{2n-2}} \cdot s\left(\hat{\theta}\right) \tag{4}$$

To evaluate a quantity that results from a functional relationship f of a series of N independent input measurands, Eq. (5) depicts the first order approximation to obtain a combined standard uncertainty s_c [4].

$$s_c = \sqrt{\sum_{i=1}^{N} \left| \frac{\delta f}{\delta x_i} \right| \cdot s^2(x_i)} \tag{5}$$

In case of a differential measurement Eq. (5) simplifies to Eq. (6). The actual measurement contains an uncertainty of both the measurement in deformed state, represented by its standard deviation s_1, and the impreciseness of the reference measurement, quantified by the standard deviation s_0. The value $s_{c,rel}$ reflects the uncertainty in the result of a single measurement of deformation.

$$s_{c,rel} = \sqrt{{s_1}^2 + {s_0}^2} \tag{6}$$

If the same instrumentation is used and the measurement can be assumed to be homoscedastic, the precision of both the reference measurement and the measurement in the deformed state are equal and Eq. (6) simplifies further to Eq. (7), where $s = s_1 = s_0$.

$$s_{c,rel} = s \cdot \sqrt{2} \tag{7}$$

2.3 Analysis of Variance Using Bootstrapping

Uncertainties from measurements propagate through subsequent calculation procedures, and they therefore affect the final evaluation of the structure. So, the imperfections inherent to statistical estimators calculated in Sect. 4.1 have to be quantified, which is performed here via bootstrapping. This algorithmic samples with replacement from the observed data to create new samples and to evaluate the distribution of the respective estimator [16]. In contrast to other methods evaluating the approximation of uncertainties, bootstrapping does not necessarily rely on assumptions regarding the underlying parent distribution, but is applicable to any kind of numeric data set [14, 15]. For further information on the method and its theoretical background, please refer to [14, 16] and for computational aspects of the methodology to [15, 17].

3 Experimental Assessment of Uncertainty

3.1 Measuring Procedure

The quantification of uncertainty using empirical methods is anchored in the GUM [4]. However, in preparation of such testing, some aspects need to be considered.

In order to gain valid information from repeated measurements, the procedure needs to provide independence in the data set [4]. The bare repetition of triggering the recording does not guarantee independence [13]. Additionally, the conditions of the field measurement should be reconstructed as accurately as possible. In the case of geodetic surveillance, these are for instance meteorological phenomena or the expertise and elaborateness of the geodesist. Concerning the subsequent statistical analysis, the number of executions has to be sufficiently large to keep the 'error in the error' small.