Networking Motorized Total Stations and GPS Receivers for Deformation Measurements

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SUMMARY

Motorized total stations (TPS) with automatic reflector recognition are now widely accepted as ideal sensors for many monitoring projects. High accuracy GPS receivers have also gained acceptance to be deployed in such applications.

Both technologies can be complementary. GPS can provide high accuracy control for TPS in unstable environments. TPS can operate in areas where few or no GPS signals are available and are more economical for measuring large numbers of points. Combining both types of sensors is much more a question of software than hardware, where basically the only physical integration task is to adapt the GPS antenna to fit a reflector to create a kind of active control point.

Traditionally most monitoring installations use only one TPS as the primary means of measuring the monitoring points. In larger or more critical applications it is necessary or preferable to deploy multiple TPS sensors to provide greater area coverage and to increase reliability.

This task becomes difficult in practical applications when the TPS sensors must be located in the area of deformation and little or no stable control points are available. Flexible geometrical design and data processing are now mandatory to insure all inspection points are accurately coordinated within a common reference frame. The topic of this presentation is a new concept of combining of network processing using a combination of motorized total stations and GPS receivers sharing common connecting points. The presented approach offers a flexible way of overcoming practical issues in conducting high accuracy monitoring with multiple TPS in areas with little or no stable control. This paper will discuss such topics as simulation, design, adjustment and quality checking.

RESUME

Les stations totales motorisées disposant de la reconnaissance automatique de réflecteurs passifs sont actuellement bien acceptées dans les projets de monitoring.
La technologie GPS précise est également largement utilisée dans ces applications.

Ces deux technologies sont même complémentaires dans le sens que les stations totales doivent être initialisées avec des paramètres que des récepteurs GPS peuvent fournir. Ces mêmes stations totales pouvant le cas échéant être utilisées là où les signaux GPS sont limités ou inaccessibles.

La combinaison des ces senseurs est davantage une question logicielle que matérielle. En effet l'intégration la plus réaliste consiste souvent simplement à monter une antenne de réception de signaux GPS sur un réflecteur panoramique fournissant de cette manière un point de référence actif.

Le succès de logiciels tel que Leica GeoMos encourage les responsables de projets de monitoring à augmenter le nombre de réflecteurs pour améliorer leur modèle de déformation.
Cette tendance influence évidemment le nombre de senseur à déployer sur la zone soumise à déformation avec la conséquence de ne plus pouvoir se référer à une définition stable de ces senseurs.

La nature même de projets de constructions ambitieux contribue à promouvoir cette tendance en ce compris pendant la période d'édification.

Une configuration géométrique flexible et du traitement en temp réel légèrement différé sont maintenant obligatoires pour s'assurer que tous les points d'inspection partagent toujours le même référentiel.

Le sujet de cette présentation est un nouveau concept de réseau mixte associant les stations totales motorisées et des récepteurs GPS se partageant des points de connexion communs. La simulation, la conception, l'ajustement et le contrôle de qualité font intégralement partie de cette nouvelle approche.

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1. INTRODUCTION

With the advent of automatic passive reflector recognition based total stations, the use of polar measurement for monitoring changes in engineering structures, mines, natural surfaces, etc. has become widespread.

Usually the total stations are installed at a permanent location and are levelled to align their main axis with the direction of local gravity. Attention is paid to select only very stable sites to ensure sure that the coordinates computed from the station will remain in a consitent reference frame to simplify the detection of movement in the monitoring points. Nevertheless in manysites, this condition is not completely fulfilled because practical constraints mean that the sensor cannot be placed in a stable area. To overcome this problem a set of control points disseminated around the unstable area is used to control the station stability by means of a free-station calculation. A very accurate dual axis compensator in the total station corrects the angular directions to account for the slight misalignment of the main axis.

Control points are used also to check the complete cycle of measurement and introduce some reliability. If several total stations are deployed to increase the coverage or the reliability, the control points are also used to link all the stations to a common reference frame. The mathematical model usually selected is based on the so-called “free station” procedure. A free station algorithm uses measurements from the total station to a number of control points to compute the station coordinates and to re-align the zero index of the horizontal circle. The control points are supposed to be installed on very stable monuments which limit the number and the availability.

Monitoring systems allow engineers to increase productivity and profitibility by taking on more risk in their designs without comprimising safety. With aldready highly advanced hardware in the market, it is important to reconsider the monitoring processes to maximise performance. In this paper, an alternative approach to the problem of dealing with station instability is considered.

Largely inspired by the analytical photogrammetry “block adjustment” method, this approach allows the total stations to be used in a full 3D reference frame. Instead of trying to physically align the instrument's main axis with the direction of gravity, the compensator is disengaged and the rotational angles of the mechanical axis are computed.

The principle is to use all connection points that overlap the different measurement sub areas of the overall site to re-compute the stations coordinates and the rotational angles of their mechanical axes. Some control points are still needed to provide the common reference frame and to solve the datum defect issue, but those points can now be installed in a much more convenient location largely outside the unstable area.

The use of the precise phase-based differential GPS receivers and processing software for monitoring project is now well accepted due to its ability to deliver centimetre or millimetre-level positions in near real time. The approach described here can also use those positions to provide active control points in the deformation area. In that case a GPS antenna is collocated with a 360° reflector and the offsets are determined. A special procedure based on the "hidden point target" used in industry and surveying has been adapted to ensure that the antenna phase centre and the 360° reflector centre coordinates are identical. The measurement technology available today is mature enough to let us use advanced processing models to meet and exceed the market expectations. Practical tests have been used to verify this new approach.

2. BASIC CONSIDERATIONS

A total station, or more generally any theodolite, can be considered as a dual axis system supporting the line of sight of a transit/telescope. For reducing the effect of the mechanical misalignments on the observations, classical operational procedures have been applied since the first use of such instruments.

Today, a total station can take these axis misalignments into account using an inbuilt dual axis compensator and special firmware to correct the resulting error in the measurements. However, the operational range of the compensators is restricted, typically to about six minutes of arc. The operator aligns the main axis coarsely by keeping the bubble of the station inside the graduation. In case of a compensator "out of range" signal, the station must be realigned manually. This procedure known by experienced operators as simply inappropriate when operating a total station remotely for long periods of time.

To remove the restriction of today that the total station must be located on a stable point or have available a number of high quality control points, it is necessary to consider this instrument as a local 3D axis system. The coordinates computed by using the observations (directions and distance) are internally consistent but must be transformed into the reference frame defined by a set of control points.

For a single total station, the problem is simply a 3D transformation also known as similarity transformation or Helmert transformation, from the name of a well known German geodetic scientist who popularised the use of the Least Square adjustment in geodesy and surveying.

When several stations are disseminated to survey all points of interest, the only way to avoid the multiplication of control points is to make use of common points (connection). Parameters are added to the mathematical model that relate the measurements to the common points to the transformation. The common points may be located in an area subject to deformation so long as they can be considered stable during the time of the measurement principle is just to keep those common points located also directly in the unstable area as fixed during the time of observation which is now quite limited due to the high performance of the total stations.

3. OBSERVATIONS REDUCTION

If we consider a full 3D model, the only reduction we should apply to the range observations is the refraction correction. Usually the well-known Barrel and Sears formula based on the dry and wet temperature (or the dry temperature and the relative wet air) observations as well as the atmospheric pressure is used. That model assumes however that the atmospheric parameters on both extremities of the range are known, which is practically impossible to realize. Another approach proposed is to measure some fixed points where the distance is accurately known so that a scale factor can be directly computed and used to correct the measurements.

If the process is divided into a 2D and 1D model, the ranges must be reduced to the horizontal and, if appropriate, to sea level by applying a projection correction due to the coordinate system. For a monitoring project, even one spread accross a large area, the system is still on a local grid and the projection correction can be neglected. For 1D, the height should also be reduced to a reference plane.

Observing the points in the two-face position of the telescope can eliminate the remaining effect of instrumental axis misalignments. With the motorized instruments used in monitoring, this is a fast and simple procedure.

4. MATHEMATICAL MODEL

4.1 Observational Data

There is a large consensus in the surveying and geodetic community to handle only the measurements in the adjustment process. Even if the coordinates are directly deduced from the measurements without any reduction process, it looks like this trend is still largely promoted. For many years now, since the availability of distance measurements of the same level of quality as the angular measurements, only few practitioners have tried to promote models that deal directly with coordinates. GPS processing results have helped to motivate that change of paradigm.

In fact, it is just a transformation from polar system to cartesian system. People involved in processing and analysis use the idea that interpretation is easier as a justification to handle measurements only. As this is not the case in deformation measurements – the results are always expressed in the position domain. As such, in this approach the coordinates will be used as observations. In such a case several authors use the expression “pseudo-observations” to differentiate the coordinates from the measurements.

Considering the measurements (zenithal direction *Vz*, horizontal direction *Hz* and slope distance *S*) the point coordinates X_p, Y_p, Z_p are obtained as:

$$\begin{bmatrix} X_P \\ Y_P \\ Z_P \end{bmatrix} = S \cdot \begin{bmatrix} \sin Vz \cdot \sin Hz \\ \sin Vz \cdot \cos Hz \\ \cos Vz \end{bmatrix}$$

In order to apply the general law of variance, we need to linearize the equations which form the content of the following matrix:

$$Q_{CC} = \begin{bmatrix} \sin Vz \cdot \sin Hz & S \cdot \cos Vz \cdot \sin Hz & S \cdot \sin Vz \cdot \cos Hz \\ \sin Vz \cdot \cos Hz & S \cdot \cos Vz \cdot \cos Hz & -S \cdot \sin Vz \cdot \sin Hz \\ \cos Vz & 0 & -S \cdot \sin Vz \end{bmatrix}$$

The estimation of the observation variance is introduced as:

$$Q_{LL} = \begin{bmatrix} \sigma_S^2 & 0 & 0 \\ 0 & \sigma_{Vz}^2 & 0 \\ 0 & 0 & \sigma_{Hz}^2 \end{bmatrix}$$

The variance covariance of the point coordinates is formulated as:

$$Q_{PP} = Q_{CC} \cdot Q_{LL} \cdot Q_{CC}^T$$

4.2 Functional Model

Any point (*x,y,z*) in a 3D cartesian frame can be transformed into another 3D cartesian frame (*X,Y,Z*) using a similarity transformation which describes the seven degrees of freedom of a solid body in space.

The seven parameters describe the three translations (T_x, T_y, T_z), the three rotations (ω,ϕ,κ) and "s" a scale factor.

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} Tx \\ Ty \\ Tz \end{bmatrix} + s \cdot \begin{bmatrix} \cos\phi \cdot \cos\kappa & -\cos\phi \cdot \sin\kappa & \sin\phi \\ \cos\omega \cdot \sin\kappa + \sin\omega \cdot \sin\phi \cdot \cos\kappa & \cos\omega \cdot \cos\kappa - \sin\omega \cdot \sin\phi \cdot \sin\kappa & -\sin\omega \cdot \cos\phi \\ \sin\omega \cdot \sin\kappa - \cos\omega \cdot \sin\phi \cdot \cos\kappa & \sin\omega \cdot \cos\kappa + \cos\omega \cdot \sin\phi \cdot \sin\kappa & \cos\omega \cdot \cos\phi \end{bmatrix} \cdot \begin{bmatrix} x \\ y \\ z \end{bmatrix}$$

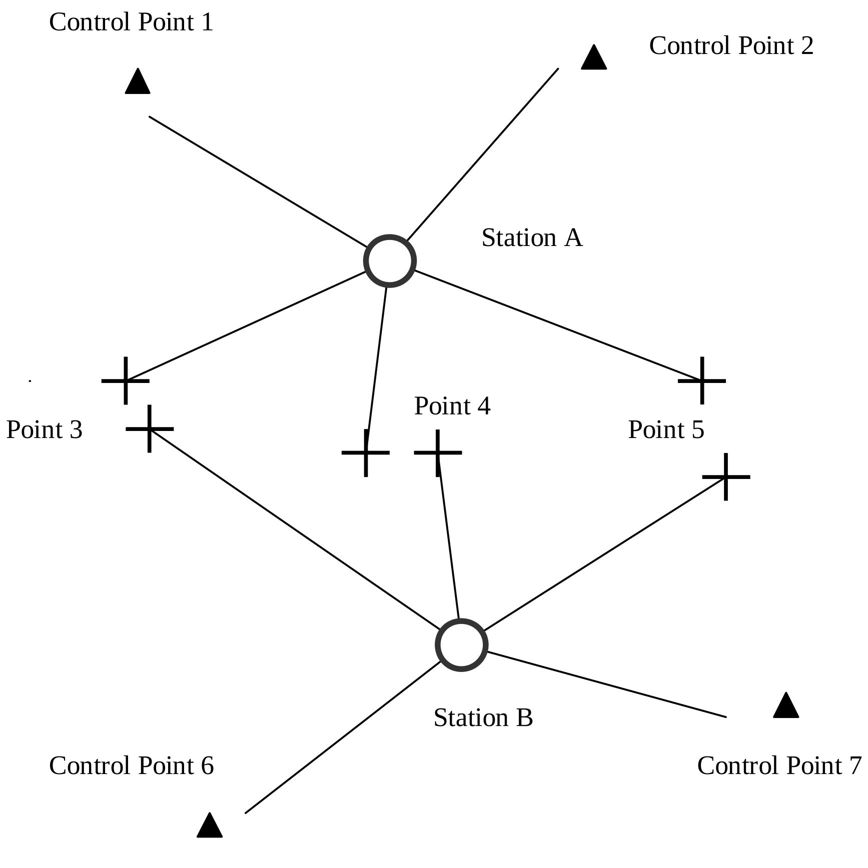
The linearized form of this equation is:

$$X = dX + (1 + ds) \cdot dR \cdot X_0$$

Or in matrix form :

$$
\begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} x_i & 0 & z_i & -y_i & 1 & 0 & 0 & -1 & 0 & 0 \\ y_i & -z_i & 0 & x_i & 0 & 1 & 0 & 0 & -1 & 0 \\ z_i & y_i & -x_i & 0 & 0 & 0 & 1 & 0 & 0 & -1 \end{bmatrix} \cdot \begin{bmatrix} ds \\ d\omega \\ d\varphi \\ d\kappa \\ dT_x \\ dT_y \\ dT_z \\ X_i \\ Y_i \\ Z_i \end{bmatrix}
$$

To clarify the mechanism of building the fuctional model, we have designed a small network where three connected points are observed by two stations. Datum is fixed by four control points.



To condense the functional model, the notation:

$$D_i^j = \begin{bmatrix} x_i^j & 0 & z_i^j & -y_i^j & 1 & 0 & 0 \\ y_i^j & -z_i^j & 0 & x_i^j & 0 & 1 & 0 \\ z_i^j & y_i^j & -x_i^j & 0 & 0 & 0 & 1 \end{bmatrix}$$

is used where the index i relates to the observed point, the index j relates to the station and the index k relates to the existing control points.

$$E = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$F_k = \begin{bmatrix} X_k \\ Y_k \\ Z_k \end{bmatrix}$$

$T^j =$ the correponding transformation parameters for the station j
$P_i =$ the corresponding coordinates for the point i

The complete functional model now associated to the example is:

$$\begin{bmatrix}
D_1^A & 0 & -E & 0 & 0 & 0 & 0 & 0 & 0 \\
D_2^A & 0 & 0 & -E & 0 & 0 & 0 & 0 & 0 \\
D_3^A & 0 & 0 & 0 & -E & 0 & 0 & 0 & 0 \\
D_4^A & 0 & 0 & 0 & 0 & -E & 0 & 0 & 0 \\
D_5^A & 0 & 0 & 0 & 0 & 0 & -E & 0 & 0 \\
0 & D_3^B & 0 & 0 & -E & 0 & 0 & 0 & 0 \\
0 & D_4^B & 0 & 0 & 0 & -E & 0 & 0 & 0 \\
0 & D_5^B & 0 & 0 & 0 & 0 & -E & 0 & 0 \\
0 & D_6^B & 0 & 0 & 0 & 0 & 0 & -E & 0 \\
0 & D_7^B & 0 & 0 & 0 & 0 & 0 & 0 & -E \\
0 & 0 & E & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & E & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & E & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & E
\end{bmatrix} \cdot \begin{bmatrix} T^A \\ T^B \\ P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \\ P_6 \\ P_7 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ F_1 \\ F_2 \\ F_3 \\ F_4 \end{bmatrix}$$

4.3 Stochastic Model

The corresponding variance covariance matrix is given for each point observed by:

- For a connection point determined by at least two or more stations:

$$Q_{PP} = Q_{CC} \cdot Q_{LL} \cdot Q_{CC}^{T}$$

For existing control points, we build the variance covariance matrix by conditioning the elements with a near zero variance value or relaxing some of them depending on their stability. It is a well-know process to condition (or relax) the variance covariance matrix to reduce the influence of errors in the control points using the a variance covariance matrix of the form

$$Q_{PP} = \begin{bmatrix} \sigma_X^2 & 0 & 0 \\ 0 & \sigma_Y^2 & 0 \\ 0 & 0 & \sigma_Z^2 \end{bmatrix}$$

- If the coordinates are provided by a GPS antenna collocated with a reflector, we will introduce the corresponding variance covariance matrix obtained after the real time or post processing solution. It's well know however that GPS produces over optimistic precision estimates. Thus it is necessary to scale the main diagonal of the resulting variance covariance matrix to give a more realistic representation of the quality of the solution. Estimation provided essentially by the baseline range scaled by a priori estimator of the standard accuracy of the GPS receiver used.

5. LEAST SQUARES ADJUSTMENT

Having defined the functional and stochastic models we can process this set of linear equations using the Least Squares adjustment method to obtain estimates for all parameters including the transformation set for each station and the coordinates of all connected points.

The Least Squares adjustment method provides the necessary statistical information that is needed to qualify the results in terms of model performance and screening of the individual observations.

The suggested approach is to use the B-method of testing developed by Professor Baarda and promoted by the University of Delft. This method allows for investigation of the internal and external reliability of the solution.

The use of motorized total station equipped with automatic passive reflector recognition reduces considerably the presence of blunder in the observations. Automatic target recognition (ATR) and signal scan technologies significantly reduce sighting errors and enable twenty-four hour day and night monitoring of targets up to approximately six kilometers away.

As we want to investigate in near real time the validity of our adjustment model for each cycle of measurement, we have investigated the use of a pre-adjustment using the L1 norm, which minimizes the weighted sum of the absolute residuals. The advantage of L1 norm minimization compared to the least squares is it robustness, which means that it is less sensitive to outliers which fits very well with the requirement for high processing speed and good quality results.

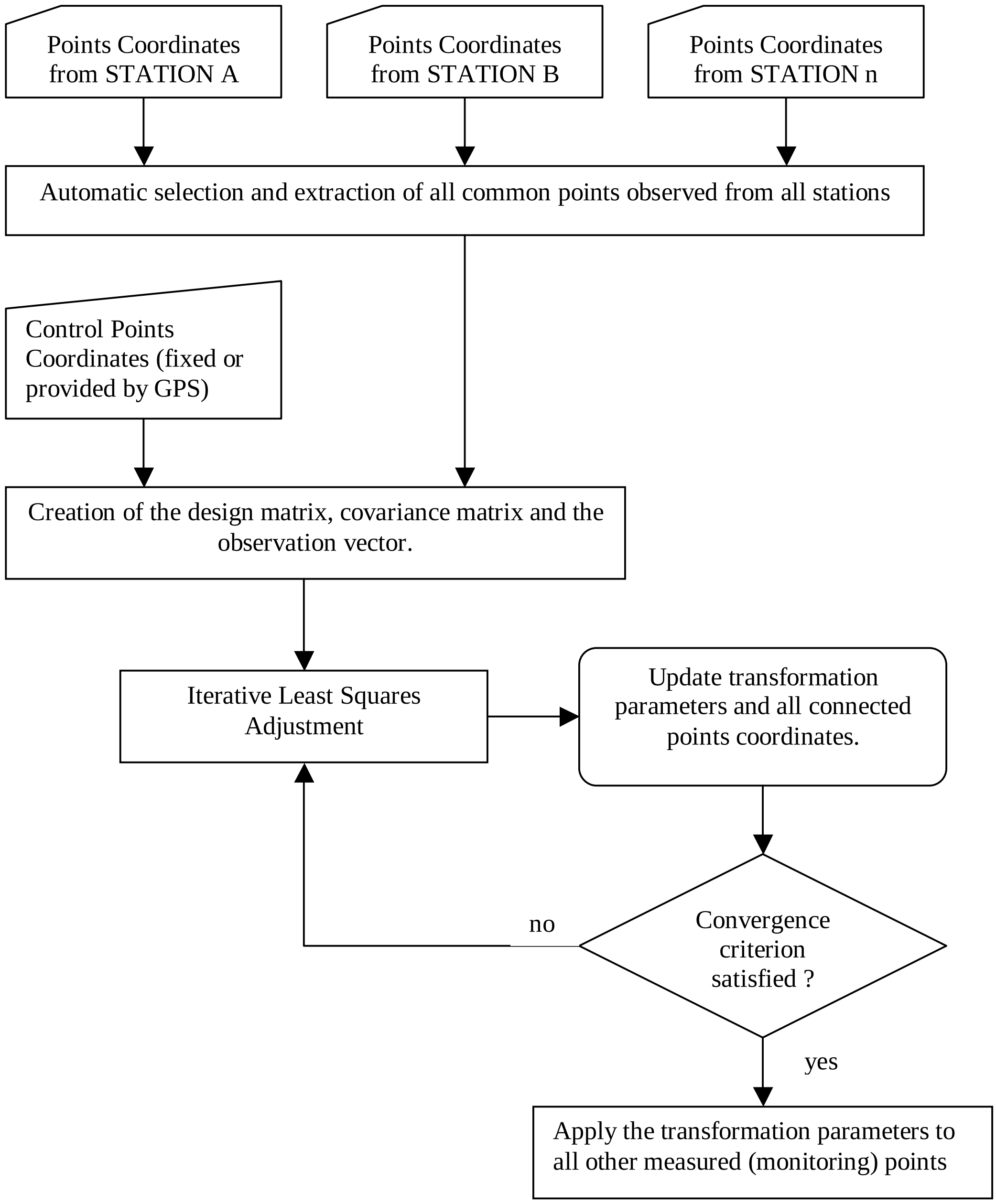
An important consideration for the monitoring network is the number of control points considered as fixed and the optimal number of connected points. For solving the normal matrix based on the functional model we need to have its determinant strictly greater than zero. As a minimum there must be at least two control points determined in 2D and three in 1D (normally we should have three 3D points). Additional control points increase the reliability of the solution by adding redundancy. The geometry of the control is also an important consideration. As always, careful network design will have a major influence on the quality of the results that are obtained from the adjustment. However, unlike with the free station method, the proposed approach allows the control to be distributed around the area by removing the need for all TPS to be able to measure to three control points.

Concerning the optimal number of connected points, we could state some empirical approach, such as having at least three connected points per station. However, the best approach is to use statistical inference based on the B-method. This method provides some estimates for checking the internal reliability that can be used in a pre-design phase to verify that the connected points will provide a sufficient contribution to strength of the network to achieve the desired results.

Another remark concerns the numerical solution of such a linear system. Modern computers have sufficient computational power and memory to easily compute the solution to such problems quickly. However, the structure itself of the design matrix (functional model) can help to reduce the computational burden, which is important for near real time processing. The question is not to how to increase the processing speed, but how to keep the numerical stability of the results well beyond the precision of the observations themselves and avoid insignificant numbers. The authors have compared two different approaches, one based on the symbolic factorization of the normal matrix and one on the modified Gram-Schmidt transformation. Both deliver the same numerical stability. The Gram-Schmidt transformation that all of the coefficients of the functional model including the zero values are stored, but with the advantage that all the variance covariance values and parameters estimation are available simultaneously.

6. GENERAL PROCESS FLOW CHART

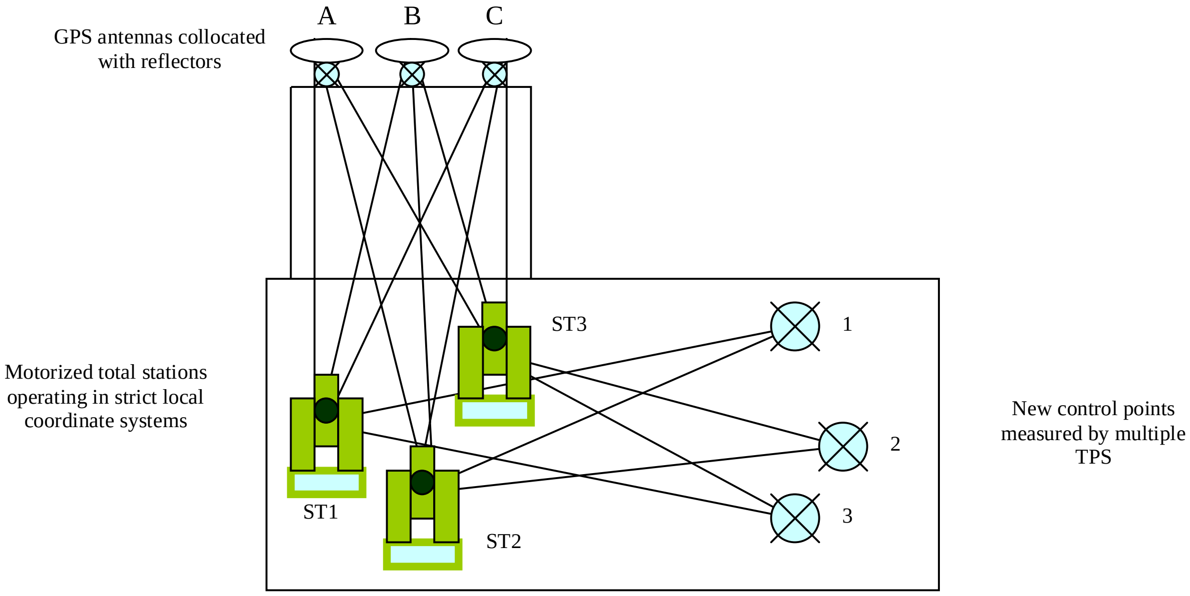
We summarize the complete process into a flow chart representation:



7. PRACTICAL TRIAL

In this trial, the proposed approach has been used in a practical underground project. In this project, three Leica TCA1800 1" motorized total stations with three connected points were used to provide a 3D transfer between three GPS antenna collocated with spherical housing reflectors located on the surface and three control points located in the start of an tunnel designed to study a six kilometer railway tunnel for the European TGV high speed train.

Each total station was initialized within a strict local reference frame (only approximate coordinates and orientation) with their compensator switched off and the total station's main axis unaligned to the gravity vertical. The processing was used to provide a solution to bring the TPS onto a common reference frame and correct for the misalignment of the vertical axes. In this example each TPS was able to measure to three active control points, however this is not a requirement since they are able to measure common points in the deformation area.



Simplified presentation of the Motorized Total Station Network.

The coordinates of the GPS antennas collocated to the reflectors are given in the table below.

	GPS A	**GPS B**	**GPS C**
X	858.6823	856.6066	854.0894
Y	267.7642	262.5281	266.7709
Z	190.3783	190.3775	190.3957

In the first step the measurements from each TPS are processed independently in the reference frame of that total station. The resulting coordinates are presented in the following tables.

Station 1	**A**	**B**	**C**	**1**	**2**	**3**
X	858.6842	856.5128	854.0738		854.6375	856.5948
Y	297.7374	262.5380	266.8269		264.1719	268.0451
Z	190.3813	190.3710	190.3888		158.7635	159.1138

Station 2	**A**	**B**	**C**	**1**	**2**	**3**
X	858.6837	856.6073	854.0906	858.9941		856.5885
Y	297.7655	262.5299	266.7727	264.3069		268.0375
Z	190.3780	190.3775	190.3956	158.7420		159.1205

Station 3	**A**	**B**	**C**	**1**	**2**	**3**
X	858.6830	856.6059	854.0890	858.9941	854.6991	
Y	297.7641	262.5278	266.7714	264.3043	264.1287	
Z	190.3783	190.3775	190.3957	158.7418	158.7700	

The above coordinates are then used in the network adjustment as measurements to compute the final coordinates and the transformation parameters for each total station. The results of the adjustment are summarized below.

Summary of the adjustment
Number of Stations : 3
Number of Target points : 6
Number of equations : 54
Number of parameters : 39
Degree of freedom : 15

Variance Factor after adjustment : 3.01E-06
Standard Deviation Weight Unit : 0.0017 m.

Parameters	**Station 1**	**Station 2**	**Station 3**
Scale factor	0.99976821	0.99988355	0.99986597
Rotation along X	-0.00031	-0.00033	-0.00032
Rotation along Y	0.00068	0.00060	0.00063
Rotation along Z	0.01812	0.00016	0.00022
Shift X	4.92010	0.02621	0.05498
Shift Y	15.52807	-0.16952	-0.21656
Shift Z	0.70873	0.62505	0.64657

The final adjusted coordinates are computed as:

Final	**A**	**B**	**C**	**1**	**2**	**3**
X	858.6823	856.6066	854.0894	858.9741	854.6801	856.5676
Y	297.7642	262.5281	266.7709	264.2950	264.1178	268.0252
Z	190.3783	190.3775	190.3957	158.7449	158.7759	159.1236

With the corresponding a posteriori standard deviation:

Quality	**A**	**B**	**C**	**1**	**2**	**3**
σX	0.0000	0.0000	0.0000	0.0026	0.0026	0.0025
σY	0.0000	0.0000	0.0000	0.0021	0.0021	0.0021
σZ	0.0000	0.0000	0.0000	0.0017	0.0017	0.0016

After the processing of all coordinates, the measurements of all TPS are brought onto a common reference frame. The results have shown a very good coherence and a precision well within the specification of the instrument used. This practical trial has also confirmed the validity of this proposed new model to be used in deformation monitoring, where the TPS may not be placed on stable control, so that changing coordinates and alignment of the vertical axis are a concern.

8. CONCLUSIONS

The concept proposed in this paper allows the use of automatic total stations for monitoring when no stable monuments are available to place the instruments and good control points are in short supply. This concept uses a combination of control and common points located in the deformation area (but which can be considered fixed during the measurement phase) to compute transformation parameters to combine the measurements from multiple TPS. This approach provides a flexible way to introduce new stations into a network, even temporarily, without unnecessary long initialisation.

Considering the use of a total station unaligned to the gravity vertical, this paper introduces the new concept of analytical total station. Mixing GPS coordinate results with total station coordinates in this approach permits monitoring in areas where no stable control is available.

In summary, with todays advanced instrumentation, the users challenge is to review the mathematical models used traditionally to process the observations and take full advantage of the latest technology.

BIOGRAPHICAL NOTES

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