Autonomous Permanent Automatic Monitoring System with Robot-Tacheometers

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Key words: Engineering Survey, Permanent Monitoring System,

SUMMARY

At the geodetic laboratory of the Technical University of Munich the permanent automatic monitoring of historical architecture has a long tradition. In the year 2003 an automatic system for permanent geodetic observations called MoSTUM (Monitoring System TUM) was developed especially for the monitoring of the behaviour of buildings. MoSTUM bases on the application of robot-tacheometers. Furthermore additional sensors for detection of exterior influences like meteorological values are supported. An optional mobile data transfer solution by GSM allows the autonomous integration of MoSTUM at arbitrary sites. It offers the possibility to check the state of the object from the office or even wireless from any other place in the world. In critical cases MoSTUM can act as an alarm system by sending short messages to mobile phones of the responsible engineers. The standard system consists of a robot-tacheometer and retro-prisms for signalization of the object points. For the installation the choice of the position of the object points is free. Moreover MoSTUM allows changing the configuration of the object points during the period of observations easily. If there is no direct sightline between robot-tacheometer and the retro prisms at important object points, an indirect line of sight can be realized by the use of plane mirrors. The collected data of the object geometry and of the exterior influences like acting forces enable an interdisciplinary interpretation in post processing. In this paper the technical design of MoSTUM and the experiences of the first three years of the practical use in Bavarian churches are presented.

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1. Introduction into the Problem

1.1 Motivation for the Installation of Permanent Monitoring Systems

Historical buildings like churches are objects of great cultural value and convey a certain religious meaning. Very often historical churches show damages like tearing obviously caused by movements of the building especially subsidence, which are related to non sufficient foundation (Figure 1). A renewing of the foundation is associated with immense expenses. So the goal of investigation is to check the necessity for taking action to assure the stability of the church.

First step is the investigation of the actual behaviour of moving of the church by geodetic measurements considering exterior influences on the building. This leads to the development of a static model. Under the control of further permanent precise monitoring the static model becomes verified in a second phase. During this phase of control the expert becomes enabled to define the stability of the building and the necessity of structural alterations. In the third phase the building may be controlled during the structural works.

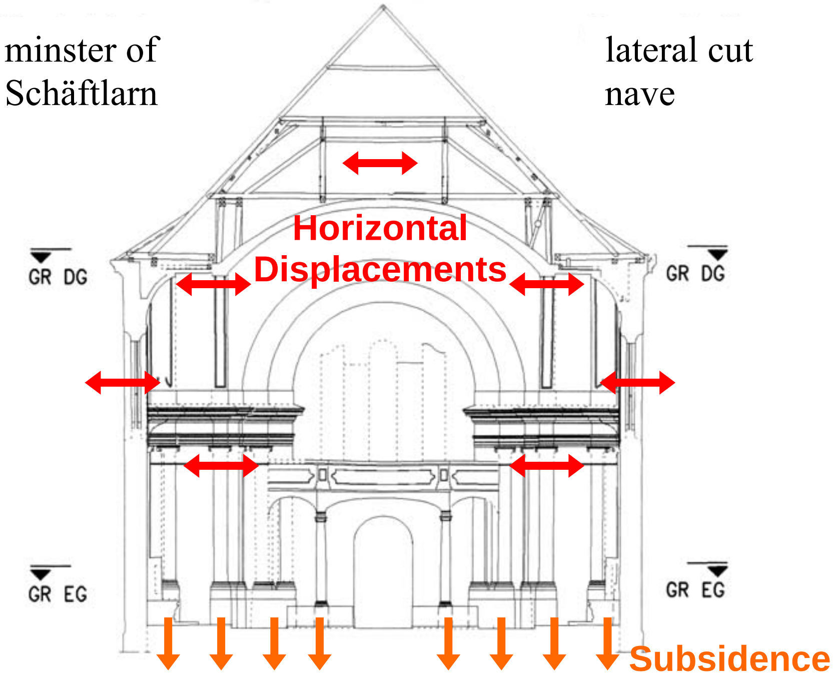


Figure 1: Unequal subsidence leads to horizontal displacements

1.2 Demands on a Permanent Monitoring System

A system for permanent monitoring of historical architecture must satisfy following requirements:

- Permanent monitoring of the behaviour of the building for the detection of regular periods (Detection of daily periods, annual periods etc. ⇒ Repetitions are depending on "Nyquist Frequency")
- Permanent registration of meteorological values temperature (inside and outside the building), pressure (inside), and humidity (inside) as mean influencing values
- The concept of the system should be very flexible to allow changes in the system configuration or even the expansion of the system by additional points on demand by minimal costs.
- Sometimes it may become necessary to configure the monitoring system as an alarm system during structural works or because of too big movements of the building. This option must be considered during planning of the system.
- The required accuracies depend on the expected movements. For three dimensional observation systems in historical buildings usually the standard deviations for each coordinate component $\sigma_x = \sigma_y = \sigma_z \leq 1\ mm$ are sufficient.
- The system must be economically convenient but also deal with the cultural meaning of the building.

1.3 Monitoring Methods for Permanent Observation of Historical Architecture

At the beginning of monitoring of an historic building, whose movements are obviously caused by subsidence, it is absolutely necessary to carry out an engineering levelling of highest precision inside and outside the building. Which kind of observation system should be installed depends on the rates of expected movements, directions of expected movements, and the local conditions in the monitored building.

The most used methods for permanent monitoring of historical architecture are:

1. Convergence measurements with invar wires
    - Analogue systems (non automatic)
    - Digital systems
2. Convergence measurements with EDM (reflectorless laser distance measurement by fix installed "Distos")
3. Inclination measurements
4. Vibration measurements
5. Application of robot-tacheometers
    - Signalisation by retro-reflectors
    - Reflectorless distance measurement

The principle of the monitoring of buildings bases on the experiences with the more simple methods 1 to 4. The application of robot tacheometers is the result of new technical developments. A detailed description of the methods 1 to 4 is given in [3].

2. Monitoring System Technical University Munich (MoSTUM)

At the geodetic laboratory of the Technical University of Munich (TUM) an automatic system for permanent geodetic observations called MoSTUM (Monitoring System TUM) was developed. MoSTUM bases on the application Robot-Tacheometers with "Automatic Target Recognition" (ATR). Furthermore additional sensors for detection of exterior influences like meteorological values are supported.

2.1 Hardware Equipment Installed Inside the Building

2.1.1 Robot-Tacheometers

Figure 2: *Leica-TCA2003*

Up to now MoSTUM bases on the application of *LEICA* Robot-Tacheometers with "Automatic Target Recognition" (ATR), especially the *TCA2003* because of its excellent accuracies for measurement of horizontal or vertical directions $\sigma_{Hz,V} \leq 0.15\ mgon$ and for electronic distance measurement $\sigma_s \leq 1\ mm + 1\ ppm$.

The robot tacheometer is mounted on a massive console, which should be installed inside the building at a possibly stable position with direct sight lines to all points of interest (object points). To avoid steel sight lines to the object points the tacheometer should be installed close to the level of the object points. In our experience the most stable position is given in the back of the church at a massive wall of the tower. To assure the stability of the console, some fixed points should be installed as reference. The most fixed area in an instable church is given close to the ground level. The stability of the reference area is to be controlled from time to time by engineering levelling of highest precision.

2.1.2 Retro-Reflector Prisms

All object and reference points are fitted with retro-reflector prisms. There are two sorts of prisms offered by *Leica* given with different accuracies: Standard prism *GPR1* (*<<1mm*) and mining prism *GPR112* (*<1mm*). In several investigations in the Geodetic Laboratory no significant difference in quality of both prisms was detected. As an additional feature the mining prism is equipped with a membrane to avoid steaming up under wet conditions, which is a big advantage for a permanent installed system.

Very often the visitors view on the ecclesiastical architecture should not be disturbed by the target prisms. So the prisms have to be varnished before installation (Figure 3).

Figure 3: *Leica*-Prism *GPR112* (*<1mm*) and *GPR1* (*<<1mm*), varnished and installed

2.1.3 Meteorological Sensors

Meteorological values like temperature and humidity cause expansions or contractions of different parts of the building. So it is necessary to detect these values to estimate the acting forces and the resultant movements. For detection of exterior influences like meteorological values the integration of additional sensors is supported. A very often used meteorological sensor is the *Reinhardt DMT 1MV*, which is a combined sensor for temperature ($\sigma_T \leq 0.3°C$), humidity ($\sigma_H \leq 2\%$), and pressure ($\sigma_P \leq 0.8\ hPa$). Additional sensors for temperature measurement can be connected to the *DMT 1MV* because of the integrated data logger (Figure 4). So the climatic circumstances can be recorded at several points of interest in and outside the building.

Figure 4: Sensors: *Reinhardt DMT 1MV* (left) and *Leica-TCA2003* (right)

2.2 Diverted Sight Lines

Sometimes there is no chance to find a position for the tacheometer inside the building from which there are direct sight lines to all points of interest. From economic point of view it is seldom possible to install a second tacheometer. So there was the idea to divert the sight line from tacheometer to prism by the use of a plane mirror. In the year 2003 the first investigations under practical conditions were realized with plane surface mirrors in the church of monastery Schäftlarn. Meanwhile a second system of mirrors and prisms is installed in the Jesuits Church in Landshut.

2.2.1 Basic Principles

Denotation:

T	position of tacheometer (intersection of axes)
M	position of plane mirror (point of reflection)
P	position of retro prism
$\mathbf{r}$	spatial vector from T to P
d_1	distance from T to M
t	bearing in T to M (with respect to the local coordinate system)
z	zenith distance in T to M
$\mathbf{r_0}$	vector of direction TM
d_2’	distance from M to P
$\mathbf{r_0}$	vector of direction MP
t_m	bearing of the outer normal to the mirror
z_m	zenith distance of the outer normal to the mirror
$\mathbf{n}$	direction vector of the outer normal to the mirror
α	angle of incidence resp. angle of reflexion in M

The shifts of the indirectly observed prisms are computed by vector analysis.

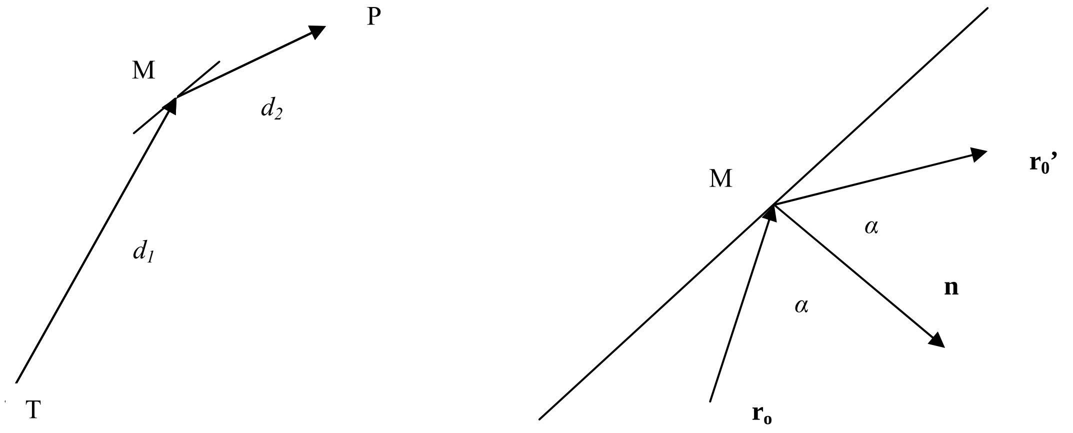


Figure 5: Basic Geometrical Principles for Diverted Sight Lines

$\mathbf{r_0}$ is changed over by reflexion in M to

$$\mathbf{r_0}' = \mathbf{r_0} - 2 \cos \alpha \, \mathbf{n} \qquad (1)$$

in which

$$\cos \alpha = \cos (t - t_m) \sin z \sin z_m + \cos z \cos z_m \qquad (2)$$

The vector **r** from instrument T to target P of real interest is consisting of two sections

$$\mathbf{r} = d_1 \mathbf{r_0} + d_2 \mathbf{r_0}' = (\mathrm{d}_1 + \mathrm{d}_2)\, \mathbf{r_0} - 2\, d_2 \cos \alpha \, \mathbf{n} \qquad (3)$$

Observable quantities are the direction t and the zenith distance z, both together representing $\mathbf{r_0}$, as well as the total distance $(d_1 + d_2)$.

The unknown normal of the plane mirror is derived from approximate coordinates of the geometrical configuration:

$$\mathbf{n} = [(d_1 + d_2)\, \mathbf{r_0} - \mathbf{r}] \,/\, (2\, d_2 \cos \alpha) \qquad (4)$$

α may be computed as half of the interior angle at M in the three dimensional triangle TMP. Because of the condition that **n** has to be an unit vector of length one, equation (4) is adjusted to this desired value via modification of the denominator. The components n_i of **n** yield the angles of alignment for the mirror:

$$\tan t_m = n_2 / n_1 \,; \qquad \cos z_m = n_3 \qquad (5)$$

From geometrical point of view M is located on an ellipse with T and P as focal points and the semi-major axis $a = (d_1 + d_2) / 2$.

2.2.2 Deformations

To determine deformations of P, the exact parameters for the orientation of the mirror are not needed, but required to be temporal constant. (To detect possible translations of the plane mirrors, there must be a directly measured prism installed in the surrounding of the mirror.)

If P is moving to P', in general the point of reflection M at the surface of the mirror is displaced. (In a very trivial case P' is part of the straight line from M to P.) Due to the planarity the normal **n** should not vary at least in theory. A variation $d\alpha_1$ of the angle α is causing a prolongation of d_1 about ($d_1 \tan \alpha \, d\alpha_1$), whereas d_2 is shortened about the same amount, concerning its starting point M. So the observed sum $(d_1 + d_2)$ remains unchanged from this point view, but is indicating the behaviour of the end point P directly.

Differentiation of formula (2) expresses $d\alpha = d\alpha_1 + d\alpha_2$ in terms of the altered instrument readings and moreover of the warped mirror in practice:

$$-\sin \alpha \, d\alpha_1 = -\sin (t - t_m) \sin z \sin z_m \, dt + [\cos (t - t_m) \cos z \sin z_m - \sin z \cos z_m] \, dz \qquad (6)$$

$$-\sin \alpha \, d\alpha_2 = \sin (t - t_m) \sin z \sin z_m \, dt_m + [\cos (t - t_m) \sin z \cos z_m - \cos z \sin z_m] \, dz_m \qquad (7)$$

Formula (3) is modified to:

$$\begin{bmatrix} r_1 + dr_1 \\ r_2 + dr_2 \\ r_3 + dr_3 \end{bmatrix} = d' \begin{bmatrix} \cos\ (t + dt)\ \sin\ (z + dz) \\ \sin\ (t + dt)\ \sin\ (z + dz) \\ \cos\ (z + dz) \end{bmatrix} - 2\ (d' \text{-} d_1 \text{-} d_1\ \tan \alpha\ d\alpha_1)\ \cos\ (\alpha + d\alpha_1 + d\alpha_2) \begin{bmatrix} \cos\ (t_m + dt_m)\ \sin\ (z_m + dz_m) \\ \sin\ (t_m + dt_m)\ \sin\ (z_m + dz_m) \\ \cos\ (z_m + dz_m) \end{bmatrix} \qquad (8)$$

By now d’ denotes the total distance from T via M to P’. Obviously the section from M to P or rather P’ should be as short as possible with respect to the error propagation.

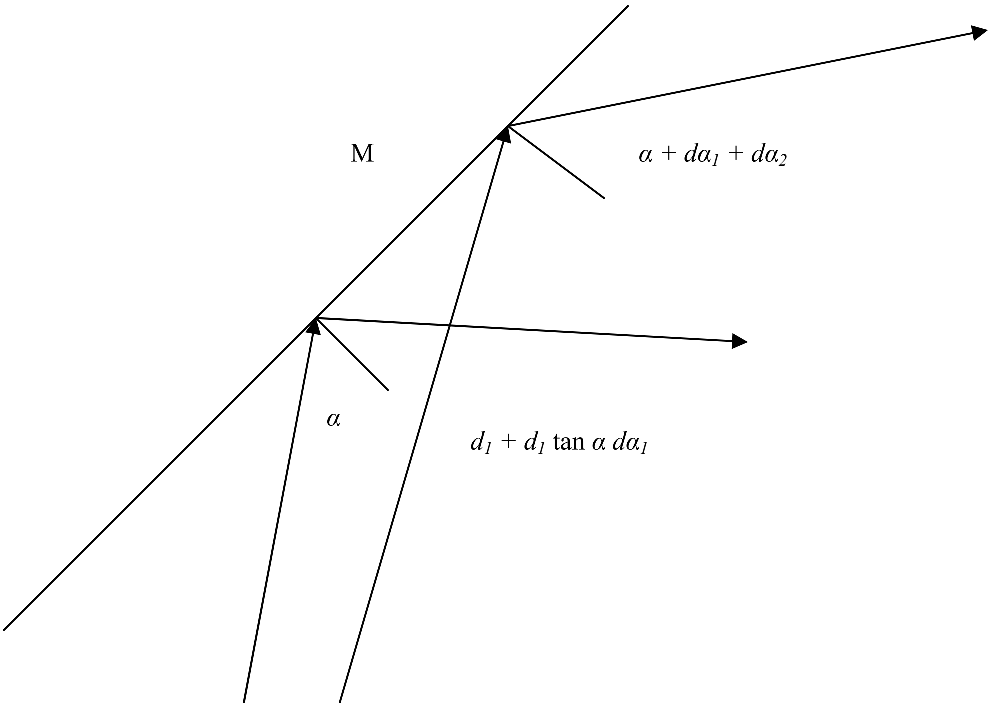


Figure 6: Deformation of the Object Point P Observed by Diverted Sight Lines

2.3 MoSTUM Software

The monitoring system is controlled by the MoSTUM software, which was developed at the Geodetic Laboratory (Figure 7). Therefore a PC station with separated power supply has to be established inside the monitored building. It is possible to install more than one robot-tacheometer inside the building. The connection between the tacheometer stations is realized by D-LAN or W-LAN. The data transfer and the maintenance are realized by a master station via internet by a separate phone line to office. There is also an alarm option. By the use of GSM mobile phone modems it is possible to send short messages (SMS) concerning the system status directly to the responsible user. In case of power blackout the full system is protected by an independent power supply. The analysis of the time series is done in post processing in office.

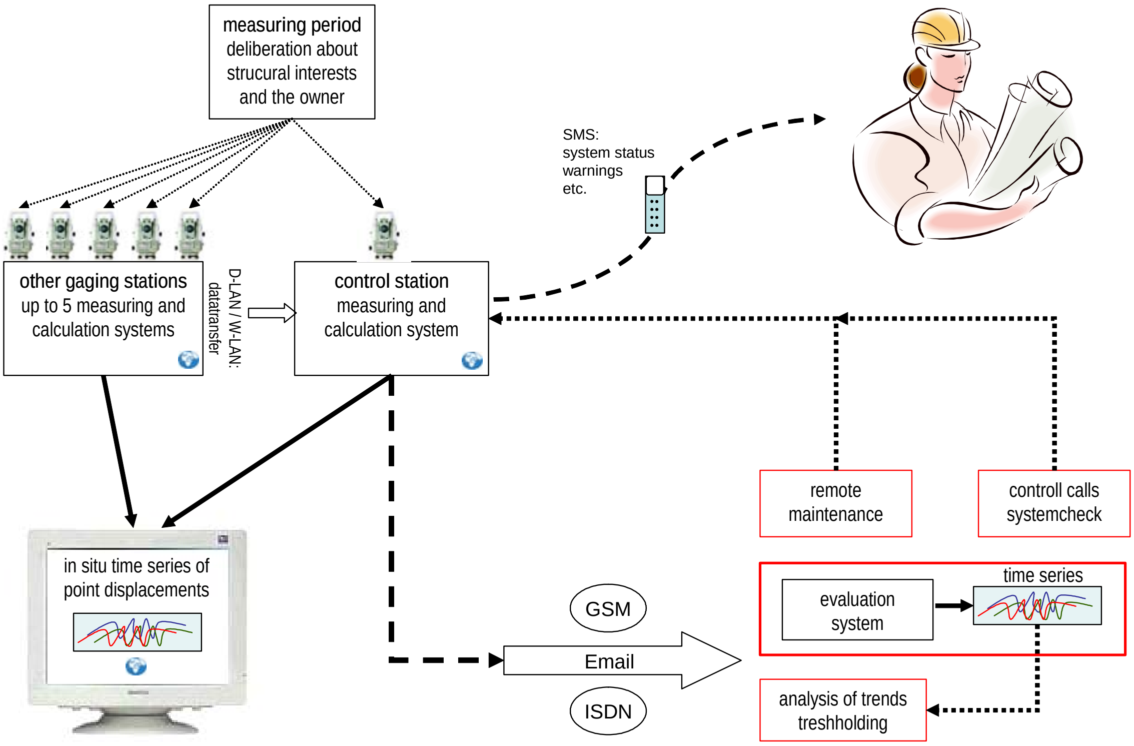


Figure 7: MoSTUM in actual state

MoSTUM is an easily mutable system. There is no problem to change the configuration of the object points or to import additional points. So even in cases of changes in the behaviour of the building there is no problem to adapt MoSTUM by minimal costs.

3. Application in Practice

3.1 System Setup and Validation in Geodetic Laboratory

Upon the installation of the sensors and the object points a first “zero epoch” measurement has to be arranged to teach the system. This “zero epoch” is the reference for all following differential views. The process of “teaching the system” is a manual one. Therefore the engineer aims each prism to give the system horizontal and vertical angels, which are exported by the tacheometer to a first memory file. After the teaching phase is finished the “zero epoch” can be started automatically in MoSTUM. The system reads out the memory file and moves the tacheometers according to both stored angels and targets the prism in view exactly by the ATR. Thus the “zero epoch” will be passed for all prisms. Now the reference angels, distances and local coordinates are stored enumerated and dated in the final “zero epoch” memory file.

Motions of prisms can now be detected by comparing the coordinates of following measurement epochs with the “zero epoch”. Therefore a lot of tests were taken in the Geodetic Laboratory of the TUM by installing the system on a trial and moving the targets in well-defined steps. Also different configurations with the plane mirror were tested in the Geodetic Laboratory. All-in it contains movements of prisms and mirrored prisms, furthermore translations and rotations of the mirror itself. For realization a mirror was installed on a tacheometer to perform movements in a well-defined way (Figure 8) to get the possibility of testifying the mathematical bases.

Figure 8: Mirror test configuration

3.2 Example Jesuit’s Church in Landshut

Meanwhile MoSTUM is installed in three important Bavarian churches. Normally one tacheometer is used. In one case of a very big church MoSTUM is running with two Leica TCA2003 simultaneously. In all installation the system runs stable and reliable.

Figure 9 shows the constellation of the monitoring system in the Jesuit’s Church in Landshut. The tacheometer is built at a massive wall of the church tower. Two meteorological sensors are installed inside and outside the church. All object points are equipped with prisms which are in the same height as the tacheometer. For two object points there are four plane mirrors to divert the sight lines. So an independend control of the results for the not directly observed points is reached. The full system from the tacheometer’s point of view is shown in Figure 10.

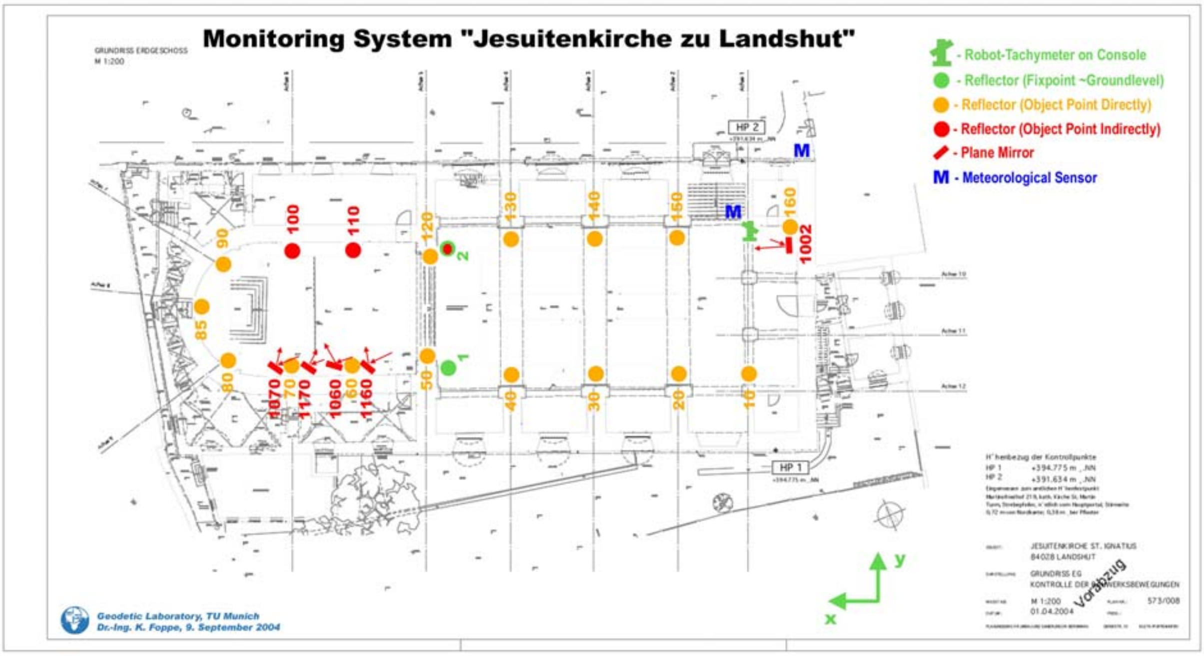
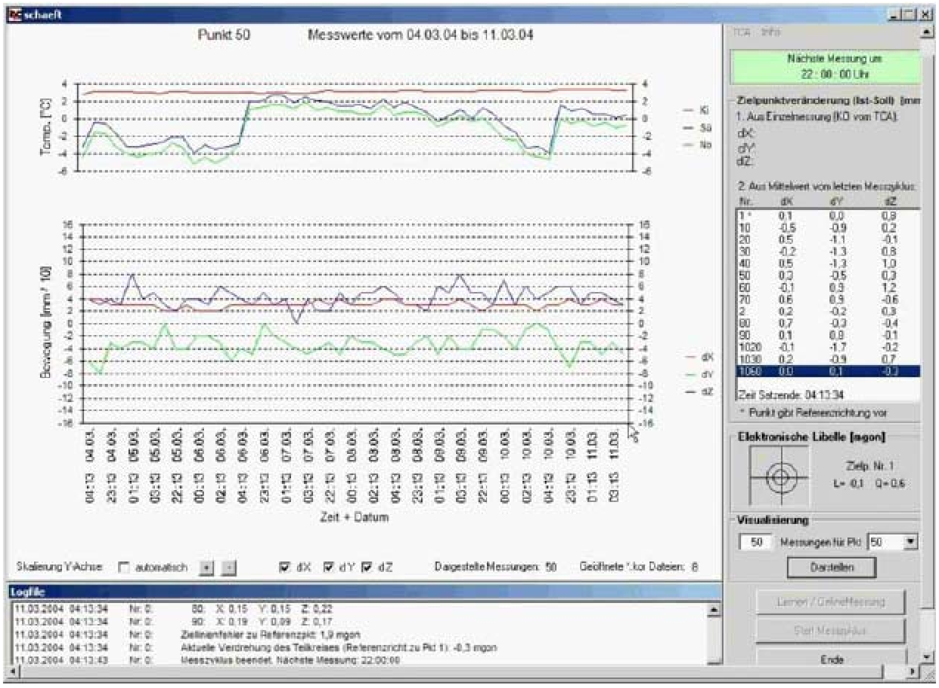


Figure 9: Constellation of the monitoring system in the Jesuit’s Church in Landshut

Figure 10: View on the monitoring system in the Jesuit’s Church in Landshut

A view on the screen of the system in situ is given in Figure 11. The analysis of the time series is realized in postprocessing in the office.



Zielpunktveränderung (Ist-Soll) [mm]

1. Aus Einzelmessung (KO vom TCA)

dX:
dY:
dZ:

2. Aus Mittelwert vom letzten Messzyklus

Nr.	dX	dY	dZ
1 *	0,1	0,0	0,8
10	-0,5	-0,9	0,2
20	0,5	-1,1	-0,1
30	-0,2	-1,3	0,8
40	0,5	-1,3	1,0
50	0,3	-0,5	0,3
60	-0,1	0,3	1,2
70	0,6	0,3	-0,6
2	0,2	-0,2	0,3
80	0,7	-0,3	-0,4
90	0,1	0,8	-0,1
1020	-0,1	-1,7	-0,2
1030	0,2	-0,9	0,7
1060	0,0	0,1	-0,3

Zeit Satzende: 04:13:34

* Punkt gibt Referenzrichtung vor

Logfile

```
11.03.2004  04:13:34    Nr: 0:        80:  X: 0,15   Y: 0,15   Z: 0,22
11.03.2004  04:13:34    Nr: 0:        90:  X: 0,19   Y: 0,09   Z: 0,17
11.03.2004  04:13:34    Nr: 0:      Ziellinienfehler zu Referenzpkt: 1,9 mgon
11.03.2004  04:13:34    Nr: 0:      Aktuelle Verdrehung des Teilkreises (Referenzricht zu Pkt 1): -0,3 mgon
11.03.2004  04:13:43    Nr: 0:      Messzyklus beendet. Nächste Messung: 22:00:00
```

Figure 11: View on the monitoring system in the Jesuit's Church in Landshut

The experiences of the first three years of the practical use of MoSTUM in the Jesuit's Church in Landshut delivers accuracies for the object points of σx= σy= σz ≤ 1 mm.

REFERENCES

[1] Bergmann, N., Stempfhuber, W., Zinsberger, St.: Online Monitoring historischer Kirchen mit einem Präzisionstacheometer mittels reflektorloser, direkter oder indirekter Winkel- und Streckenmessung, Ingenieurvermessung 2004, Zürich 2004

[2] Foppe, K.: Ingenieurgeodätische Überwachungsmessungen in und an historischen Bauwerken, Manuskript zum Vortrag an der Hochschule Neubrandenburg, 16.06.2004

[3] Foppe, K.: Permanent Automatic Monitoring of Historical Ecclesiastical Architecture, 3rd IAG Symposium on Geodesy for Geotechnical and Structural Engineering / 12th FIG Symposium on Deformation Measurements, Baden (Austria), May 22nd-24th, 2006

[4] Maurer, W., Roßmeier, F., Schnädelbach, K.: Determination of Periodic Displacements of Buildings and Machines with the Aid of a Laser-Interferometer, 5th International FIG Symposium on Deformation Measurements, Fredericton N.B., Canada, 6.-9.6.88.

[5] Maurer, W., Schnädelbach, K.: Measurement of Displacements in Buildings With Invar Wires, The Earth and the Universe, a Volume Dedicated to Porfessor Lyssimachos

Mavridis on the Occasion of his Completing Forty-Five Years of Academic Activities, Aristotle University of Thessaloniki, 1997.

[6] Schnädelbach, K.: Deformationsmessungen mit Invardrähten, Vermessungswesen und Raumordnung 48, p. 313-321, 1986

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