GNSS BASED STRUCTURAL HEALTH MONITORING SYSTEM FOR HIGH-RISE CONCRETE CHIMNEYS

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ABSTRACT

This paper describes results of projects which have been led by the Centre of Applied Geomatics at Military University of Technology since 2008. During this period different solutions were developed to use Global Navigation Satellite Systems as reliable source of construction geometry monitoring. This is crucial to provide studies of buildings and structures safety parameters. CAG MUT developed laboratory and field tests at different objects to create efficient, high accuracy measurement solution for constructions geometry real-time monitoring. Results of the first applications of GNSS based systems on real structures (bridges and high-rise industrial chimneys) in Poland are described in this paper. Results of taken test aim to build efficient and reliable Structural Health Monitoring system for high-rise concrete chimneys. Moreover, measurement and telematics concepts are presented in details.

Keywords: GNSS, GPS, SHM, high-rise structures

INTRODUCTION

Global Navigation Satellite System (GNSS) for monitoring displacements of engineering structures is relatively well known method used successfully around the world [1,14] .From the early beginning potential of this method becomes stronger with new hardware and software solution [2]. The first stage in this process was using Global Positioning System (NAVSTAR) to develop accurate tracking solutions related on post processing differential multiband signal computing. At the end of 90’ it was obvious that GPS is able to serve as alternative sensor for Structural Health Monitoring Systems used in big scale building structures [3]. Today engineers are also able to use GLONASS (Globalnaja Nawigacjonaja Sputnikowa Sistema) satellite signal for positioning. In next few years Galileo satellite navigation system will be released as fully operational. It gives more possibilities for implementation of real-time GNSS solutions on different type of structures to provide continuously monitoring. The development of SHM systems allow for the practical use in cases where other measurement methods were not usable or not effective [6,9,11,12]. All this can be done only under one condition - user has full knowledge about the quality of the data. Otherwise, it would be not possible to detect real deformations from the measurement noise. Standard noise level for GNSS real time solution should not exceed 1cm for horizontal displacement [9]. Noise level as also unexpected errors related with GNSS observation conditions decreases accuracy of the measurement up to tens of cm. Information hit by such error might not be useful for diagnosis and analysis purposes and may cause false interpretation. Based on the experience of research teams dealing with this subject, the author conducted since 2008 to study possible methods for complete characterization of GNSS as a method of measuring the displacement of high rise concrete structures [7].

PROJECT DESCRIPTION

After the end of 2012 an agreement on cooperation between the MUT and Vattenfal Heat Poland was signed. At that time Vattenfal Heat Poland (now PGNiG Termika) was a managing institution of five power plants infrastructure in the mazovia region . Under the agreement MUT was able to access facilities and build periodic laboratory on 300m height concrete chimney in Kaweczyn Power plant. According to sources contained in the online encyclopedia Wikipedia, the chimney is the second highest in Poland, the 18th in Europe and 50 in the world . Created laboratory was based on local server mounted in the technical rooms inside chimney construction.

The scale of the object was a major obstacle in the construction of infrastructure to enable the implementation of the method of measurement RTN.RTK GNSS . At the top of the structure is installed GNSS antenna (19 level design). Use the 20 and 30 meter antenna cables adjusted signal from antennas to receivers located inside the mantle at the 18th level .

Due to the use of Ethernet ports for data transmission (used receivers with built-in modem, Ethernet (Trimble SPS 851 and NetR9) or adapter MoxaRS232 to Ethernet (Receivers Trimble 5700) it was necessary to drag the copper cable to the server installation on a 12th floor. Due to the distance of about 80 meters separating the two points was necessary to use the device amplifying the signal - so-called repeater - at the 12th floor through consultation with the local Internet server provided realizing measured by the GNSS . Equipment mounted at the construction enabled it to provide continuous data for testing and operational purposes by Centre of Applied Geomatics at MUT.

The main objective of developed system was to use real time GNSS methods to obtain reliable information about the state of the geometric and dynamic characteristics of the structure to allow further health investigation [9]. Two key parameters to be measured is a method based on amplitude and frequency of vibration displacement of the structure with a known degree of reliability.

The task of the designed algorithm is:

- Acquisition of measurement data that meet accepted quality criteria.
- Estimation of measurement errors.
- Calculate the displacement amplitudes.
- Calculation of the natural frequency.

These tasks are defined on the basis of qualitative and quantitative requirements for measuring the geometry of structures for its diagnosis method of dynamic [2,4]. As the literature the basic parameters helpful in diagnosing the condition of the structure by this method are about crossing warning and alarm levels of displacements values and frequency vibrations which change over time may be indicative of the occurrence of damage [1,5].

SYSTEM DESCRIPTION

This module algorithm is responsible for carrying out the measurement data used in the later stages of the displacement monitoring process. At the first step the NMEA GGA message is investigated about the key major factors influence at GNSS measurements quality as:

The number of visible satellites

This parameter is taken into account as the first in the filtration process . The value of "0" will mean no satellite signal at the input to the receiver. This may be due to the complete screening of the antenna or the lack of connection between the antenna and the receiver. From our own experience and the literature [3] shows that for a correct determination of the position by real time GNSS is necessary to use the observation of a minimum of 5 satellites.

Coefficient of PDOP (Percentage Dilution of Precision)

The PDOP is another parameter to be taken into account in the process of filtration. According to the recommendations of Polish Head Office of Geodesy and Cartography (Technical Guidelines G-1.12) assumed that the maximum level of PDOP should not exceed 4 during precise measurements. In any other case, the information will be considered as unreliable.

Solution status

This parameter is the information contained in the NMEA stream . This parameter assigns different operating modes of GNSS receiver corresponding number in the range 1-8 . For the operation of geodetic measurements with high accuracy is essential work RTK (parameter = 4). Data do not meet this condition are considered unreliable. 6,7,8 - valued parameters are not used. Parameter with a value of "0" indicates the irregularities related to the visibility of satellites.

The age of the telegram

Another condition that must be met to coordinate the measurement was made with centimeter accuracy is information on the age of the message , i.e., the time (in seconds) elapsed since receipt of the last message from the navigation system to support the work of GNSS. Experience shows that a common problem when measuring method RTK/RTN is the need to ensure continuous access to the source of navigation messages from augmentation systems [3]. Disruption in the continuity of data stream transmission cause errors. The result of increasing age of the message is a dropping down the quality of GNSS solution [10] .

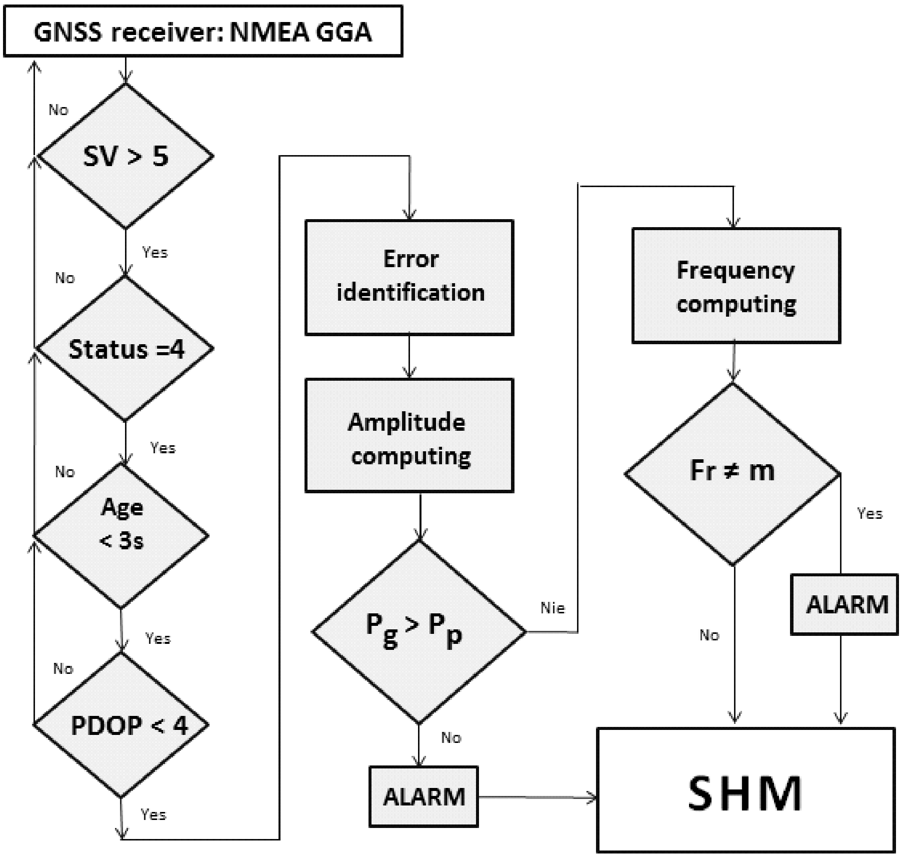

Fig. 1. Filtration algorithm description

Figure 1 shows the main modules and the order of operations performed in data acquisition module. Data processing begins with a series of load data acquisition module. Range of data undergoing analysis stems from the need to register at least a few complete cycles of oscillation of the structure in order to properly determine the frequency of vibration. In the case of the use of data on the frequency of 5Hz full oscillation period includes 25 points. Then the data are verified because of the quality of the observations in the following order (chosen because of the size effect on the final result designate the coordinates): the number of observed satellites, the status of solutions, age correction message, the coefficient of CIT. The order of these parameters was selected because of their impact on the quality of the obtained coordinates [8]. In the event of failure to comply with accepted criteria , the measurement data are marked as unreliable, i.e. not suitable as a source for reliable analysis of the structure. In a further step, the statistical analysis and data filtering are done to eliminate data outliers. This kind of errors are generally: multipath signal momentarily obscure the horizon or atmospheric disturbances that cause cycle slips [1]. Based on the data after filtering amplitudes are calculated in x and y direction in 2000 reference system . If the assumed threshold is exceeded , an alarm is signaled directed to the SHM or BMS (Building Management System). The last step of the algorithm is to determine the oscillation frequency to track the differences related to changes in the material structure [4]. If the change exceeds the established criteria, an alarm is triggered forwarded to the SHM. Obtained in this way, information can be collected and periodically removed after a certain time, such as one day. These data will be used in further works by the construction engineers during diagnostic process.

RESULTS

Figure 2 shows sample results of using designed system from period 11.01.2012 11:00:00-11:00:25. The average wind speed was approximately 15m/s Frequency designate position - 5Hz. First two data sets shows horizontal displacements in east-west and north-south directions. It is easily seen that in those weather conditions the Karman vortex effect can be easily seen and investigated.

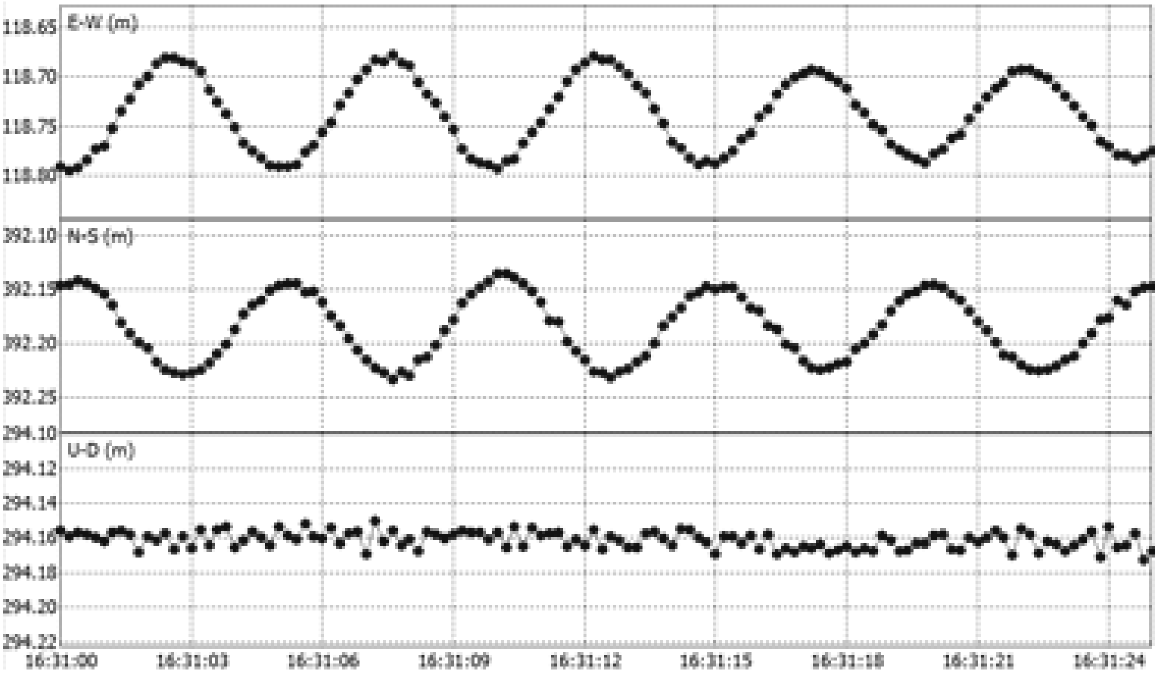

Fig. 2. Sample result of measurements took during 15 m/s wind loading on the 300m concrete chimney.

SUMMARY

As a result of the described algorithm it was possible to develop tools that meet the required functionality and boundary conditions of diagnostics purposes. Fulfilling them is to ensure effective selection of data and reduce errors in their interpretation. For the purposes set out above analysis is based on data obtained during several measurement campaigns in the past five years. The results obtained from the comparison of two independent measurements indicate the possibility of measuring the amplitude of displacement of the structure with an average error not exceeding 1 cm. Observation characterized by large errors are possible to identify and remove in the process of appointment of the amplitude and frequency of vibration of the structure. Only apply full control to the extent described above algorithm allows the direct use of GNSS as a input for diagnostic systems.

The solution developed based on the experiences of the past five years can be implemented in practice. Confirmed experimentally [11,12] utility measurements conducted by the GNSS allows to increase the efficiency of the diagnostic process design.

As a result, SWOT analysis of using GNSS in SHM systems is written below:

- Strengths
  - Determination of position changes in three directions - Positioning GNSS allows you to specify changes in the position orthocartesian defined by the user
  - Automation of measurement - measurement is performed unattended automatically without operator intervention which allows unattended operation when the system starts.
  - Fast measurement - the measurement result using RTK / RTN available immediately (if there are no adverse observing conditions affecting the implementation of the differential phase measurement) [2].
  - High accuracy - Differential GNSS measurements allow you to specify the position of a single point with an accuracy of 0.5-1 cm in the post-processing. Use of the method allows to achieve RTK accuracy of 1 cm for the horizontal components [2].
  - High frequency of acquisition - the possibility of registering the data with a frequency of up to 20Hz . Most of the current market geodetic GNSS receivers is based on the measurement card tracking satellite signal with a frequency of 20Hz. Some of the producers (Javad, Novatel) provide solutions to determine the position of the frequency to 100Hz.
  - Distant to reference base - through solutions NRTK network can be implemented measure to stable external reference system [4,5].
  - Without measurement of survey reference points - With the use of existing GNSS ground augmented infrastructure measurements of displacement can take place without the need for additional operations such as matrix measurement reference points or stabilization. All activities related to the setting of benchmarks carried the network administrator. The effective implementation of the provisions of the Law Surveying and Cartography and the accompanying guidelines ensures high reliability (accuracy) of the reference base constituting the control points of the base.
  - Work at night and during the difficult (for the observer) weather conditions - thanks to this structure, it is possible to monitor continuously for longer periods casu daily allowing inference of geometry of the structure induced changes thermal loading [8].
- Weaknesses
  - Limited credibility - random errors necessitate ongoing follow-up and quality control services to support the process of designation position [15].
  - Limited accuracy - Dynamic change in the conditions of observation during the measurement results in a lack of stability of the results and change of coordinates in the range of ± 0,5 cm for the horizontal component.
  - Need to support the information from the outside - to achieve high accuracy requires the participation of additional information in the process of designation position [6,12].

- Opportunities
  - The use of ASG- EUPOS - New opportunities creates launched in June 2008 Active Geodetic Network - EUPOS (European Position Determination System) support the work of mobile receivers operating GNSS RTK method. In 2012 began the construction of three private networks of reference stations to be met similar to ASG- EUPOS features for users GNSS specific brands. Increase of competitiveness contributes to the gradual improvement of the quality of services provided real-time and thus the quality of the measurement results of displacement.
  - The ability to use the method of RTK / RTN measurements of fast movements where the influence of errors due to the conditions of observation is smaller because of its long-term character. The examples from the literature and our own experience indicate the possibility of measuring the magnitude of the displacement amplitude of the average error of < 1cm.
  - Verification of data quality - Current control observation allows for quick detection of gross errors caused by a momentary loss of status "fix".
  - Integration of the antenna, receiver and modem in one device - Trends in the construction of GNSS receivers allow today the use of instruments in one box containing all the necessary elements to implement measured by RTK or RTN.
- Restrictions
  - Exposed horizon - This requirement is crucial for the use of GNSS technology, regardless of the measurement method [10].
  - Susceptibility of observation conditions in a method for RTK / RTN - nature of errors in these embodiments prevent the real- time monitoring of the cyclic movements of a value below 0.03 m [12].

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REFERENCES

[1] Ashkenazi V., Dodson A.h., Moore T., Roberts G.W. Monitoring the movement of bridges by GPS, Proc. ION-GPS-97, The 10th technical meeting of the satellite division of Institute on Navigation, Kansas City, USA, pp.1165-1172, 1997.

[2] Ashkenazi V., Dosdson S.H., Moore. T., Roberts G.W. Real Time OTF GPS Monitoring of the humbler bridge, Surveying World, 4(4), pp.26-28,

[4] Cosser E. Bridge deflection monitoring and frequency identification with single frequency GPS receiver, Institute of Engineering Surveying and Space Geodesy, University of Nottingham, 2003.

[5] Diggelen F. GPS and GPS+GLONASS RTK. ION, Kansas, pp. 139-144, 1996.

[6] Diggelen F. A-GPS: Assisted GPS,GNSS and SBAS. Norwood, MA: Artech House, 2009.

[7] Figurski M., Wrona M. GNSS-based Multi-Sensor System for Structural Monitoring Applications. Proceedings of the 2012 International Technical Meeting of The Institute of Navigation, Newport Beach, CA, pp. 186-194, January 2012.

[7] Klobuchar, J.A. Ionospheric effects on GPS, Global Positioning System: Theory and Applications, Volume I, Chapter 12, pp. 485-515, Washington (D.C.): AiAA, 1996.

[8] Lamparski J., Świątek K. GPS w praktyce geodezyjnej. 2007.

[9] Larocca A.P.C., Shaal R.E. Milimeters in Motion – Dynamic response precisely measured. GPSWorld, vol. 16, No.1, pp.16-24, 2005.

[10] Tamura Y. A proposal of simultaneous monitoring of responses of tall buildings in an urban area during strong winds and earthquakes using GPS-Construction of a new disaster prevention system, Res. Archit. 139, 2000.

[11] Tamura Y., Matsui, M., Paginini, L.-C., Ishibashi, R., Yoshida, A. Measurements of wind-induced responseof buildings using RTK-GPS. Journal of Wind Engineering and Industrial Aerodynamic 90, 1783-1793, 2002.

[12] Tamura Y., Suganuma, S. Evaluation of amplitude-dependent damping and natural frequency of buildingsduring strong winds. Journal of Wind Engineering and Industrial Aerodynamic 59, 115-130, 1996.

[13] Tamura Y., Yoshida, A., Zhang, L. Damping in buildings and estimation techniques. Proceedings of the 6th Asia-Pacific Conference on Wind Engineering. Seoul, S. Korea, Sept. 12-14, 193-214, 2005.

[14] Wrona M., Bogusz J., Nykiel G., Szołucha M., Szymański P. Zintegrowany system kontrolno-monitorujący dla obiektów inżynierskich – koncepcja i wyniki testów. Logistyka, Poland, vol. 6,str. 237-247, 2011.