GPS-BASED ONLINE CONTROL AND ALARM SYSTEM (GOCA)

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Abstract

A GPS-based online control and alarm system (GOCA) for the monitoring of three-dimensional movements has been developed at the Karlsruhe University of Applied Sciences in cooperation with the EuroNav, Wunstorf. The GOCA hardware consists of an array of GPS sensors and communication units to be placed in the monitoring area. The hardware dependent control software communicates with the GPS sensors and provides the GPS baseline data and covariance information to the GOCA deformation analysis software. The GOCA center, which comprises both the control software and the GOCA software, may be linked over a long distance to another PC which serves as a remote control station. GOCA is able to provide the full capabilities of a classical deformation analysis online. The stations are grouped into stable points and moving object points. The object points are determined with respect to the stable points by a network adjustment which is performed for each interval of data collection. The coordinate and covariance information may optionally be transformed into a specific reference system (e.g. the building system). Unstable reference points are to be detected by statistical tests.

Concerning the modeling of the object point field, the basic version of GOCA performs a so-called geometrical deformation analysis. For each object point, displacement, velocity and acceleration is computed by a Kalman-Filter-approach. Simultaneously object point time series, used as model observations are filtered with respect to gross errors using robust estimation techniques. Based on the results of Kalman-Filtering the probability for a critical state at the object, which is predefined by the user, is computed. If one of those probabilities reaches a given value, an alarm is sounded by the GOCA-Software.

The contribution treats an outlook on the further development of deformation analysis models in the direction of a system analysis. While a so-called "geometrical deformation analysis" presently realized in GOCA aims at the mathematical modeling of the objects displacement field and related standard functions in a descriptive mode, a system analysis related deformation analysis is directed to take the systems differential or integral equations into account. The principle is to refer the recorded displacements as an input of "the system", which is done on the base of a so-called black box, a grey box or a discrete way of a mathematical treatment of a system and to identify and/or to calibrate completely or by parts the system and deformation characteristics respectively. An installation example concerning the online monitoring of a building in a coal-mining area is pointed out.

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1. Introduction

GOCA uses GPS vector observations for the real-time monitoring of movements on the earth's surface, of geotechnical structures, buildings and the environment (see fig. 1).

It can be set up as an early warning system when anticipating natural hazards such as land slides, volcano activity and earthquakes. For example, the cost of damage solely caused by land slides presently reaches an amount of US$15-20 billion per year world-wide (Krauter, 1998). Using GPS for the online monitoring of danger zones can contribute to the prevention of disasters.

The GOCA hardware consists of a set of GPS sensors and communication units set up in the monitoring area. GOCA accepts standard DGPS baseline output. The "GOCA-Center", which consists of a personal computer and a data link device, collects and evaluates the DGPS data further. Any of the local GOCA-Center units may be linked over a long distance to another PC, e.g. by an ISDN telephone link. The linked PC serves as a remote control station. In this way several local or regional projects can be monitored simultaneously. GOCA may be set up in an object area as a permanent array or as a mobile "task force system" in areas where danger becomes imminent.

A so-called geometrical deformation analysis was implemented in the basic version. This includes modeling and statistical testing of the object's displacement field, computing related functions (e.g. velocity, acceleration etc.) and trend estimations.

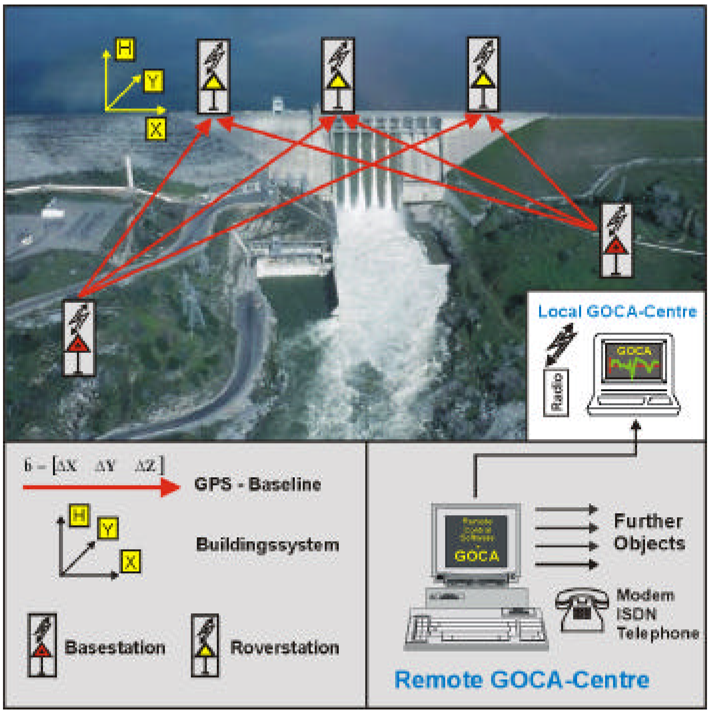

Figure 1: GOCA-Principle

Additionally a system analysis approach is in development to take the object's system equations and respective system parameters into account.

2. Basic Objectives and Requirements for a GPS-based Online Monitoring System

A major goal of GOCA is the online modeling of a classical deformation network. This includes an absolute deformation network. In such a network the object geometry (coordinates of moving stations) $\mathbf{x}_O$ is determined by relative measurements $\mathbf{l}$ of the type 'vector observation' with respect to a reference system $\mathbf{x}_R$. All observations $\mathbf{l}$ which may – according to the GPS station design – either take place between the reference points $\mathbf{x}_R$ or between the object points $\mathbf{x}_O$ or between reference points $\mathbf{x}_R$ and object points $\mathbf{x}_O$ are included in an online sequential network adjustment. The observations $\mathbf{l}_i$ and $\mathbf{l}_j$ performed at different periods t_i and t_j accordingly imply the determination of the coordinates $\mathbf{x}_{Oi}$

and $\mathbf{x}_{Oj}$ of the object points $\mathbf{x}_O$ relative to the reference points $\mathbf{x}_R$. Simultaneously the total set of all observations allows the control of the reference frame $\mathbf{x}_R$.
At period t_i the observations $\mathbf{l}_i$ are the GPS baseline vectors (fig. 1) together with their respective 3x3 covariance matrices $\mathbf{C}_{li}$. For two successive periods we get the following system of observation equations (**A** = design matrix):

$$\mathbf{l}_i + \mathbf{v}_i = \mathbf{A}_{Ri} \cdot \mathbf{x}_{Ri} + \mathbf{A}_{Oi} \cdot \mathbf{x}_{Oi} \text{ and } \mathbf{C}_{li} \tag{1a}$$
$$\mathbf{l}_j + \mathbf{v}_j = \mathbf{A}_{Rj} \cdot \mathbf{x}_{Rj} + \mathbf{A}_{Oj} \cdot \mathbf{x}_{Oj} \text{ and } \mathbf{C}_{lj} \tag{1b}$$

Upon imposing the stability constraint $\mathbf{x}_{Ri} = \mathbf{x}_{Rj} = \mathbf{x}_R$ we obtain the vectors of the object coordinates $\mathbf{x}_{Oi}$ and $\mathbf{x}_{Oj}$ at different periods relative to $\mathbf{x}_R$ and the respective covariance matrix from the least-squares solution. At present the minimum period of the GOCA-System is $\Delta t_{min} = 15\text{s}$. GOCA can carry out online computations of the time dependent vector $\mathbf{x}_O$, the respective object point displacement field **u**, its derivatives, and other deformation functions $f(\mathbf{x}_O)$.

3. Hardware and Communication designs

Presently the GOCA-System is operating with Trimble single frequency receivers 4600LS (fig. 2), with the Leica 200/300 systems or with the so-called "GOCA-receiver" recently developed by the co-operation partner EuroNav (fig.3). Generally the GOCA-Software can be enabled with any GPS receiver system because there is a clearly defined data structure for the software interface. The power can be supplied from 12 V batteries, solar panels or a fixed outlet.

Figure 2: GOCA operating with a Trimble 4600LS receiver and a Trimtalk radio modem in a landslide area

The data from the GPS reference station(s) are transmitted to the GPS rover sensors where the baselines are computed. The estimated baseline vectors **l** and the related information are transferred to the GOCA-Center by means of radio modems. In the case of a permanent installation it is also possible to transmit data by a fixed cable network.

The control software, MONITOR, is responsible for controlling communication with the GPS receivers (Kälber et al., 1999a,b, 2000). MONITOR is able to set the rover sensors in a static mode and then carry out the static baseline processing using carrier phases. The estimated baseline vectors and their covariance matrices are transmitted to the GOCA-Center for use in the deformation analysis. The GOCA-Center is also able to handle NMEA format using an interface software called LeGoTerm.

3.1. Software Interface between Control Software and GOCA-Software

For the system to function with any GPS hardware, the GOCA-Software has a well-defined software interface. A complete data set must contain, as a minimum, the following information:

- Identification of base station and rover sensor
- Time of registration
- Cartesian vector components between stations
- Covariance matrix for individual vectors.

3.2. Hybrid System Design and Data Management in GOCA

As shown in fig. 4, it is possible to use GOCA in network configurations which use permanently occupied points, as well as points which are occupied intermittently. Such a hybrid configuration may be best suited when cost is an issue (minimizing the number of receivers) or to prevent destruction of GPS sensors in dangerous locations.

The baselines are estimated for each individual occupation period. Time series are derived for all object points covering all occupation periods in a sequential network adjustment

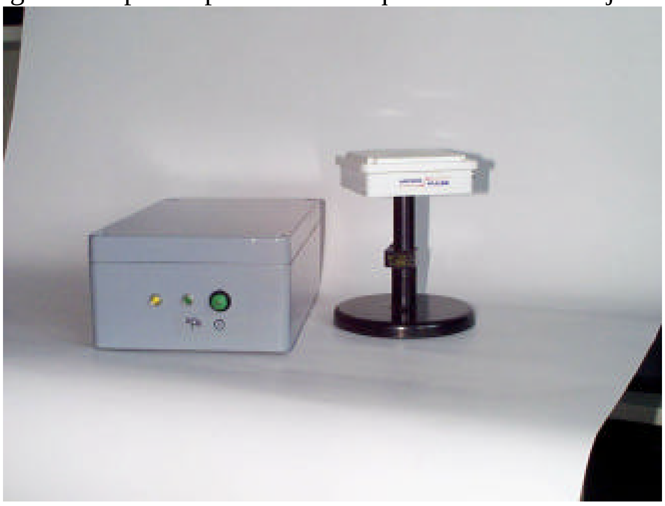

Figure 3: GOCA DGPS-receiver constructed by EuroNav

When the moving rover sensor occupies a reference point, the data is used for checking the stability of the reference points.

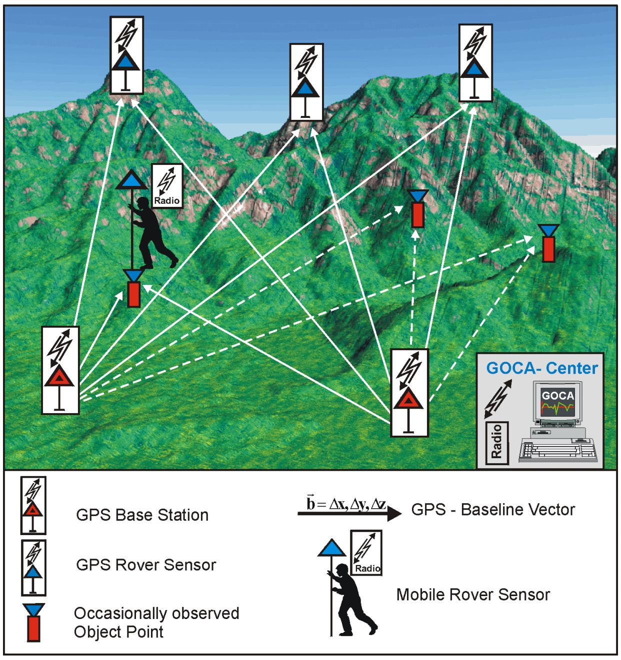

Figure 4: Hybrid system design

4. Monitoring and Deformation Analysis of GOCA

4.1. Project Setup

The GOCA-Software, written for the Windows 95/98/NT operating systems, is able to organize projects, i.e. project specific information is stored in a particular file. Therefore it is possible to interrupt a specific project for a period of time and to continue monitoring later without loss of information. A project setup includes specifying the deformation network design, i.e, setting the attributes "stable point" or "object point" for each rover sensor and for the base stations (fig. 5), as well as the definition of a local reference system.

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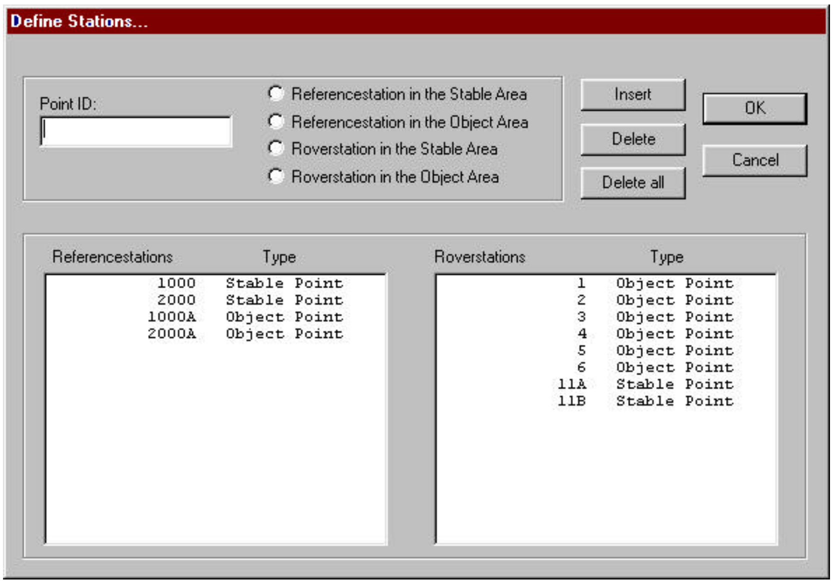

Figure 5: Specification of the GPS sensor attributes

4.2. Project Initialization – Determination of a Reference Frame

During the project initialization phase the coordinates of the reference system $\mathbf{x}_R$ are determined by least squares estimation in a free network adjustment using the observations $\mathbf{l}$ from the initial period, e.g. the first day of data collection. Object points $\mathbf{x}_O$ are introduced as epoch unknowns with respect to a user prescribed time interval Δt. The result of this adjustment are the coordinates of the reference points $\mathbf{x}_R$ and their covariance-matrix $\mathbf{C}_{XR}$. They are stored in an internal database. The object point coordinates are further determined in reference to these stable points. Additionaly they are used to determine the transformation parameters to enable transformation to the local system (e.g. the coordinate system of the structure).

4.3. Checking the Stability of Reference Points

To ensure a stable reference system during the monitoring, the quality control processes in GOCA include the checking of reference points. This is based on a deformation analysis in the observation-related model (1a,b). This procedure is carried out with respect to two observation periods t_i and t_j (e.g. the first day of observations and the actual monitoring day). The common reference points $\mathbf{x}_R$ are introduced just once as unknowns, whereas the object points $\mathbf{x}_O$ are introduced with individual coordinates $\mathbf{x}_{O,i}$ and $\mathbf{x}_{O,j}$ with respect to an individual prescribed time interval for each period. With the general congruency condition $\mathbf{x}_{R,i} = \mathbf{x}_{R,j} = \ldots = \mathbf{x}_{R,m}$ of m peroids, the state vector of the object points and the related covariance-matrix $\mathbf{C}_X$ of the deformation network, referring to the reference datum $\mathbf{x}_R$, is determined.

To detect deformations ∇_{XR} at the reference points, an a posteriori variance related test statistic is computed for each reference point (Kälber et al., 1999 a,b; Kälber and Jäger 2000a,b). An estimated value for the deformation ∇_{XR} is computed and tested for significance. This is based on the extension of the design-matrix $\mathbf{A}_R$ (1a,b) with respect to the part of a gross error design matrix $\mathbf{A}_{\nabla R}$ referring to the respective reference point. The significance test for ∇_{XR} is:

$$T = \frac{\nabla^T_{x_R} \cdot \mathbf{Q}^{-1}_{\nabla_{XR}} \cdot \nabla_{x_R}}{b \cdot \hat{\sigma}^2} \sim F_{b,r-b} \tag{2}$$

$F_{b,r-b}$	Fisher distribution,
r	redundancy
b	dimension of the network with b = 2 (plan) and b = 1 (height),
∇_{x_R}	estimated gross error for reference point $\mathbf{x}_R$,
$\mathbf{Q}_{\nabla_{x_R}} = \left(\mathbf{A}^T_{\nabla R}\mathbf{P}\mathbf{Q}_v\mathbf{P}\mathbf{A}_{\nabla R}\right)^{-1}$	cofactor matrix of the estimated gross error,
$\mathbf{A}_{\nabla R}$	design matrix for estimation of ∇x_R,
$\mathbf{P}, \mathbf{Q}_v$	weight and cofactor matrices of the residuals of the baseline observations **l** in model (1a,b),
$\hat{\sigma}^2 = \dfrac{\Omega - \nabla^T_{x_R} \cdot \mathbf{Q}^{-1}_{\nabla_{x_R}} \cdot \nabla_{x_R}}{r - b}$	reduced a posteriori variance factor,
$\Omega = \mathbf{v}^T\mathbf{P}\mathbf{v}$	residual sum of squares.

The testing with (2) for stability of reference points $\mathbf{x_R}$ is carried out as an automated iterative data snooping process for multidimensional correlated observations. The reference point that was detected as unstable by the highest test value is used as an object point in the next adjustment.

5. Basic Modules of a Geometrical Deformation Analysis of Object Point Time Series

GOCA gives first priority and provides basic modules to dealing with the time series $\mathbf{x}_O(t)$ and the functions $\mathbf{f}(\mathbf{x}_O)$ of the object point positions $\mathbf{x}_O$. Different least squares (L2-norm) and minimum absolute deviation (L1-norm) estimation strategies and filters are implemented. The second priority is with three-dimensional displacement, velocity and accelerations of object points $(\mathbf{u}_O, \dot{\mathbf{u}}_O, \ddot{\mathbf{u}}_O)$.

5.1. Filtering and Visualization of Object Point Displacement Time Series

The coordinates of the object points $\mathbf{x}_O$ are estimated by least squares within each sampling interval Δt with respect to the reference frame and datum defined by $\mathbf{x}_R$ (fig. 1). The result is a continuous time series for the object points. The graphics window displays the object point time series for a given time period and a selected object point (fig. 6). Coordinate components time series as well as the results of using various smoothing functions can be selectively visualized (Kälber et al., 1999 a,b; Kälber and Jäger, 2000a,b).

Moving average functions are computed online or postprocessed for a given number of data sets, either by means of least squares, or by other robust estimation techniques (L1-Norm, Huber-estimation). Fig. 6 shows very clearly the benefit of the L1-norm, which helps very effectively to avoid the influence of blunders and respective misinterpretations in the result of the filtering. Polynomials are to be computed by a sequential least-squares adjustment in the online mode. In the postprocessing mode the smoothing by means of splines or polynomials may be done, either by least squares or by robust estimation techniques for a specified object point and epoch.

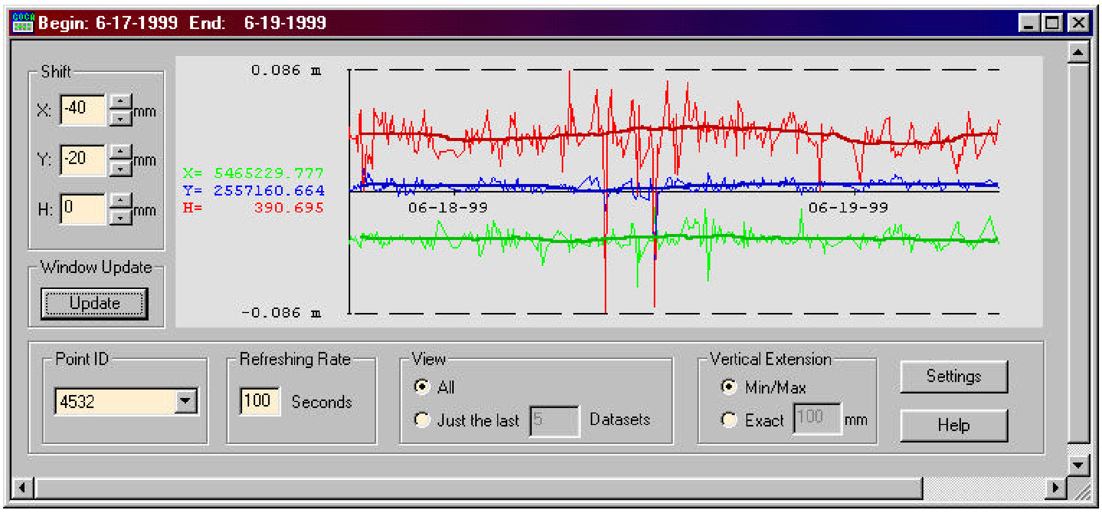

Figure 6: Visualization and robust L1-norm online moving average smoothing of object point time series during monitoring

5.2. Estimation of the displacement, velocity and acceleration field and alerting functionality

Up to now the automatic alarm in GOCA is to be defined by a critical state vector related to $(\mathbf{u}_O, \dot{\mathbf{u}}_O, \ddot{\mathbf{u}}_O)$ namely the displacements $\mathbf{u}_O$ relative to the initial positions $\mathbf{x}_O$ of the object points and the respective velocities $\dot{\mathbf{u}}_O$ and accelerations $\ddot{\mathbf{u}}_O$ (Schneid, 2000; Schneid and Schwäble, 2000; Kälber et. al. 2000; Kälber and Jäger, 2000a,b). The state vector $(\mathbf{u}_O, \dot{\mathbf{u}}_O, \ddot{\mathbf{u}}_O)$ is also in the scope of the geotechnical point of view (Krauter, 1998). Accordingly the threedimensional displacement, velocity and acceleration field of the object points $(\mathbf{u}_O, \dot{\mathbf{u}}_O, \ddot{\mathbf{u}}_O)$ are finally estimated in GOCA using the following state vector transition part in a Kalman filter procedure realized both for L2- and L1-norm:

$$\begin{bmatrix} \mathbf{u}_O(k+1) \\ \dot{\mathbf{u}}_O(k+1) \\ \ddot{\mathbf{u}}_O(k+1) \end{bmatrix} = \begin{bmatrix} \mathbf{I} & [\Delta t] & \left[\frac{1}{2}\Delta t^2\right] \\ \mathbf{0} & \mathbf{I} & [\Delta t] \\ \mathbf{0} & \mathbf{0} & \mathbf{I} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{u}_O(k \\ \dot{\mathbf{u}}_O(k) \\ \ddot{\mathbf{u}}_O(k) \end{bmatrix} \quad . \tag{3a}$$

$[\mathbf{x}]$ means a diagonal matrix. The measurement vector $\mathbf{l}$ and its covariance matrix

$$\mathbf{l}_{k+1} = \mathbf{x}_O(k+1), \quad \mathbf{C}_{l_{k+1}} = \mathbf{C}_{x_O,k+1} \tag{3b}$$

are taken at each new sampling interval Δt from the permanent online adjustment module implemented in GOCA according to the object point position $\mathbf{x}_O$ in equation (1a,b). Based on (3a,b) the corresponding Kalman filter is often applied for the system description of physical processes (see e.g. Mönicke, 1991; Kahmen and Palte, 1993), but it is to be noted that the "system" state vector $(\mathbf{u}_O, \dot{\mathbf{u}}_O, \ddot{\mathbf{u}}_O)$ is then completely evaluated from the observation information, and it therefore remains a *descriptive geometrical deformation* analysis. The Kalman filter however has the benefits to save computation time due to sequential processing and to provide "on-the-line" the state vector $(\mathbf{u}_O, \dot{\mathbf{u}}_O, \ddot{\mathbf{u}}_O)$, what are both important necessities of an online control and alarm system.

For each object point a critical state vector for displacement, velocity and acceleration is predefined by the user (fig. 7, left). Based on the results of Kalman filtering the alerting probabilities are computed and graphically displayed (fig. 7, right). If one of those probabilities reaches a given threshold value, GOCA sounds automatically the alarm (Schneid, 2000; Schneid and Schwäble, 2000).

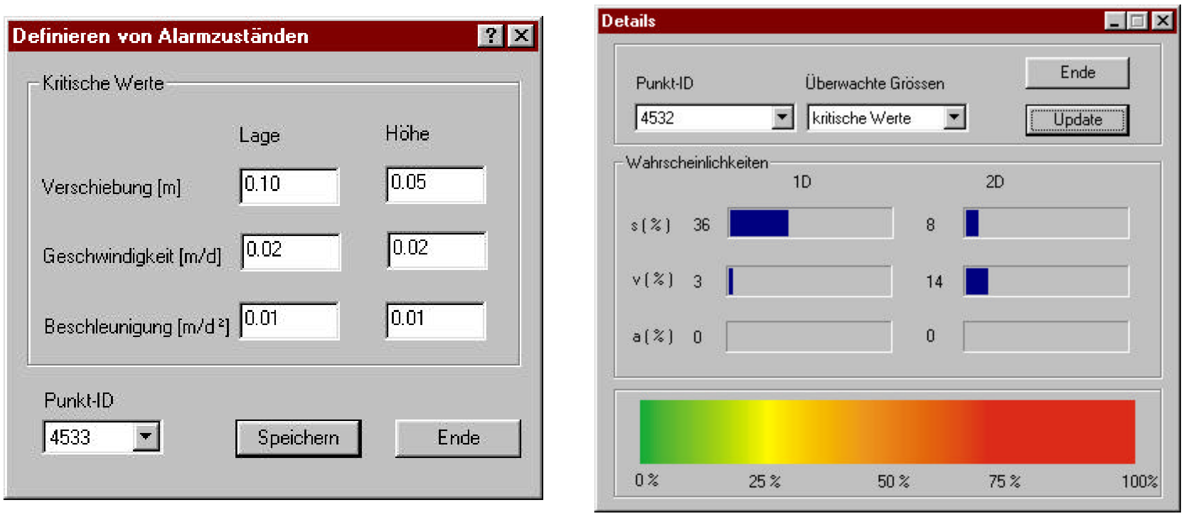

Figure 7: Alerting functionality of GOCA: Definition of a critical state vectors for the object points (left) and visualization of alerting probabilities for the object points (right).

6. Advanced Deformation Analysis and System Analysis

Classical *geometric deformation analysis models* are restricted in use to the estimation of state vectors of object coordinates $\mathbf{x}_O$ and functions $f(\mathbf{x}_O)$ and for their respective derivatives in time and space. Typical functions $f(\mathbf{x}_O)$ for *static deformation* networks are the object point displacement vector $f(\mathbf{x}_O) = \mathbf{u} = \mathbf{x}_{Oi} - \mathbf{x}_{Oj}$ between different measurement periods and the strain parameters evaluated from the first derivatives of $\mathbf{u}$ in space. Other deformation functions are difference surfaces $s(\mathbf{x}_O)$, e.g. modeled space dependent coefficients $\mathbf{a}_{ik}(\mathbf{x})$ of a finite element surface approximation in subsidence modeling. In case of *kinematic deformation modeling* the determination of derivatives of $\mathbf{x}_O$ (velocities, accelerations, etc.) and related deformation functions $f(\mathbf{x}_O, \dot{\mathbf{x}}_O, \ddot{\mathbf{x}}_O)$ are the objectives of parameter estimation. The significance of a deformation function $f = f(\mathbf{x}_O, \dot{\mathbf{x}}_O, \ddot{\mathbf{x}}_O)$ or more generally of a vector function $\mathbf{f} = \mathbf{f}(\mathbf{x}_O, \dot{\mathbf{x}}_O, \ddot{\mathbf{x}}_O)$ of dimension dim($\mathbf{f}$) is detected by the following test statistics related to the $F_{\dim(\mathbf{f}),\infty}$ Fisher distribution:

$$T = \frac{\mathbf{f}^T \mathbf{C}_f^{-1} \mathbf{f}}{\dim(\mathbf{f})} \sim F_{\dim(\mathbf{f}),\infty} \tag{4}$$

The covariance matrix $\mathbf{C}_f$ is evaluated on applying the law of error propagation to the special function $\mathbf{f}$ and the covariance matrix resulting from the adjustment according to (1a,b). A *geometric deformation analysis* is characterized by the fact that the information concerning the physics of the deformation process is used only in a passive way. That means that it is used in order to make the basic deformation network design (stable points, object points) as well as to select the most helpful deformation functions $\mathbf{f}(\mathbf{x}_O, \dot{\mathbf{x}}_O, \ddot{\mathbf{x}}_O)$ to be estimated so as to interpret as best as possible the behaviour of the deformation process. In the standard version of GOCA the first priority (basic modules) are concerned with the time series $\mathbf{x}_O$ and functions $\mathbf{f}(\mathbf{x}_O)$ of the object point displacements in plan and height. Here different least squares (L2-norm) and minimum absolute deviation (L1-norm) estimation strategies and filters are provided, see section 5.

The latest trends in deformation analysis clearly attempt to regard *geodetic observations* ***l***, equation 7b, as *signals of the object* with respect to its *physical state and parameters* (Szostak-Chrzanowski et al., 1994; Heunecke, 1995; Jäger, 1997). This further development of deformation analysis is becoming more prominent with safety critical constructions such as dams (Kälber et. al. 2000).

If the lake behind a dam is emptied or filled, likely that the object points move. This is just one example where estimation of the physical parameters of a system is required. System analysis is used in the pursuit of classical geometrical deformation analysis. Sometimes it is necessary to determine these parameters by an online system like GOCA. But the greater concern may be whether the points move because of an unexpected and dangerous state of the dam (hidden fissures, lacks of stiffness etc.) or because of natural, predictable and non threatening factors. We start from considerations of pure geometrical deformation analysis with a *system analysis approach*. Here the observation samples **l** are assumed to depend instantaneously also on the physical parameters **p** of an object. A *system analysis approach* is performed to evaluate the position observations **l=:x** in connection with a physical system equations **F**(**x**,**p**) = **0**. In terms of system theory we differentiate the kind of system equations between a *discrete*, a *grey*- and a *black-box* system of modeling (Heunecke, 1995).

The Kalman filter system equations (3a,b) may either be dictated by the physical system equations or by a purely kinematic or geometrical model. In the practical application of GOCA, finite elements provide the most appropriate type of discrete system equation modeling **F**(**x**,**p**) = **0**. The parameters **p** comprise the physical state of the object and may be used to describe the system, e.g. system disturbances or local damage to be investigated by online monitoring of an object. An example of a system analysis in the context of a *static deformation analysis* scheme and a discrete *finite element system* description for the detection of damage to discrete object points **p**, e.g. a dam structure, is given in Jäger, 1997. For the statistical detection of damage we can apply the test statistic from (4) for pure geometrical deformation functions **f** (Jäger, 1997). If we return to the above Kalman filter model of the kinematic case of equations 3a,b, we can easily modify the equation in order to perform a system analysis with the third equation of 3a. An example is the physical system equation of a vibrating structure. In the case of eigenvibrations, and on introducing with **M**(p), **C**(p) and **K**(p) are the mass matrix, the damping matrix and the stiffness matrix of the structure (Zienkiewicz, 1984), we arrive at:

$$\begin{bmatrix} \mathbf{u}_O(k+1) \\ \dot{\mathbf{u}}_O(k+1) \\ \ddot{\mathbf{u}}_O(k+1) \end{bmatrix} = \begin{bmatrix} \mathbf{I} & [\Delta t] & \left[\frac{1}{2}\Delta t^2\right] \\ \mathbf{0} & \mathbf{I} & [\Delta t] \\ \mathbf{0} & [-\mathbf{M}(\mathbf{p}_M)^{-1}\cdot\mathbf{K}(\mathbf{p}_K)\cdot\Delta t] & [\mathbf{I}-\mathbf{M}(\mathbf{p}_M)^{-1}\cdot\mathbf{C}(\mathbf{p}_C)\cdot\Delta t] \end{bmatrix} \cdot \begin{bmatrix} \mathbf{u}_O(k) \\ \dot{\mathbf{u}}_O(k) \\ \ddot{\mathbf{u}}_O(k) \end{bmatrix} \tag{5}$$

The parameters $\mathbf{p}_M$, $\mathbf{p}_C$ and $\mathbf{p}_K$ indicate different disturbance models for the physical state of the system, which is to be investigated by an online monitoring system. An example concerning $\mathbf{p}_K$ and a testing procedure related to equation 4 for the static problem is given in Jäger, 1997. Presently, a critical state vector of the parameters $(\mathbf{u}_O, \dot{\mathbf{u}}_O, \ddot{\mathbf{u}}_O)$ sets the automatic alarm in GOCA. This also relates to geotechnical considerations (Krauter, 1998). One of the main aims in the further development of GOCA is to improve theory and software in *system analysis* related to deformation monitoring procedures by discrete finite elements and by grey- and black-box models.

7. Installation Example

The GOCA-System was installed in the period from August 2nd 1999 to February 7th 2000 for the monitoring of a school building in a coal-mining area in Reisbach, Germany. Due to the progressive undermining in this area a subsidence hollow arises at the earths surface (fig. 8). As the deformations endangered the stability of buildings, a permanent monitoring of the subsidence area was necessary.

In the past, the deformations were monitored by terrestrial or by classical GPS measurements. As an example deformations in the plan component of up to 0.25 m and in the height component of up to 0.90 m were detected in the frame of a diploma thesis at the Fachhochschule Karlsruhe, when the area was monitored in a period of 3 months in 6 epochs by means of a classical GPS network of 23 object points and 5 stable points. To minimize the time-expenditure for the monitoring, the GOCA-System was installed at a discrete object in the subsidence-area (fig. 8).

In the present case the system was operating with only one GPS reference station in the object area and one GPS rover station in the stable area, but it is of course be possible with GOCA to monitor the whole subsidence area by a permanent array of GPS sensors divided in stable points and moving object points. The hardware consisted of a set of Leica 300 receivers and a set of radio modems to transmit data between reference station and rover station. The standard NMEA output of the rover station was directly transmitted to the GOCA-Center which was located close to the rover station with a tracking rate of 60 s.

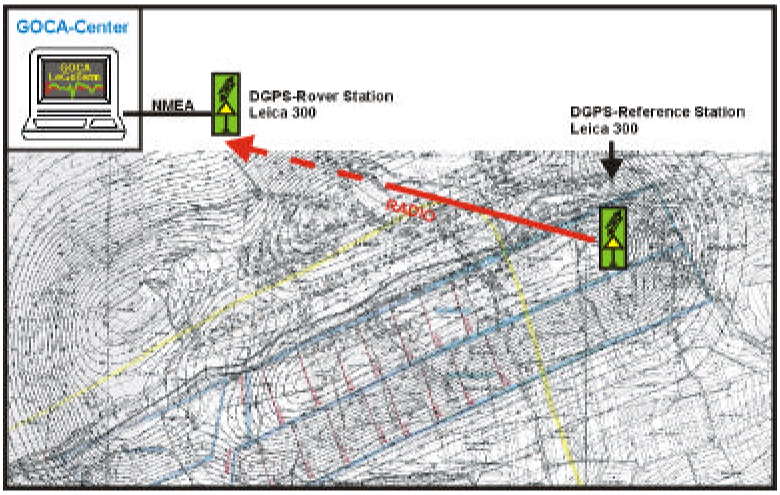

Figure 8: Configuration of the GPS monitoring array at Reisbach

Fig. 9 shows the displacement, velocity and acceleration series estimated for the time series of the object point (school building Reisbach) by the Kalman filter model (3a,b) for a period of five weeks. At the weekends the excavation of coal is interrupted. Therefore the subsidence rate decreases at the earth's surface. The time series for velocity and acceleration show these effects in a weekly cycle (fig. 9). The total deformation and the deformation rate were computed of the approximate 40000 observations in the monitoring period from August 2nd 1999 to February 7th 2000 by means of polynomials of third order based on L1-Norm adjustment. The results are summarized in the tab. 1 below.

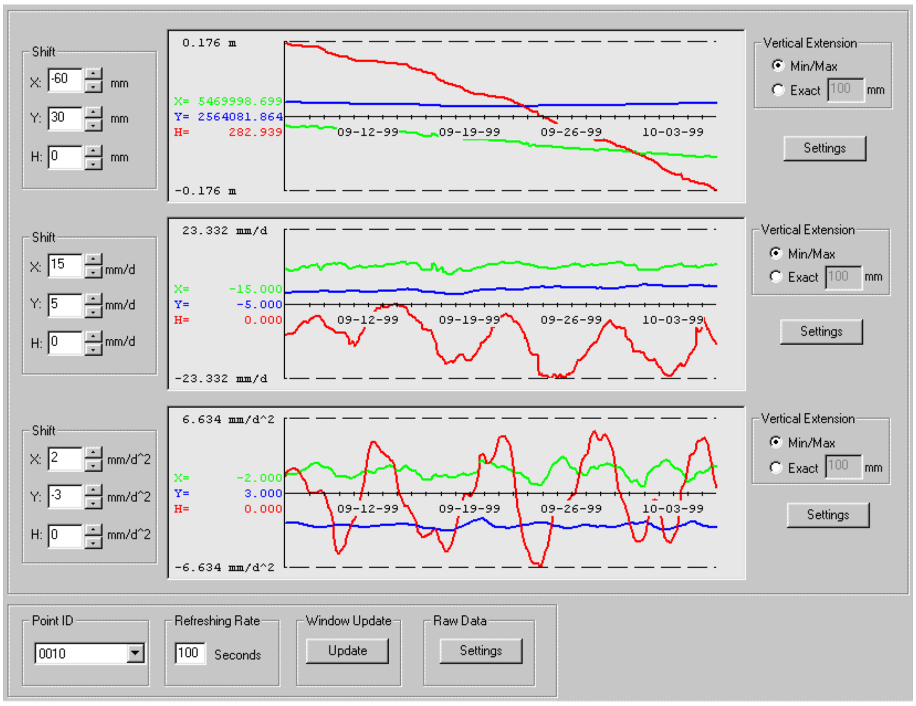

Figure 9: Displacement, velocity and acceleration series estimated by the Kalman filter model (3a,b) for a period of five weeks

	Total deformation	**Maximum deformation rate**
Eastern	0.18 m	1.5 mm/day
Northern	0.19 m	2.0 mm/day
Height	**1.23 m**	**20 mm/day**

Tab. 1: Total deformations and average deformation rate

8. Conclusions

The contribution treats the presentation of a GPS-based online control and alarm system (GOCA). The GOCA-Software sets up an array of GPS-sensors equiped with a telemetric or cable communication network and provides the continuous monitoring of movements on the earths surface with a prescribed tracking rate. Hereby GOCA is designed to control any type of GPS hardware. Additionally a so-called hybrid network design is enabled, meaning that the deformation network points may be occupied both in a permanently mode as well as intermittently. The local GOCA-Center consisting of a PC with the GOCA-Software and a communication unit may work also in a long distance control mode so that several different projects may be supervised centrally. The conceptional strength of the GOCA-System consists in the fact that a strict sequential least-squares network adjustment based on the input of baseline vectors and covariance-matrices guarantees online a complete sophisticated mathematical model standard a classical deformation network analysis. In addition robust estimation techniques are applied to make the object point time series of point displacements, velocities and accelerations resistant against the influence of gross errors in filtering and trend estimation. So a reliable setting of an alarm in case of a hazard is enabled. The evaluation of continuous time series of an objects displacement field provided by GOCA opens new perspectives in deformation analysis and model calibaration. This concerns the transition from the classical geometric deformation analysis to system analysis based approaches as required by the interest of other disciplines such as geodynamics, geotechnics and civil engineering.

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