How to Transfer Geodetic Network Orientation Through Deep Vertical Shafts – An Inertial Approach

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Key words: autocollimation, inertial measurement, geodetic network orientation.

SUMMARY

In deep vertical shafts, it is not possible to use common engineering measurement techniques like e. g. traversing. Therefore the transfer of geodetic networks consists of the separate transfer of both the position and the bearing. Whereas the transfer of the position can be managed by mechanical or optical plumbs, the orientation of the underground network often is determinded by high-precision surveying gyroscopes for north-seeking. This method however, is influenced by deflections from the vertical which are not exactly known.

This paper describes a novel method to transfer the bearing by combination of autocollimation with a high-precision inertial navigation system (INS). The principles of autocollimation and INS are introduced. The motion-sequence consists of a reverse movement - comparable to a meaurement in two faces - which provides a symmetric measurement and therefore minimizes the influence of systematic and time-proportional errors of INS.

ZUSAMMENFASSUNG

In tiefen Schächten ist es nicht möglich, klassische Vermessungsmethoden wie z. B. Polygonierung einzusetzen. Daher wird die Netzmessung durch eine getrennte Positions- und Richtungsübertragung durchgeführt. Die Position kann einfach mit mechanischen oder optischen Messgeräten abgelotet werden. Die Orientierung wird häufig durch Präzisionsvermessungskreisel bestimmt, die die Nordrichtung vorgeben. Diese Methode wird jedoch von Lotabweichungen beeinflusst, welche nicht exakt bekannt sind.

Dieser Artikel beschreibt eine neue Methode zur Richtungsübertragung durch Kombination von Autokollimation mit einem hochgenauen Inertialnavigationssystem (INS). Die Prinzipien der Autokollimation und des INS werden vorgestellt. Der Bewegungsablauf besteht aus einer gegenläufigen Bewegung – vergleichbar mit einer Messung in zwei Lagen –, die einen symmetrischen Messablauf liefert und damit systematische und zeitproportionale Fehler des INS minimiert.

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1. INTRODUCTION

In deep vertical shafts, it is not possible to use common engineering measurement techniques like e. g. traversing. Therefore the transfer of geodetic networks consists of the separate transfer of both the position and the bearing.

The transfer of the position can be realized with high effort by mechanical or optical plumbs. The orientation of the underground network can be determined by a second plumb in a sufficient distance. Also a common way to determine the orientation is to use high-precision surveying gyroscopes for north-seeking, e. g the GYROMAT 2000. This method however, is influenced by deflections from the vertical which are not exactly known.

An independent method to transfer the bearing can be realized by combination of autocollimation with a high-precision inertial navigation system (INS). This novel method was developed for the Gotthard Basetunnel in Switzerland. To shorten the time of construction, the tunnel with its whole length of 57 km is built proceeded from three intermediate attacks. One of them is near “Sedrun” and consists of a tunnel with a length of 1 km and a shaft of nearly 800 m. This complexity is shown in figure 1.

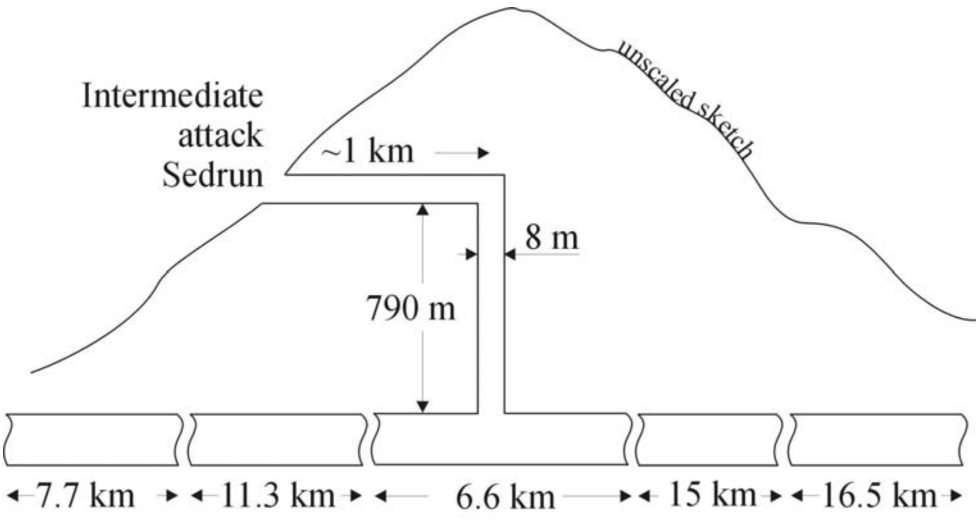

Fig. 1: Cross-section through the intermediate attack in Sedrun.

To connect the network above and underground, there is only the shaft with a diameter of 8 m. Even with the novel technique the transfer of the position from the top to underground is based on mechanical and optical plumbing. The “Konsortioum Vermessungsingenieure-Gotthard-Basistunnel (VI-GBT)” was responsible for planning and realizing the plumbing and was competently supported by the chair of Geodetic Metrology of the Eidgenössiche Technische Hochschule (ETH) Zurich. More information about this topic can be found in Schätti/Ryf, 2004.

The transfer of the bearing however, is independently verified by the novel method, which will be described in the following chapters.

2. MEASUREMENT TECHNIQUES

2.1 Autocollimation

Collimation is an optical measurement method with parallel lines of sight from different instruments. For auto-collimation the cross-hairs of a tacheometer are illuminated from behind and the telescope is focused for infinity. Aimed at a mirror, the “real” cross-hairs can be covered with its reflection; then both lines of sight are perpendicular to the mirror and therefore parallel. As the lines of sight are reflected into themselves, this method is called auto-collimation.

Fig. 2: Autocollimation-eyepiece from Leica Geosystems and Autocollimation-mirror GAP1 form Wild Heerbrugg.

Autocollimation is a simple, but useful technique to propagate the orientation both onto and from a platform, on which e. g. the INS is mounted.

Looking at a mirror, the angle of incidence is the same as the angle of reflection. Therefore, the accuracy of autocollimation is twice better than the accuracy of a common measurement with a tacheometer. Further on, because of the parallel lines of sight, the station is independent on the reduction to center.

2.2 Inertial Navigation System

2.2.1 Sensors

An INS consists of three gyros and three accelerometers, which are arranged in pairs and mounted orthogonal to each other (see figure 3).

The gyros (ω) are measuring spin rates, once integrated they deliver the rotation. On the other hand, the accelerations are sensed by the accelerometers (a), then integrated twice. The result is the translation. The spin rates and accelerations are measured for each of the three axes.

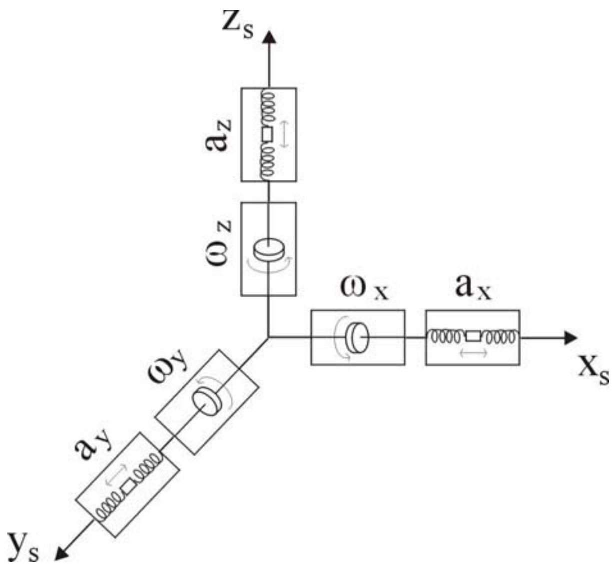

Fig. 3: Arrangement of sensor-axes of an IMU.

Usually the rotation angle around the x-axis is called roll, the angle around y-axis is named pitch. The rotation around z-axis is called heading. In the application this paper discusses, this angle is also called azimuth. The three angles are also called attitude-angles.

The sensors are measuring the data in the sensor system, referred to the inertial system. So first the orientation of the sensor related to the navigation coordinate frame must be determined in the so called alignment, i. e., the angles roll, pitch and azimuth are computed. The connection from the navigation system over the earth-centered, earth-fixed system to the inertial system can be found in various technical references, e. g. in Stoval, 1997.

Scanned in a high frequency we are dealing with infinite coordinate differences, which can be summed up for the trajectory. With the rotations and translations a coordinate transformation can compute the positions, still under consideration of different errors.

2.2.2 Error Models

Both systematic and time-proportional errors take influence on the measurement data. In order to increase the accuracy of the coordinates, the errors must be taken into consideration. This is necessary in particular, because even the smallest errors sum up over time due to the integration process.

The most important error is the bias. It changes at every start, but is constant during the measurement, and is determined during the alignment. The scale factor and non-linearity are also fixed in the alignment. Errors like eccentric mounted sensors or non-orthogonality are corrected within the evaluation model.

Disturbances inside the instrument create a non-systematic sensor drift. They result in a random walk around the characteristic curve of the sensor and therefore can not be computed. One possibility to minimize the drifts is the so called zero velocity update (ZUPT). At a ZUPT the INS doesn't move in the navigation frame, so the velocity (one time integrated acceleration) and spin rate are set to zero.

3. MEASUREMENT METHOD TO TRANSFER GEODETIC NETWORK ORIENTATION

At the top of the shaft the geodetic network was transferred with the means of autocollimation by a tacheometer stationed right in front of the mine cage from a remote target in the tunnel onto a platform, mounted in the mine cage. You can see the platform in figure 4, with a plane mirror for autocollimation and a redundant special prism for autocollimation called "GAP1". Under the safety box in the middle is the position of the INS. Of course there must be a power supply and a notebook for controlling the INS. In the background you can see the floor of the mine cage.

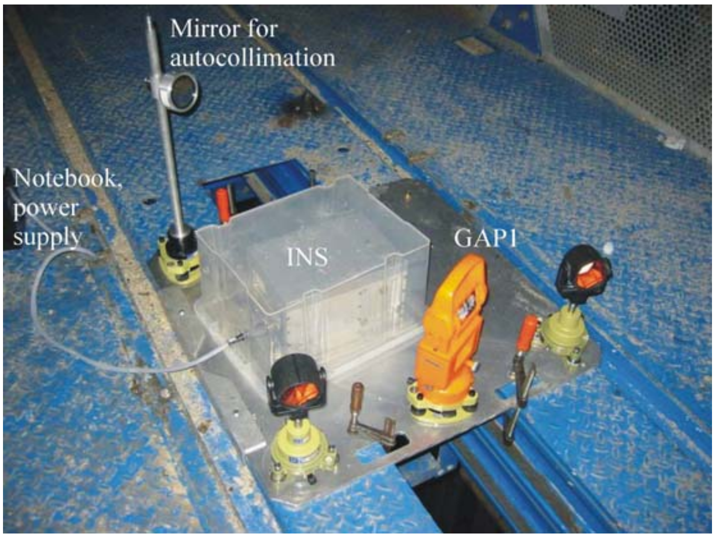

Fig. 4: mounted platform in the hoisting plant.

After the alignment, the mine cage went underground, where another tacheometer, straight in the same line as at top, transferred the bearing off the mirror resp. the "GAP1" to the underground network. The installation of the stations was quite difficult, because of the lack of firm foundation in front of the mine cage's door both at top and underground. The stations both on top and underground have been positioned in the network before and after the measurements. Additionally the platform was coordinated via the two reflectors in figure 4.

The sequence and principle of measurement is also shown in figure 5 in the ground-plan. Black is the situation at the top of the shaft. ($\beta_t + \alpha_t$) is the angle between the remote target and the mirror for autocollimation resp. the GAP1. From the remote target to the control-mirror the angle is called β_t, the annexing angle α_t is the angle between the control-mirror and the mirror for autocollimation resp. the GAP1. There were additional control-mirrors at top and underground to prove that the orientation stayed stable and there is no twisting of the pillar.

The central figure of the whole measurement is Ψ. This is the result of the inertial measurements. As in chapter 2.2.1 already mentioned, the azimuth is used to compute the change of the bearing between top and underground. The INS senses the change in the bearing with it's gyros during the shift from top to bottom of the vertical shaft, and the orientation of gravity is provided by the accelerometers.

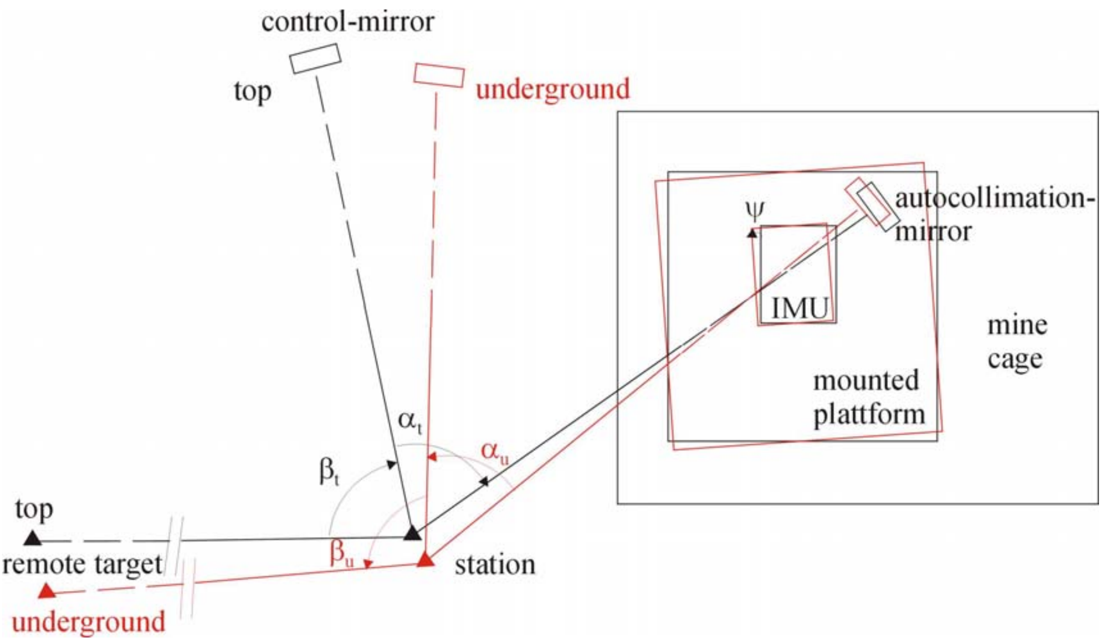

Fig. 5: Sequence of measurement.

When the hoisting platform has reached the future level of the tunnel, the bearing is transferred from again the autocollimation mirror and the GAP1, brought forward to the remote target in the tunnel and therefore to the underground network. Like above those are the angles $\beta_u + \alpha_u$.

A reverse movement – comparable to a measurement in two faces – from the bottom to the shaft provides a symmetric measurement and therefore minimizes the influence of systematic and time-proportional errors of INS.

Together with the coordinates from the station and the remote target, which result in the angle of direction at the top of the shaft t_t, the angle of direction of the underground network t_u can be computed as follows

$$t_u = t_t + \beta_t + \alpha_t + \Psi - (\beta_u + \alpha_u).$$

The angle of direction of the underground network is determined analogous to the bearing of traversing, but with the difference, that all angles except one are measured with a tacheometer. And the very special one Ψ is determined by an INS.

4. MEASUREMENT CAMPAIGNS AND RESULTS

This novel observing operation was tested in the elevator shaft of Munich Olympic Tower. The application was successfully copied to the shaft of Sedrun of the Gotthard-Base-Tunnel in Switzerland. The Chair of Geodetic Metrology of the ETH Zurich and the Chair of Geodesy of the Technische Universität (TU) München carried out two measurement campaigns in 2004 and 2005.

During the mining break at Easter in April of 2004, the mine cage was available mainly for the measurements. But simultaneous to the measurements people were transported in the hoisting plant. Therefore the maximum speed was twelve m/s. The hop-on and hop-off of people caused time delays of several minutes. As the time-proportional errors increase with time, the results were negatively influenced. Due to controlling, the mine cage didn't engage at the future tunnel level, but had to undergo a corrective movement, to enable the autocollimation. At this campaign, five measurements were carried out, i. e. five times downwards and five times upwards.

To verify the good results in another campaign, in January of 2005 a second measurement was executed. All negative influences of the first campaign could be banished, except the corrective movement. As no people were allowed in the mine cage, the speed was increased up to 16 m/s and the time for the hop-on-hop-off process became inapplicable. Additionally the team was increased to six people and the instruments have been improved. Due to these changes the duration of a single measurement movement was minimized. Because of technical difficulties and a service interruption of the mine cage, only three measurements were accepted.

The data were processed with the software KingsPad™, developed by the Department of Geomatics Engineering of the University of Calgary. More information about the processing can be found in Neuhierl 2005. We are greatly indebted to Profs. K.P. Schwarz and El-Sheimy for the posiibility to use KingsPad™ for this unique research project.

Both campaigns are equally weighted. The first one consists of more measurements, but the second one was carried out with improved equipment. The first campaign resulted in a difference to the geodetic network provided by the high-precision surveying gyroscope GYROMAT 2000 of + 0,7 mgon, the result of second campaign was + 3,7 mgon. The weighted mean value is + 2,2 mgon. Considering the accuracy of the INS, the centering accuracy, the accuracy of the tacheometer for autocollimation and to the remote targets, the standard derivation of the novel method is 1,5 mgon, which is comparable to the GYROMAT 2000. The difference of + 2,2 mgon is not significant. Due to the result of the combined autocollimation and INS measurements no correction of the underground network orientation proved necessary.

5. CONCLUSION

Concluding, it can be assessed that a kinematic propagation of the bearing was developed, set up and carried out by coupling inertial measurement with autocollimation. A novel method to transfer geodetic network orientation through deep vertical shafts was introduced, which independently verified previous third-party measurements with the high-precision surveying gyroscope GYROMAT 2000.

6. THANKS

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BIOGRAPHICAL NOTES

Theresa Neuhierl has studied Geodesy at the TU München between 1993 and 1998. As a scientific assistant she was working for the Chair of Geodesy of the TU München from 1998 till 2005. She finished her dissertation in September 2005. Since June 2005 she is a trainee for the Bavarian Surveying Administration and for Rural Development.

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