# 50 Years of Deformation Monitoring - What has been achieved?

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**Abstract**

In 1975 the "1st International Symposium on Deformation Measurements with Geodetic Methods" took place in Krokow, Poland, organised by FIG. I had the pleasure to attend this meeting and most of the subsequent symposia in this series.

In this paper I'll give a – personally biased - overview on the advances in the field of geodetic deformation studies from 1975 till today. There is an impressive progress in sensor technology as well as data capture and data analysis, as in 1975 modern systems, e.g. GNSS, Lasercanning or UAVs, are not at all visible at the horizon. The same is valid for data preprocessing and analysis: Automated data storage devices or online processing as well as advanced computational methods including AI applications were unknown. In the area of deformation modelling several advances can be reported, but challenging tasks still remain. Some remarks regarding competence and acceptance of our profession finalize the paper.

***Keywords***: Progress in sensor technology, Advanced analysis methods, Deformation modelling

## 1 Introduction

In the Oxford Dictionary a still valid definition of monitoring is given:
*"To observe, supervise, or keep under review, to measure or test at intervals, especially for the purpose of regulation or control, or to check or regulate the technical quality of something."* This definition includes:
i) to take those observations at an object, that are relevant for an assessment; regular intervalls or continuous measurements are possible,
ii) to compare the results with normal or irregular behaviour of the object, i.e. to take conclusions on the functionality and safety of the object; if required to give steering information to correct an abnormal behaviour,
iii) the sensor and processing system has to be complete, of sufficient quality and physically stable over the necessary period of monitoring.

Already in 1975 FIG Commission 6 "Engineering Surveys" was aware of this challenge and organised the "1st International Symposium on Deformation Measurements with Geodetic Methods" in Krakow, Poland with support of the local University. This happened during the times of "Cold War" between East and West; for young scientists it was one of the few possibilities to meet colleagues from the other side of the iron curtain.
At that time FIG had three official languages, English, French and German, what makes it necessary to have simultaneous translations during the conference.
As presentation techniques diapositives, overhead slides and blackboard with chalk were available; some speakers made a real oral presentation or were just reading their manuscript.

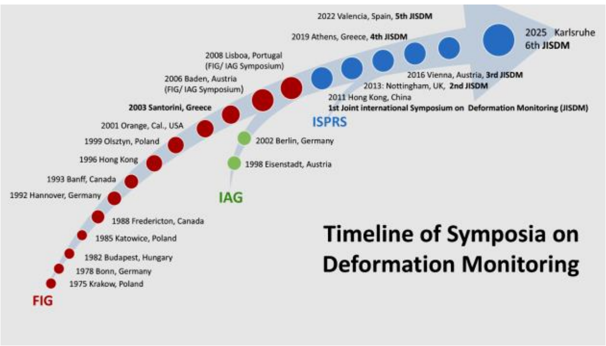


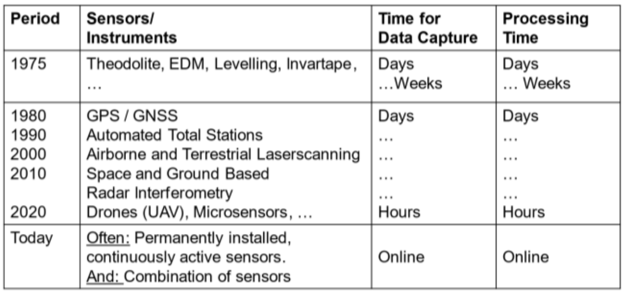
Figure 1: Symposia on Deformation Monitoring

As depicted in Fig. 1, there is a long tradition of these symposia on deformation measurements and analysis. For the first decades FIG was the only organizer, the topics were oriented to engineering structures and local geoobjects, mainly. Since 2006 FIG and IAG combined their activities, what led to an inclusion of earth system related aspects in the symposium. These co-called combined symposia in Baden/Austria and Lisboa led in 2011 to the new and still valid format: “Joint International Symposium on Deformation Monitoring”. In 2016 ISPRS became integral part of this symposia series, beeing aware that a lot of common interests exist, mainly in the application of laserscanning, drones and radar interferometry.

## 2 Overview on technological and conceptual developments

In 1975 the main geodetic instruments resp. observation techniques for monitoring were classical theodolites, electronic distance meters (EDM), levelling systems and special devices, e.g. for dam monitoring “alignement systems” and for tunnel convergence measurements “invar bars”.

In the following decades a lot of modern sensors and related observation techniques appeared, which had a tremendous influence on the set-up of monitoring systems, data capture and processing concepts. Main effect is that the “speed” to get results has increased dramatically, i.e. the processing time is reduced from weeks to online results in modern applications.These developments are depicted in summary in Fig. 2, being aware that this figure is not complete and it is personally biased!



| Period | Sensors/ Instruments | Time for Data Capture | Processing Time |
|---|---|---|---|
| 1975 | Theodolite, EDM, Levelling, Invartape, … | Days<br>…Weeks | Days<br>… Weeks |
| 1980<br>1990<br>2000<br>2010<br><br>2020 | GPS / GNSS<br>Automated Total Stations<br>Airborne and Terrestrial Laserscanning<br>Space and Ground Based<br>Radar Interferometry<br>Drones (UAV), Microsensors, … | Days<br>…<br>…<br>…<br>…<br>Hours | Days<br>…<br>…<br>…<br>…<br>Hours |
| Today | Often: Permanently installed, continuously active sensors.<br>And: Combination of sensors | Online | Online |

Figure 2. Overview on developments in geodetic deformation monitoring from 1975 till today

Aside from technological developments one aspect of geodetic work is fundamental, as it is unique within all disciplines that deal with monitoring aspects. As depicted in Fig. 3, only with geodetic techniques one can monitor the behavior of an object from outside, i.e. one can detect so-called “absolute” displacements and not just “inner” or “intrinsic” deformations.

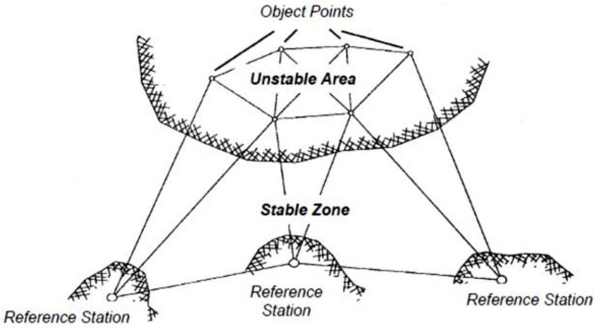


Figure 3. Fundamental demand: Search for a stable reference in geodetic monitoring

This search for a long-lasting *stable datum*, valid at least for the duration of a monitoring project, is one of the most challenging demands since 1975.

### 2.1 Networks approach

The classical concept for monitoring still is to establish a geodetic network with sufficient target points to represent the object and a limited number of reference stations, which are supposed to lay outside the influence area, i.e. to be stable. To get the observations for one timestamp (epoch) often field campaigns of days or weeks were required, where all sensor and environmental data were achieved manually in field books.
For monitoring of a dam - see network sketch in Fig. 4 - in general two epochs per year were necessary. For studying crustal motions - see Fig. 5 - it was only realistic to take observations with time intervalls of a few years.

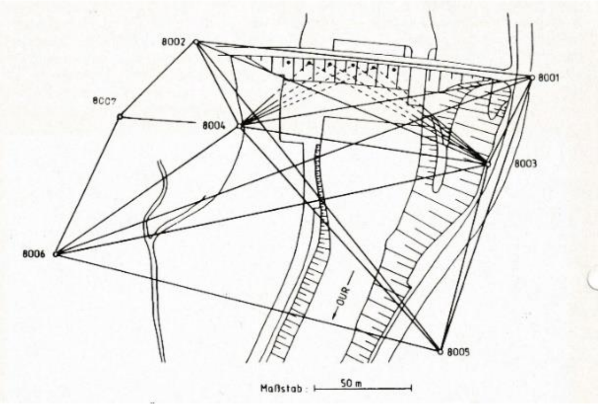


Figure 4. Monitoring network Lohmühle Dam, Luxemburg, with reference and object points

To detect tectonic displacements often a network is used, similar to the sketch in Fig. 5. Here the problem is, that no part of the network can be considered as stable a priori. As long as relative observation techniques are applied, it is only possible to determine displacements of the left side of the fault system relative to the right section or of the right side relative to the left section. This means, here just relative displacements can be derived; but for most geophysical interpretations (e.g. local tension, strain) this is the information in question!

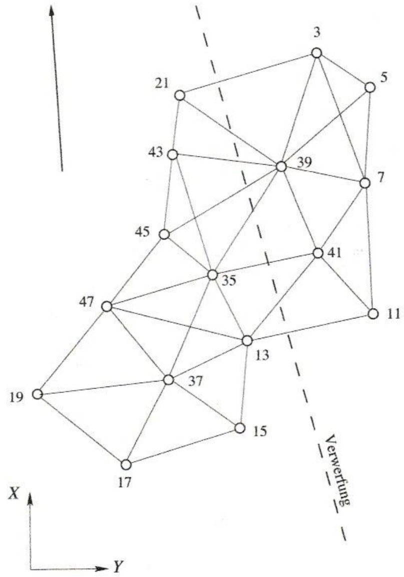


Figure 5. Monitoring network to detect displacements at a fault
(*Delft test net*, Niemeier 2008))

## 2.2 Area-related concepts

Further development steps are regarding the completeness of the object to be covered by the geodetic information. With networks, as given in Fig. 4 and 5, a so-called *point-related approach* is followed, where just a few points are selected to represent the behaviour the structure. In modern applications with e.g. laserscanning, digital cameras or radar interferometry, an *area-related approach* is possible, which allows to monitor a structure as complete as possible.

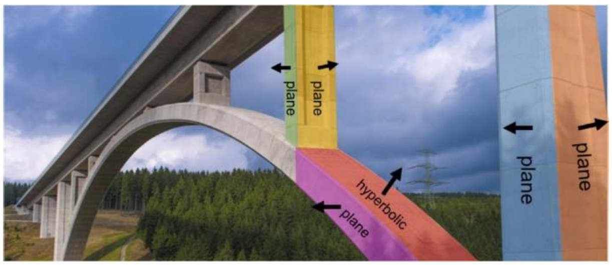


Figure 6. Capture and monitoring of a bridge surface with terrestrial laserscanning
(Wunderlich et al. 2016)

In Fig. 6 an area-related concept is depicted for monitoring of a concrete bridge with terrestrial laserscanning. The processing steps:

- Segmentation of the structure by mathematical functions (areas with position and orientation)

- Repeated determination of the parameters of each function, i.e. for times $t_1$, $t_2$, ...$t_n$.
- Application of congruency tests (see section 3.2.1) for the parameters of each segment between epochs.

A further technique for area-related monitoring is *space-based radar interferometry InSAR*. In Fig. 7 InSAR is applied with PSIs (persistent scatterers) for determination of displacements of buildings during the construction of a tunnel.

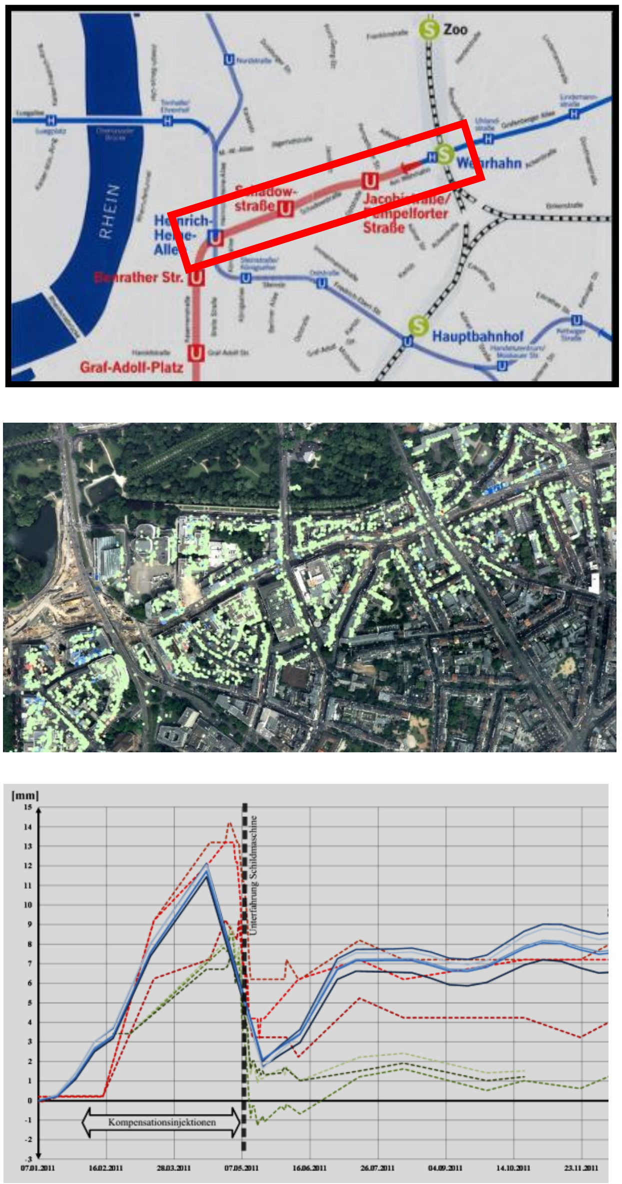


Figure 7. Monitoring of an inner city area with InSAR during tunnel construction
(Mark et al. 2012)

In the upper part of Fig. 7 the project is outlined, being a 1.1 km long section of a new subway line in Düsseldorf/Germany. Main objective was to investigate the interactions between tunnel driving and overlying buildings in a detailed way and to determine subsidence and uplift of buildings during the construction phase.

In the middle of Fig. 7 the used PSIs are depicted, showing that a relatively dense monitoring of the buildings was possible.

In the lower part of Fig. 7 vertical displacements due to "compensation grouting" are studied. By this technique an injection of concrete suspension is performed to avoid heavy damages. It produces an uplift of the building, that will be compensated when the tunnel boring machine passes. In this sketch the vertical displacements of PSIs (blue), levelling (red) and tube water levels (green) are compared to each other for such a compensation grouting phase. They show good coincidence what allows to use InSAR for similar questions. Only disadvantage of InSAR is, that online results cannot be achieved.

### 2.3 Rapid displacements

Important progress is made regarding the potential of geodetic techniques to detect so-called *rapid displacements*. In general, one can differenciate between:

i) *Slow motion displacements*, where the time to take the observations can be neglected. Here it is sufficient to determine the geometry of an object with an intervall of weeks, months or years.

ii) *Rapid displacements*, where online mesurements and online processing are required. For engineering structures here the resolution of the sensors have to be in the range of 1 – 10 Hz, or even higher. These monitoring problems are still not in the main focus of geodesy!

Adequate sensors for monitoring displacements with a frequency of 1 – 10 Hz or higher are e.g. *accelerometers*, *digital cameras*, *MEMS* and - available since about 15 years - *ground based radar systems*.

As example, by application of the ground-based radar IBIS-S a monitoring of the behaviour of a bridge during load tests is presented in Fig. 8 (Lehmann et al. 2013). This system is a real aperture radar within the frequency band Ku and a range resolution of 0,75 m. It is a monodimensional profiler with a resolution of 0,01 – 0,1 mm (depending on distance), a maximum range of 1000 m and measuring rate of up to 200 Hz.

Given in Fig. 8 are the set-up of the system, the vertical displacements due to a load test in total and with high temporal resolution. Out of these data frequency spectra can be derived easily.

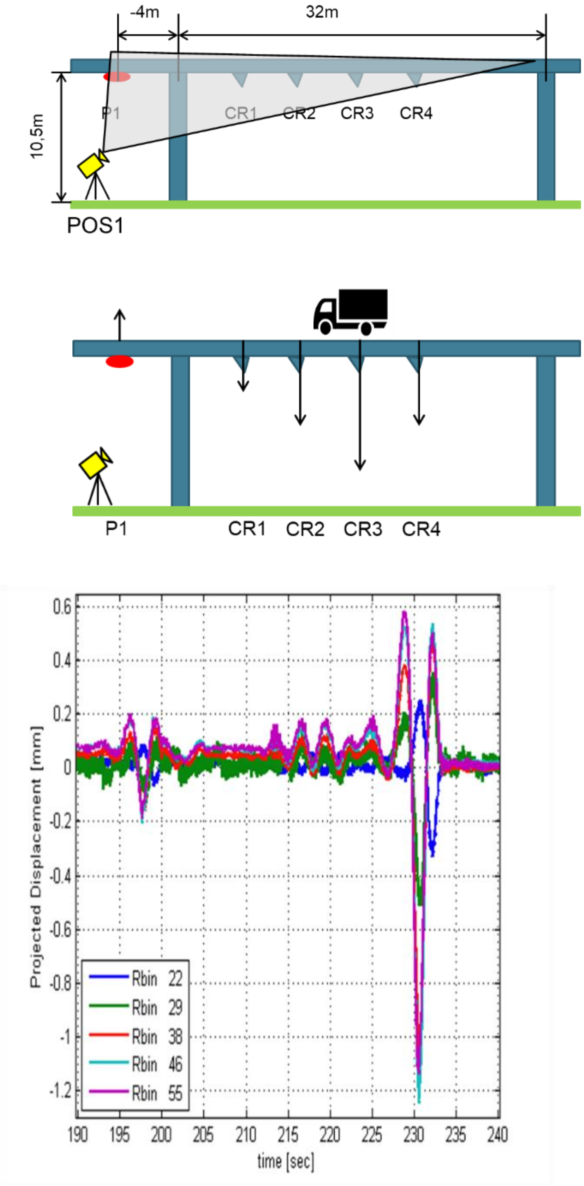


Figure 8. Online monitoring of a bridge with ground based radar (Lehmann et al. 2013)

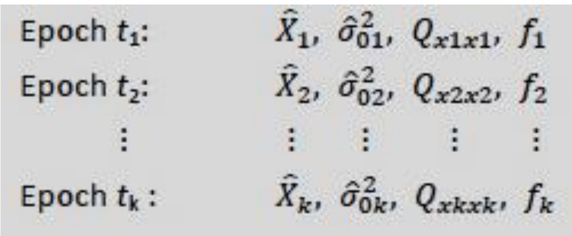
## 3 Modelling of Deformations

### 3.1 Zero step: Parameter sets per epoch

First step in the processing chain within the network approach is the combination of all data of each epoch. The classical concept is a parametric approach applying an adjustment after least squares in a well defined coordinate frame, supported by thorough error detection and variance component estimation. An alternative is outlined in section 4.

As result one gets per observation time (epoch) $t_i$ the coordinate estimates $X_i$, their covariance matrices $Q_{xixi}$, an estimate for the variance factor $\hat{\sigma}_{0i}^2$ and the related degrees of freedom $f_i$.

Table 1. Information on object geometry in k epochs



| | | | | |
|---|---|---|---|---|
| Epoch $t_1$: | $\hat{X}_1$, | $\hat{\sigma}_{01}^2$, | $Q_{x1x1}$, | $f_1$ |
| Epoch $t_2$: | $\hat{X}_2$, | $\hat{\sigma}_{02}^2$, | $Q_{x2x2}$, | $f_2$ |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| Epoch $t_k$ : | $\hat{X}_k$, | $\hat{\sigma}_{0k}^2$, | $Q_{xkxk}$, | $f_k$ |

For area-related concepts, according to the principle depicted in Fig. 6, the parameters of the selected area functions are estimated instead of coordinates of points.

## 3.2 Selection of displacement models

This is one of the main aspects in all deformation monitoring tasks. Of course, before starting a monitoring project, one has to have an idea on the potential displacements: A priori knowledge on magnitude, direction, character of movements and the influenced area are essential to set-up an adequate monitoring system.

### 3.2.1 Congruency tests

In 1975 and for a long time just the deviations between two or more data sets (see Table 1) were analysed. Here a step forward was made by Hans Pelzer (1971), who derived a rigorous statistical test concept, based on variance analysis. The tests answer the question whether or not the found geometrical differences between the coordinates in two epochs are statistically significant or not. As these test analyse deviations from identity, see Fig. 7, they are known today as *congruency tests*. The deformation model is simple: Congruency/Identity over all epochs, i.e. stability of network points or stability of sections in an area-related approach.

A congruency test consists of two phases: At first in a *global test* the oberall existence of significant displacements is checked. In a second step by *localisation tests* those individual points or group of points are identified by adequte testing, that have significant displacements.

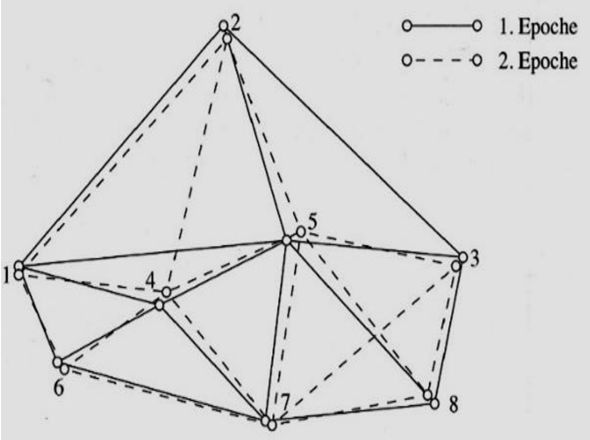


Figure 9. Principle of congruency tests (Niemeier 2008)

During the last decades more sophisticated analysis techniques were developed, e.g. *Msplit-estimations* (Zienkiewicz 2019), which are a more detailed analysis concept.
By *sequential multi-epoch analysis (Niemeier 2008)* a comparing of epochs 1-2, 2-3, 3-4 or 1-2, 1-3, 1-4 are performed in a rigorous manner.
In geophysics often *strain computations* (Fagan and Postema 2007). are performed, based of identical type of observations in all epochs.
By *clustering* (e.g. Fletling 2010) groups of points are looked for, which show similar behaviour, i.e. one looks for displacement pattern in the data.

A lot of software systems are developed, based on these congruency tests, as this concept is still the standard analysis tool.

### 3.2.2 Linear movements

For vertical movements studies of larger areas the most common concept for modelling of displacements is the assumption that some or all object points have a *linear movement*. If some stable areas can be assumed, one can derive e.g. a map of vertical movement rates, as depicted in Fig. 10 for Northern Germany. (Wanninger et al. 2009). Here information from GNNS stations and repeated levellings were combined, the displacement model is simplified by:

$$X_t = X_{ref} + \dot{X} \cdot (t - t_{ref}) = X_{ref} + \Delta X_t$$

In additon to this simple formular one assumed a similar behaviour of neighborhoods, modelled by *radial basis functions*, and seasonal effects near to the coastlines, modelled by *periodic functions*.

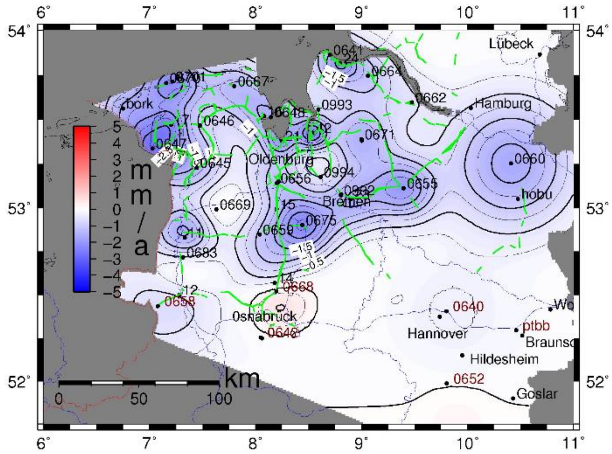


Figure 10. Vertical movement rates in Northern Germany, derived from GNNS and Levelling (Wanninger et al. 2009)

## 3.3 Neural Networks

For about 10 years we monitored an old bridge in the city of Brunswick/Germany by an automated total station, which took 3D-measurments to 180 object points 3-times a day. The instrument was positioned below the bridge itself and its position and orientation had to be controlled each time by using a reference net of 4 pillars, see Fig. 11. The stability of these pillars was testesd periodically and refraction effect had to be considered, as the observations were taken close to the water level.

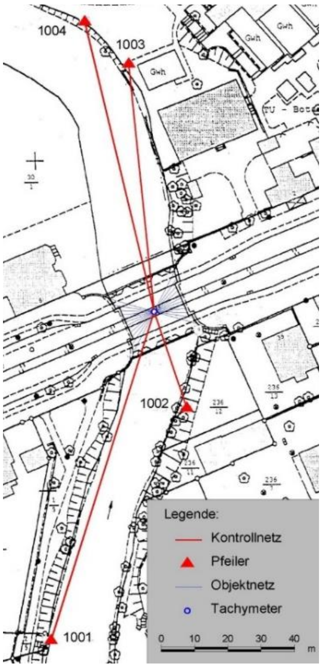


Figure 11. Monitoring network for automated control of a bridge in Brunswick (Heinert and Niemeier 2007)

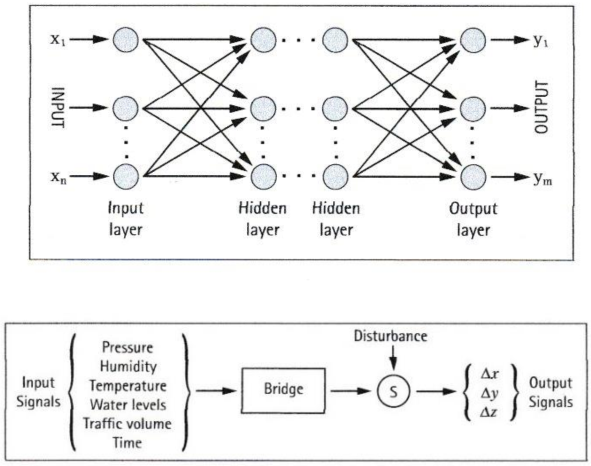


Figure 12. Modelling the behaviour of a bridge as neural network. (Miima and Niemeier 2004)

We tried to model the behaviour of the bridge according to systems theory. Therefore we registered - as possible influence factors - air temperature and pressure, humidity, water level and traffic volume parallel to the displacements rates x, y and z. Out of these data records for about 3 years it was possible to feed a neural network, designed as multilayer feed-forward system, given in the upper part of Fig. 12.

With these given relevant (?) influence quantities as input values and the displacement rates as output it was possible to decribe the behaviour of the bridge and to predict it for about 3 month just using the input quantities!

Criticism was focussed on the number of learning data sets, as we had just 3 full seasons with data. Second aspect is that this model is just an approximation within the given range of input data, i.e. every external resp. extrem situation is not covered.

Anyway, the application of AI-technologies is promising and one of the big challenges for future monitoring projects. *Here intensive research has to be initiated by our community!*

## 3.4 Physical Modelling

A big challenge for the geodetic community is an adequate participation in relation to physical modelling of structures. Nowadays, this mechanical or physical modelling is done by finite-element-analysis (FE-analysis), and here displacements are secondary terms, only.

In Buffi et al., (2017) the behaviour of the Ridracoli dam in the Appenines/Italy is studied, where - due to a high earthquake risk - the dynamic characterization is essential, i.e. the monitoring system consists of accelerometers, strain gauges and pressure cells; not geodetic techniques.

But the main input catagories for a structural analysis are the *geometry*, the *material properties* and the *acting forces*, and here an active and important input can be generated by our profession: A detailed survey by UAV, supported by total stations, GNSS and laserscanning, allowed the definition of a high-fidelity 3D geometry model of the structure, the foundation area and the surrounding rock and site topography. This model served as input in the FE-analysis.
In Fig. 13 in white the vertical contraction joints are given, which are modelled with cm accuracy and which are important elements in the FE analysis.

In Fig. 14 the complete geometric mesh of the FE analysis is depicted, derived at the surface by UAV survey. The base of the FE model is placed at depth of 150 m and is assumed as a rigid, perfectly rough body. The interaction of the dam to the foundation, the rock mass and site topography is modelled by “tie” constraints:
*Here a precise geodetic monitoring can support the validity of such assumptions!*

Figure 13. UAV survey of the Ridracoli dam structure lines (Buffi et al. 2017)

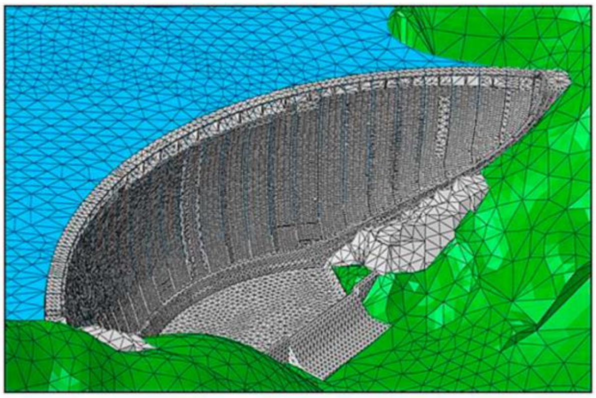


Figure 14. Details of the geometry of the FE model on the dam structure (Buffi et al. 2017)

## 4 Combination of Sensors

For decades the processing and analysis of sensor data was made separately, i.e. each sensor came out with its own results. Often these results did not fit to each other sufficiently, mainly caused by missing point identities, different coordinate systems or variable displacements.
The combined processing of different sensors is a laborious tasks, as the data are collected in different times, see Fig. 15, and the local assignment between point and area related information is not simple.

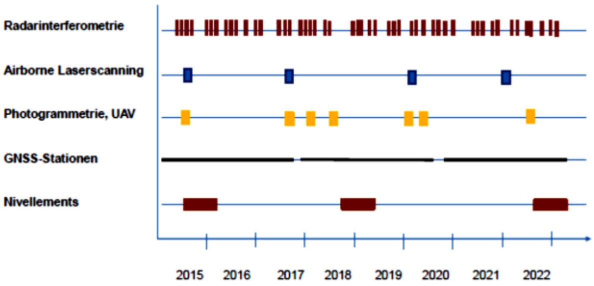


Fig. 15. Data collection of different sensors during a monitoring project.

For long time the combination of sensor data was performed in an extended and often sophisticated *functional model* with lots of assumptions, see e.g. in section 3.2.1. As alternative in Fig. 16 a so-called *geostatistic approach* is outlines.

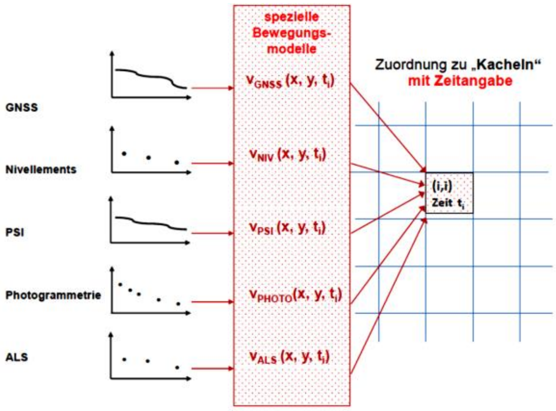


Figure 16. Geostatistical concept for combination of different sensors

The vehicle to do this is the use of tiles or patches, i.e. to split-up of the surface of an object in regular areas of m x m for structures or 10m x 10 m or more for parts of the earth surface. The information, derived for each sensor individually, is assigned to the corresponding patch using e.g. a linear model or directly velocity information. This approach was applied already for combination of levelling data and InSAR results in Rieken et al. (2019), but should be used much more in geodetic monitoring.

## 5 Summary

What has been achieved after 50 years of deformation monitoring?

- There is a tremendeous progress in sensor technology, a huge amount of new and powerful sensors are added to our portfolio. In addition , due to technological progress, the time required for data capture and processing is reduced dramatically.

- The range of potential applications is extended, aside from network-based concepts nowadays we have valuable area-related applications and we made real progress in the domain of rapid displacements.

- In the modelling of deformations the basic technique still is the well established congruency test, but there are more complex approaches with advanced movement models, as well. First applications of neural networks are successful, but the use of modern *artificial intelligence (AI)* techniques should be emphazied during the next years.

- The pure functional combination of sensor data is often laborious and requires assumptions; here geostatistical concepts may support our work.

Real progress was been achieved, but I want to state that geodetic deformation monitoring still is and will be a demanding discipline. We have real competence to do moniitoring work, but we have to work hard to acquire an adequate position within the various disciplines that claim to be experts in deformation monitoring.

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