TASKS AND NEWEST TRENDS IN GEODETIC DEFORMATION ANALYSIS: A TUTORIAL

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ABSTRACT

Within the last years a fundamental change took place in the methodology of geodetic deformation analysis. High sensitive sensor networks enable the installation of area-wide monitoring systems and require new methods for modelling of measuring errors. The classical stochastic view is extended to fuzzified approaches quantifying remaining uncertainties in the error budget. In addition the geometrical deformation analysis dealing with kinematic displacement fields has changed to cause-response models which also quantify monitored trigger events like temperature, wind etc. One challenge is to find deformation transfer functions for complex structures. In this context also AI-methods are trained and used.

The paper will give a brief overview over the current state of the art and newest developments in geodetic deformation analysis.

1. INTRODUCTION

Monitoring and analysis of short- and long-term deformation signals of buildings (e.g. dams, bridges) and natural structures (e.g. local and regional geodynamic processes, slopes etc.) is a central task for geodetic applications in environmental monitoring. It is an essential precondition for the development of reliable alarm systems and the prevention of human and material damage.

In the last years a fundamental change took place in the general view of geodetic deformation analysis and the used methodologies:

- High sensitive sensor networks enable the installation of area-wide monitoring networks. The monitoring data is used as input for real-time operating alarm systems (e.g. in tunneling).
- New methods for modelling of measuring errors are developed. The classical stochastic view is extended to fuzzified approaches which quantify remaining uncertainties in the error budget (e.g. the “observation imprecision”). The fuzzyfication enables new concepts for error propagation and statistical tests.
- The pure geometrical analysis dealing with kinematic displacement fields has changed to so called “cause-response” approaches which also quantify monitored trigger events like traffic loads, temperature, wind etc. One major challenge is now to find non- or parametric deformation transfer functions for often complex structures which combine the influence quantities with the deformation signals and to separate the (in most cases considerable) disturbances. In this context also methods from artifial intelligence (e.g. neural networks) are trained and used. Other suitable tools are provided by adaptive Kalman-filtering.

The following brief overview over techniques and trends in geodetic deformation analysis will present the progression from data acquisition and monitoring over data analysis to deformation modelling.

2. MONITORING AND ALARM SYSTEMS

The basic principle of current geodetic alarm systems for large constructions (e.g. tunnels, dams or bridges) and local respectively regional geomechanical processes (e.g. settlements in mining, landslides etc.) is the combination of a monitoring system with predefined alarm factors (e.g. [19] and [20]). The monitoring system normally consists of geodetic sensors like GPS (= Global Positioning System) and robot tacheometers and / or geotechnical sensors like surface extensometers, borehole inclinometers, temperature and acceleration sensors. In control centres the measured time series are directly used for the detection of critical events (see figure 1).

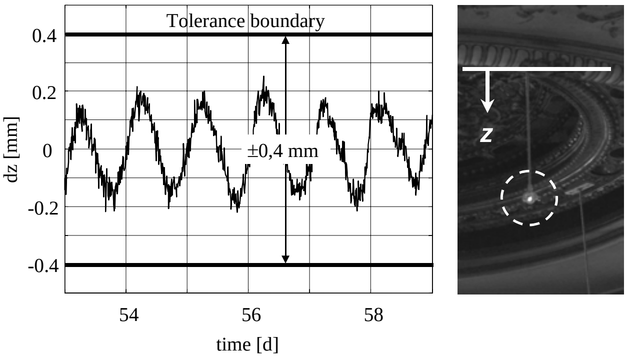

Figure 1 – Relative vertical displacements *dz* of an object point (on a theatre ceiling [5])

Common indicators are the relative changes of displacements combined with associated velocities and / or accelerations. If these quantities exceed predefined tolerance boundaries (see figure 1) warning or alarm messages are shown on computer screens and submitted by email or SMS to authorised users. A typical warning / alerting strategy can be a traffic light scheme: starting from green for normal condition and changing over yellow (warning level) to red in emergency case.

A representative example for the current state of the art of geodetic monitoring and alarm systems is GOCA (= GNSS/LPS/LS-based online Control and Alarm System, see [9]). In figure 2 the architecture of the system is shown. The monitoring system (e.g. GPS reference and rover stations) is installed in the object area and transmits the measured signals to a local control centre. The control centre manages the data processing (e.g. smoothing) and analysis (detection of peaks and signal trends with respect to the predefined tolerance boundaries) and automatically submits the alarm messages. Human experts must make the final decision if the alarm is justified or not. Remote control and maintenance of the system can be realised via Internet.

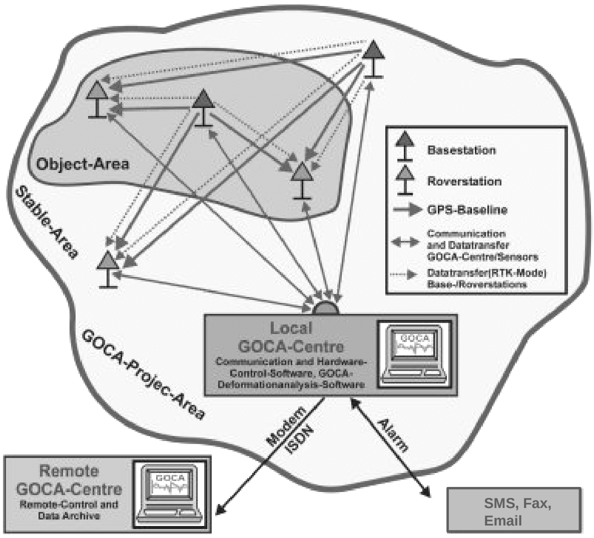

Figure 2 – Monitoring and alarm system GOCA [9]

Basic problems for the analysis and interpretation of the monitoring data are

- the handling of systematic and stochastic measuring errors (which may lead to false alarms),
- increasing autocorrelations as a result of high measuring frequencies (up to 10 Hz with GPS or modern robot tacheometers in kinematic mode),
- and the limited representativeness of the monitoring data.

The sensor systems are typically installed in discrete object points which are mostly restricted close to the surface of the object area. The monitoring results and related alarm levels only reflect a small cutout of the full deformation process and require a complex interpretation by human experts.

Newest trends aim to integrate also trigger events and the mechanisms of the deformation processes by numerical models and methods from artificial intelligence (AI-methods, see section 4).

3. DATA ANALYSIS AND ERROR MODELLING

3.1 Main tasks

Processing and analysis of geodetic monitoring data are often directly connected with the following tasks:

- Synchronisation and filling of gaps in the measured time series.
- Blunder detection.
- Smoothing.
- Detection and reduction of sensor drift.
- Determination of major frequencies.
- Determination of auto- and cross-correlation functions.
- Separation of deformation signals and disturbance influences.

Major goals are the derivation of appropriate error models for the sensors and the collection of empirical information about the deformation process. The results are integrated into non-parametric or parametric deformation models (see section 4).

3.2 Standard techniques

In geodetic deformation analysis the tasks from section 3.1 are naturally realized with standard techniques like

- polynomial regression,
- one- or multi-dimensional outlier tests,
- diverse filter techniques (e.g. low-, band- and high-pass filtering, Wiener- and Kalman-filtering),
- ARMA (auto regressive moving average) models
- and Fourier analysis.

The theoretical background to these well known methods is described e.g. in [2], [7], [13] and [16].

One usual assumption is the existence of normal distributed measuring values. This leads to the use of unbiased least squares estimators for the calculation of the results (e.g. [13]). The influence of outliers (measuring values beyond the threefold standard deviation of the measuring quantity) can be reduced by the use of robust estimators (e.g. [3])

3.3 New developments

The adequate quantification of error models (e.g. variances, covariance matrices etc.) for measured respectively derived deformation quantities is an important precondition for the creation of deformation models. In this respect one major task is a realistic error propagation from an epoch t_k to an epoch t_{k+1} which enables the correct evaluation of the calculation results. This can be the application of statistical tests for significant changes in the deformation signal.

In the field of sensor error modelling and creation of stochastic models some new developments are represented by the quantification of synthetic covariance matrices (using so called “elementar error models”, [13] and [15]) and the application of Fuzzy methods for the consideration of remaining non reducible systematics in the error budget (so called “observation imprecision” [11]). In the following a short overview will be given.

3.3.1 Creation of synthetic covariance matrices

Increasing sampling rates of geodetic measurements (e.g. GPS-coordinates) require the consideration of their inter-epochal correlations. One appropriate method is the direct use of the measured time series for the calculation of empirical correlation functions. Practical problems may occur by not sufficient measuring quantities (e.g. in geodetic networks) [13] and the difficult separation of coloured and white noise [16].

An alternative strategy for the determination of correlations and the creation of synthetic covariance matrices is given by "elementar error models" [13]. The stochastic error budget $\boldsymbol{\varepsilon}$ of the measuring quantities is divided into elementar errors $\boldsymbol{\xi}$ and $\boldsymbol{\delta}$:

$$\boldsymbol{\varepsilon} = \boldsymbol{F}\,\boldsymbol{\xi} + \sum_{j=1}^{p} \boldsymbol{D}_j\,\boldsymbol{\delta}_j$$

$$\text{with :} \tag{1}$$

$$\boldsymbol{\varepsilon} = \begin{pmatrix} \varepsilon_1 \\ \vdots \\ \varepsilon_m \end{pmatrix} ;\; \boldsymbol{\xi} = \begin{pmatrix} \xi_1 \\ \vdots \\ \xi_m \end{pmatrix} ;\; \boldsymbol{\delta}_j = \begin{pmatrix} \delta_{1j} \\ \vdots \\ \delta_{nj} \end{pmatrix}$$

$$\boldsymbol{F} = \begin{pmatrix} f_{11} & \cdots & f_{1m} \\ \vdots & \ddots & \vdots \\ f_{n1} & \cdots & f_{nm} \end{pmatrix} ;\; \boldsymbol{D}_j = \begin{pmatrix} d_{1j} & & \boldsymbol{O} \\ & \ddots & \\ \boldsymbol{O} & & d_{nj} \end{pmatrix}$$

In (1) an elementar error ξ_i influences several quantities ε_i and creates the correlations in $\boldsymbol{\varepsilon}$. $\boldsymbol{F}$ quantifies the magnitude of the correlations. $\boldsymbol{D}$ quantifies the individual (non-correlative) influence of elementar errors $\boldsymbol{\delta}$ on $\boldsymbol{\varepsilon}$.

The synthetic covariance matrix $\boldsymbol{\Sigma}$ for $\boldsymbol{\varepsilon}$ is then received in a second step by ordinary error propagation:

$$\boldsymbol{\Sigma}_{\varepsilon\varepsilon} = \boldsymbol{F}\,\boldsymbol{\Sigma}_{\xi\xi}\,\boldsymbol{F}^{\mathrm{T}} + \sum_{j=1}^{p} \boldsymbol{D}_j\,\boldsymbol{\Sigma}_{\delta\delta}\,\boldsymbol{D}_j^{\mathrm{T}} \tag{2}$$

The practical application of (1) and (2) for temporal correlated GPS measurements with an explicite synthetic modelling of $\boldsymbol{F}$, $\boldsymbol{\xi}$, $\boldsymbol{D}_j$ and $\boldsymbol{\delta}$ is described in [15].

3.3.2 Modelling of "observation imprecision"

Another new approach for the creation of error models is modelling of "observation imprecision". This research field extends the common view of pure random variations (stochastics) in the uncertainty budget of geodetic measurement and analysis processes to the additional consideration of non reducible systematics. This may be remaining systematic errors which could not be eliminated by sensor calibration, measuring design or by parametric extensions in the adjustment model. The basic idea is the creation of fuzzy intervals (e.g. [1]) for the description of the full uncertainty ([11] and [12]). Amongst others this fuzzyfication leads to improved statistical tests in deformation analysis (e.g. for congruence tests of a multi-epoch geodetic deformation network or the detection of outliers in deformation measurements).

An example for a fuzzyfied test is shown in figure 3. The decision for acceptance or rejection of a null hypothesis (e.g. congruence between two epochs) is not only dependent from the absolute position of the imprecise test value T (left or right from a quantile $\chi^2_{1-\gamma}$) but also from the membership *m* to the regions of acceptance (A) or rejection (R). The final test decision is created by the calculation of the areas of acceptance (horizontal stripes) and rejection (vertical stripes) and the comparison (so called "rejectability"). This enables a more precise evaluation of the test results than in standard tests.

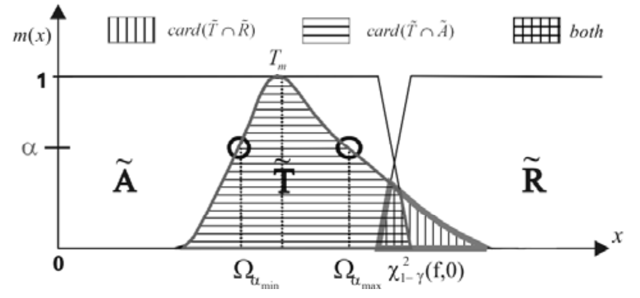

Figure 3 – Fuzzyfied test with imprecise test value T [11]

Diverse examples for the modelling of observation imprecision and the fuzzyfication of tests in monitoring applications are described in [11] and [12].

4. DEFORMATION MODELS

Major goal of the analysis of deformation processes is the creation of realistic deformation models which enable the processing of the following tasks [17]:

- Timely detection of movements and deformations of the measuring object (e.g. building, tunnel, bridge) as precondition for alerting and the application of constructive measures.
- Confirmation of functionality and stability.
- Conservation of evidence in case of damage.
- Investigation of the inner structure of the object (e.g. material properties).
- Detection of major influence quantities (e.g. temperature or wind loads).
- Prognosis / simulation of defomations under static or dynamic loads.
- Collecting knowledge for planning of similar constructions.

4.1 Classification of geodetic deformation models

According to [18] geodetic deformation models are divided into four groups: Congruence models, kinematic models, static and dynamic models (see figure 4). Congruence and kinematic models are restricted to the pure geometrical description of the deformation process. They do not contain any influence quantities like temperature, wind or traffic loads. Examples for these descriptive models are given by the common analysis of deformation networks (e.g. by congruence tests etc. [13]).

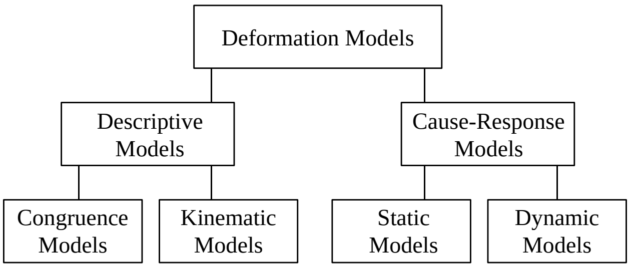

Figure 4 – Classification of deformation models [18]

Cause-response deformation models quantify the reaction of the construction to external influence quantities. Depending on the kind of loading (static or dynamic) and the interested frequency domain of the deformation signals static or dynamic models are quantified.

Cause-response models can be non-parametric or parametric [18]. Non-parametric models are directly derived from measured influence (input) and deformation quantities (output). Typical examples are weight functions and ARMA-models (see section 4.2) or neural networks (see section 4.3). Parametric models require an underlying physical model. They are quantified by systems of partial or ordinary differential equations and represent the inner structure of the construction. Examples are given by numerical models like Finite Element (FE) or Finite Difference (FD) models.

4.2 State of the art

One part of the state of the art of geodetic deformation models can be focussed on the use of descriptive models (see section 4.1) for the analysis of the temporal behaviour of deformation networks (e.g. control networks for dams, mining or tunneling).

The other part is represented by non-parametric models. Geodetic monitoring data is used for the quantification of transfer functions which quantify the relation between acting loads and the resulting deformations. In most cases the deformation processes are assumed to be stationary and the transmission behaviour to be linear (in a close environment of a mean working point). Typical geodetic applications of non-parametric models can be found in thermal deformation analysis with weight functions *g* (e.g. [14])

$$y(t) = \int_0^\infty g(\tau)\, u(t-\tau)\, d\tau \tag{3}$$

and ARMA models (e.g. [6]).

$$\begin{aligned} y(t_k) = {} & a_1\, y(t_{k-1}) + a_2\, y(t_{k-2}) + \dots + a_q\, y(t_{k-q}) \\ & + b_0\, u(t_k) + b_1\, u(t_{k-1}) + \dots + b_p\, u(t_{k-p}) \end{aligned} \tag{4}$$

Eq. (3) and (4) are specified for a single input and a single output quantity with $u(t)$ representing the temporal progress of the thermal load and $y(t)$ the resulting deflection.

One big problem of non-parametric models is their limited capability for prediction. Significant changes in the progress of the loads may lead to wrong calculation results and require a re-calibration of the model parameters.

Applying AI-methods newest developments aim at improving the non-parametric models. On the other hand parametric models are created for the quantification of realistic deformation predictors and simulators.

4.3 New research fields

New developments in geodetic deformation modelling are focussed on two research fields:

- Application of AI-methods.
- Creation and calibration of parametric models.

Artificial neural networks are promising tools for the creation of effective non-parametric models. They are used for the creation of multi-input / multi-output (MIMO) systems (see figure 5). Typical inputs are temperature, water-level variations or traffic volume. Outputs are deformation quantities like displacements of material points (e.g. [10]).

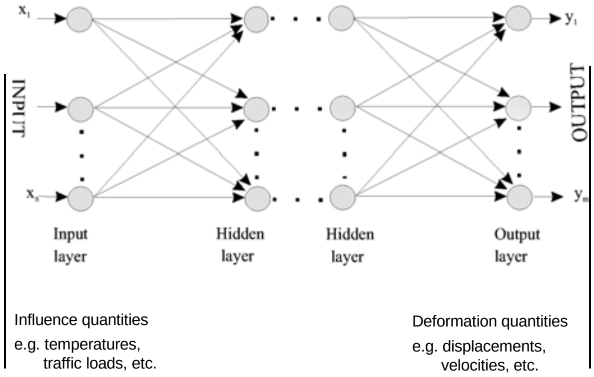

Figure 5 – Multi-layer neural network, MIMO system [10]

Figure 6 shows the efficiency of a trained neural network for deformation modelling of a control point at a bridge under various loads (e.g. traffic and river water level variations).

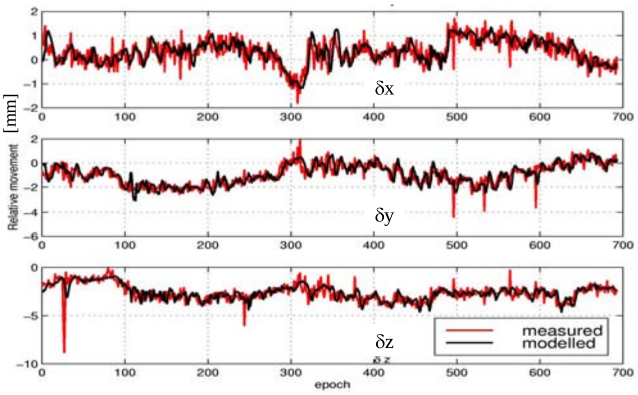

Figure 6 – Measured and modelled displacements [10]

In cooperation with civil or mechanical engineers parametric deformation models are created as static or dynamic FE / FD models. One basic problem is the determination of realistic physical model parameters (e.g. Young’s modulus, Poisson’s ratio, temperature expansion coefficient etc.). The application of adaptive Kalman-filtering techniques (e.g. [4] and [8]) is a suitable strategy to do this job. It combines the theoretical parametric model with empirical deformation measurements and enables the optimal estimation of the model parameters.

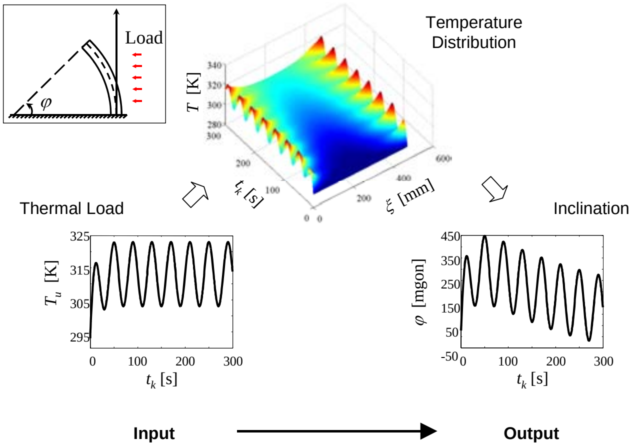

Figure 7 – Thermal bend of a machine tool [4]

In figure 7 an application from mechanical engineering is presented. It shows the simulation of the thermal deformation (thermal bend) of a bar-shaped machine tool under dynamic thermal loading.

5. CONCLUSIONS AND PERSPECTIVES

The new research fields in geodetic deformation analysis will require an increasing teamwork of geodesists and civil respectively mechanical engineers. This is and will be realized by cooperations in commercial projects (third-party funds) and research projects (e.g. European Union funding). Effective work is done since about 20 years in the fields of mining, dam and bridge control. New measurement and analysis strategies open the gate to structural engineering and industry. Geodetic deformation analysis is full integrated into complex construction concepts.

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