# SYSTEM OF MONITORING OF THE FOREST OPERA IN SOPOT STRUCTURE AND ROOFING

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## ABSTRACT

The authors present a solution realized in Forest Opera (name in Polish: Opera Leśna) in Sopot (Poland) in connection with the modernization and construction of a new roof. The complicated structure of the roof of the facility and the used covering in form of membrane made of technical fabric required (for security reasons) to install the unit of devices allowing for the continuous geodetic monitoring of the facility.

Monitoring of relocations in case of engineering structures of a complex design allows for the extended safety of their use. Realized (for this purpose) geodetic measurements require (to be useful) a high accuracy, full automation making the assessment independent from the human factor and the use of reference points.

The main element of the presented system is a motorized total station used for the determination of roof cover relocations, whereas the complementary elements are vibration and temperature sensors and weather conditions monitoring station. Data recorders from the entire facility are connected to the computer central unit, providing automation of measurements and archiving of results along with their analysis.

The problem occurring in the analyzed object is relatively unstable (subject to vibration) total station. Therefore, the solution implemented for Opera Leśna in Sopot assumes, that it is required to carry out measurements against reference points before every measurement of controlled points. On the basis of these measurements, for each measurement epoch the coordinates and relocation vectors for the tachymeter station are checked as well as analyses of an accuracy suitable for this process. The solution of this problem is useful for monitoring in other movable or subject to relocation engineering facilities.

The article signalizes the problem of accuracy of surveying. For this purpose, the preliminary analyses of an accuracy were carried out. They made it possible to determine the expected errors of the reference points location in the designed network geometry and position of the total station for two variants: with and without taking into account the erroneous of reference points location.

To summarize, we can say that the automatic measurement systems are an appropriate method for the continuous observation of the construction condition, however, they must be based on accurate, repeatable (for each measurement epoch) analyses of the observation of both monitored elements as well as their spatial references./

**Keywords:** geodetic monitoring, system concept, measurement of technical textiles, the structure load measurement

## INTRODUCTION - CHARACTERISTICS OF THE FACILITY

Currently, the building constructions are an increasing challenge for the engineers - the structures have wider and wider span and a a large number of people may stay inside them. These are factors to look for new, more innovative solutions to ensure the safety of the facility during its use. Due to the use of computer programs to design and analyze structure work, it is important for these solutions to provide the full automation of the structure control measurements.

Therefore, more and more popular are monitoring systems allowing to examine the specified structure parameters in a continuous mode and to compare them with design parameters [2-4,6-7,9-16,18-20]. This is advantageous not only to improve safety, but it also supports the maintenance procedures.

One of the objects in which the automatic monitoring system is installed is the Forest Opera in Sopot. Performing the continuous control measurement is necessary due to the custom construction of this facility [1,8,21].

Roofs cover as a form of leaf is designed as made of technical fabric with a thickness of less than 1 mm. The structure is made up of 10 segments spanning between catenaries, edge lines attached to the supporting pillars and arches. These arches, due to the terrain conditions have been designed as steel tubes with spans of 102.96 m and 93.20 m. The maximum span of the membrane roof covering is 104 m and the total length – 85 m.

With such a roof structure, there is a possibility of the occurrence of large deflections caused by the retention of snow cover. In the most unfavorable loads configuration, the designed displacement of the membrane for the boundary supporting condition can reach of even up to 1.9 m.

## A SYSTEM OF ROOFING STRUCTURE MONITORING

The response to the need for constant supervision of movements and other operating parameters of the structure is a monitoring system consisting of four modules: the measurement, analysis, expert and notification module. All the modules are linked together to form one coherent system.

The initial module is a measurement module which includes all the measuring devices and the system of data processing and transmission. The main element of the measuring module is a motorized Leica TS 15I tachymeter with 32 prisms representing the displacement measurement points of roof covering and reference points. Complementary elements of the measuring part of the system are 4 acceleration and temperature sensors, weather station and video surveillance cameras. The arrangement of the measurement module elements is presented in the figure 1.

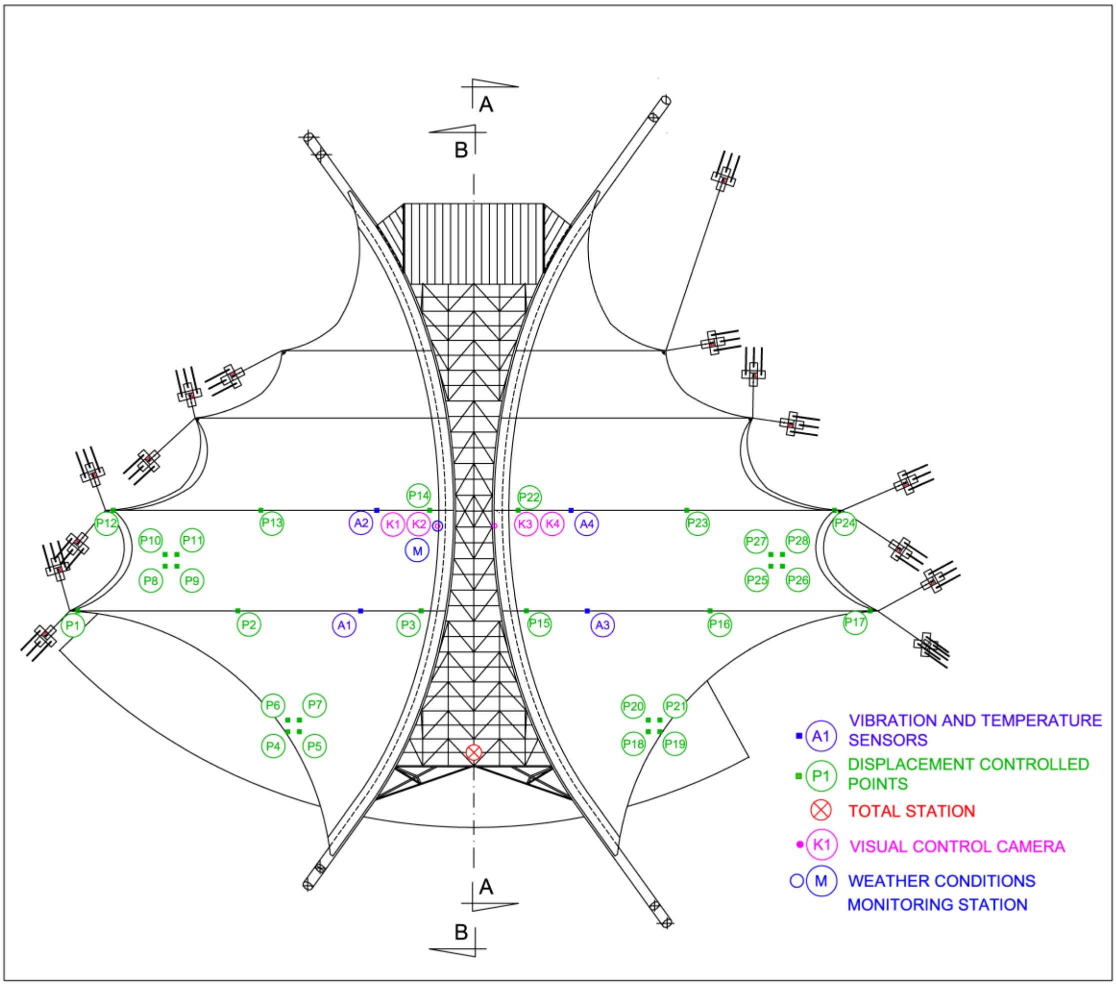


**Fig.1. Location of the covering surface monitoring elements - view from the top: A - acceleration and structure temperature measuring point, P - points of the measurement of covering surface displacement, K- camera outside the surface of the covering, M - meteorological station, ⊗ - a tachymeter station (TotalStation).**

The measuring module is designed to provide information about the movements of roof covering, vibration and temperature of lines and concerning the general conditions in the premises of the facility as well as it has to send data to the analysis module.

**Analysis module** is designed to analyze the signals and process data from the measuring elements and camera. These data are compared during the numerical analyses with design values. The obtained information as well as the images from the video camera are transmitted to the expert module.

**Expert module**, otherwise known as the database module, on the basis of measurement data and threshold values allows to determine the current condition of the structure. It was assumed that there can be three conditions: "Safe structure", "Alert Status" which indicates the need to perform certain actions in order to restore the structure safety or "Fault", when an immediate evacuation of people within the entire facility is required. This module allows to collect data.

The main function of the **notification module** is to provide information on the construction, as well as the archiving of collected data. The main component of this module is a web portal of SMK Forest Opera. It allows to present the current measurement data, view from the cameras, as well as the structural condition determined by the expert module.

The main type of measurements are surveying which are supported by data from other sensors. The use of accelerometers, allows you to (among others) check whether the lines were not put in very strong vibrations during measurement for prisms on catenaries because that would result in a misstatement of the measurement.

Geodetic measurements are designed to determine the displacement of catenaries and the membrane cover spanned on them. For this purpose the automated TS 15I Leica photo-tachymeter was used. It is characterized by high accuracy of measurement which is required for measuring such type of the structure. The tachymeter performs automatic series of observations to prisms mounted on an roof covering, presenting measurement points and to the prisms mounted on the foundations of the main arches - reference points.

**Fig. 2. Location of the box with TotalStation.**

A some kind of difficulty to carry out the surveying was the necessity to protect the tachymeter against the weather conditions. For this purpose, on the basis of the analysis of controlled points arrangement, the special box was designed. Its structure provides the results of measurement depending on the refraction influence in some, negligible way.

Box (Fig. 2) is a housing for tachymeter and powering components. It is designed and prepared specially for the necessity of Forest Opera roof monitoring system. It aims to protect the tachymeter against adverse weather conditions, as well as to provide them operational safety.

The bottom and roof of the box are constructed of stainless steel, and all the side walls are made of glass with a thickness of 3 mm. Glazing of all the side walls allows to monitor existing points of displacements measurement, as well as those which in the future may be additionally mounted on a Opera covering. The box is attached to the technical platform.

**Fig. 3. GMP104 prism.**

At points of displacement measurement and at reference points, the precise Leica GMP104 prisms were located (Fig. 3). The prisms include a metal L-shaped bracket, allowing for the installation in the appropriate point on the structure. They allow for the measurement of directions and distances between the tachymeter and the signaled point.

The box was designed on the basis of the analysis of location of all measured points in such method that the angle between the surface of the windscreen and a beam range of the rangefinder was the closest to the right angle. Thanks to this, during the measurement, the rangefinder beam is only slightly deviated. This allows to obtain the measurement results that will be negligibly dependent on the influence of refraction.

General distribution of controlled points using a tachymeter is shown in the Fig. 1. It can be seen that they are placed on the largest (in terms of the surface) membrane sheets and catenaries. The measurement points located on the membrane are arranged in the squares (Fig. 4 and 5), and the coordinates of each controlled point are determined every hour.

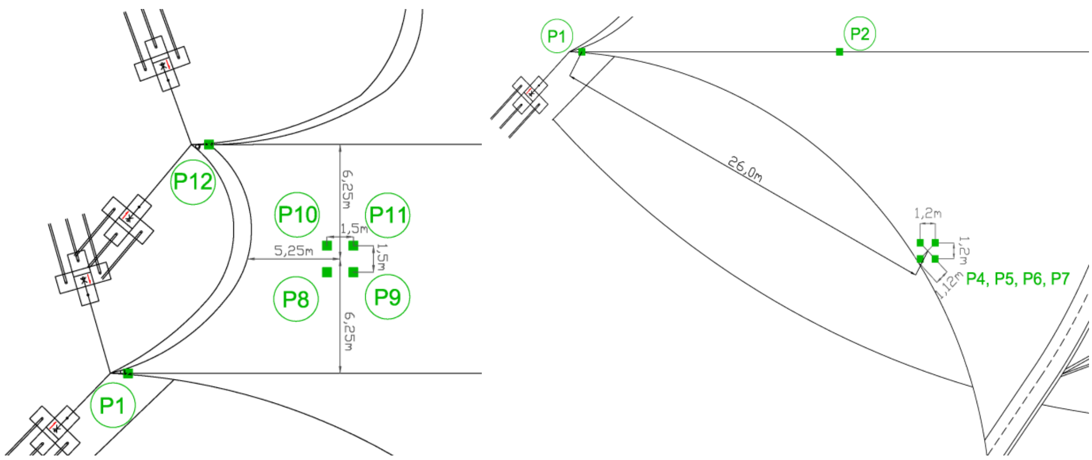


**Fig. 4. Detailed arrangement of controlled prisms on the membrane.**

**Fig. 5. View onto the Opera covering with GMP104 prisms installed on the membrane.**

Table 1. GMP104 prism parameters:

| | |
|---|---|
| measurement range | 2000 m |
| prism constant | +8.9 mm |
| series | Professional 1000 |
| laser beam deviation | 6” |

Table 2. Parameters of Apek AV32Lan.12 system:

| | | |
|---|---|---|
| acceleration | Range | 0.1-100 Hz |
| | Resolution | 0.001 g |
| Temperature | Range | -35°C÷70°C |
| | Accuracy | 0.1°C |
| Wind direction | Accuracy | 5° |
| Wind speed | Range | 0÷50 m/s |
| | Accuracy | 1 m/s |
| Air humidity | Range | 0÷100% |
| | Accuracy | 1% |

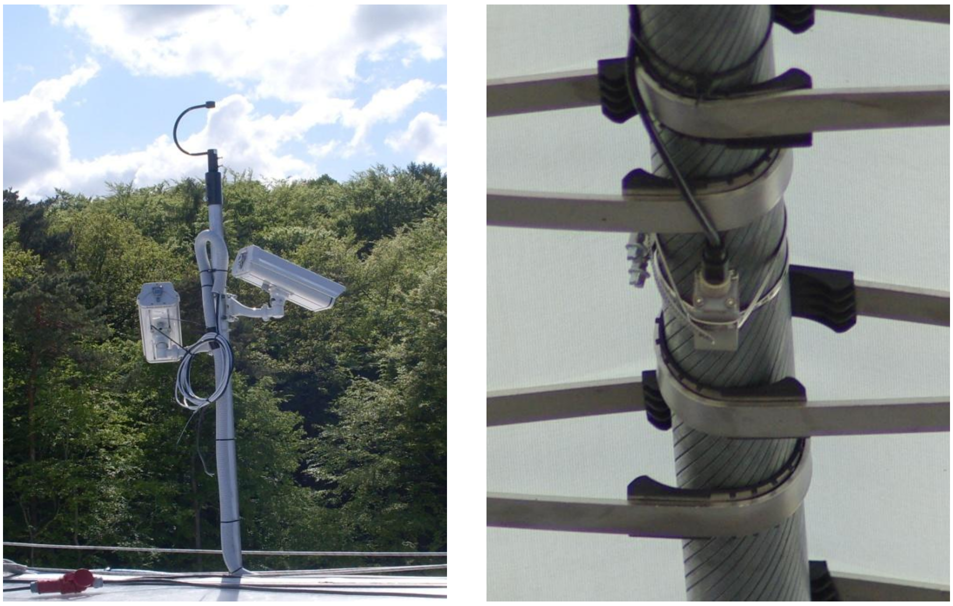

**Fig. 6. Apek AV32Lan.12 - Weather Station (left)
and Apek AV32Lan.12 - acceleration and temperature sensor (right).**

Apek AV32Lan.12 system (Fig. 6) is a set of devices designed and manufactured for the purpose of Forest Opera covering technical monitoring system. The system performs registration of measurement data from 4 acceleration sensors, 4 structure temperature sensors, wind direction sensor, device which measures the wind speed, humidity sensor and air temperature sensor. The data from Apek AV32Lan.12 system recorder are sent to a central management unit. Table 2 shows the basic parameters of the system.

For the image recording and collection on the additional information on the condition of the covering and snow coverage on the technical fabric, the TV-IP512P cameras were used. This solution is used for remote monitoring and high quality video transmission in the real time via Internet. Advanced options include, among others, email notification, compressing to MPEG-4 / MJPEG formats, full-duplex audio signal, interchangeable lenses, digital zoom and built-in SD card slot which allows you to record images directly to a memory card.

Central management unit has been designed and constructed for the purposes of Forest Opera structure technical monitoring system. It was developed on the basis of the Fujitsu – Siemens Primergy line server.

In order to ensure an uninterrupted power supply for the monitoring devices in Forest Opera, the UPS PowerMust 2000 USB Mustek module was used.

## CONCLUSION

Roof covering of the Forest Opera, due to the shape and used material is an untypical structure. Even today, there are only a few facilities of this type with such a large area of technical fabric and the span between catenaries. Uncertainty in the way of untypical structures work makes the Forest Opera monitoring system an important component providing data on the operation of the structure of the covering itself and the steel structure of main arches.

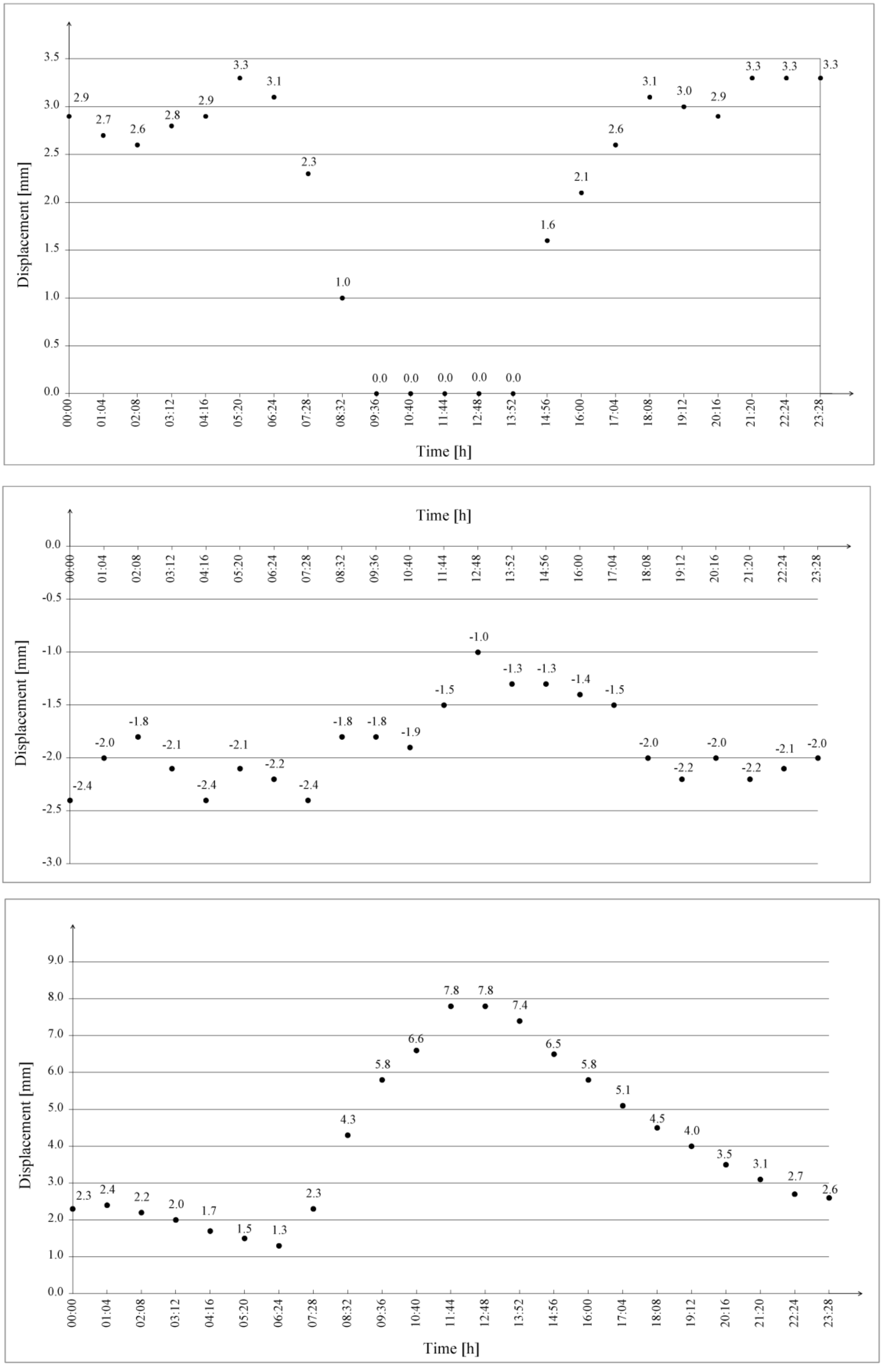


**Fig. 7. Displacements TotalStation – the registration of one day.**

Automatic measurement systems are an important element in increasing the safety of facility usage. They allow to obtain information on actual and not only designed work of the monitored structure under various conditions and this is important during further operation of the facility.

But we should not have an uncritical attitude to the operation of automated systems. From time to time, their work should be monitored during the traditional measurement.

The system allows for ongoing monitoring of covering construction parameters and deflections of the technical fabric, thanks to which, the safety of facility usage will be increased. This is important because of the mass events organized in the facility. The advantage of the installed monitoring system is the use of the latest technologies. Not without significance is the fact that some devices were designed specifically for the needs of the system, allowing for their better adaptation to the monitored structure. Implemented automation allows for remote management of the system, without the necessity to perform measurements alone. It is a great facilitation, because observations can be performed in a continuous mode, and thus, the design parameters and deflections are checked on the regular basis. It enables rapid response in case of exceeding the specified values. In addition, the high quality equipment allows to perform measurements with very high accuracy which, as demonstrated in preliminary accuracy calculations, allows to determine the coordinates of the reference points with an accuracy of 1 mm.

The installation of prisms on the reference points was very important from the perspective of the proper operation of the system, because as stable reference points they allow to calculate the change in the location of tachymeter, installed on the technical platform.

According to preliminary analyzes, the geometry of reference points allows to obtain high accuracies of the results. It should be however taken into account that for the purpose of calculations, the average errors in the observation, determined on the stable station were used and it was assumed that $m_0{}^2$=1. During calculations of the tachymeter position displacement, the calculated values $m_0$ parameters were within the range of 2.86 to 4.65, allowing to notice, that the errors assumed tor the calculations of preliminary accuracies have low values. For greater reliability of the calculation, it is necessary to determine precisely the average distance measurement errors, and horizontal and vertical angles separately for each observed point [5,13,17].

In order to improve the measurement algorithm, the observed points should be divided into three groups. The first group would be created by reference points. located on the foundations of the main arches. The second group would include control points, located on the membrane covering, and the last group would include controlled points, located on the catenaries. An accurate measurement cycle should be developed on the basis of the detailed analysis of displacement increase of each group of prisms.

The issues not included in the first version of the system, and which are very important for full functionality of the monitoring system include the analysis of the tachymeter displacement for under the various weather conditions and different seasons.

Analyzing the tachymeter displacement, pre-registered during one day (Fig. 7), it can be noticed that during day time, the vertical displacements increase along with the increase of temperature. For this reason, it is important to determine the relation between the displacements of the tachymeter station and the ambient temperature. This analysis will allow you to optimize the number of measurements made to the reference points.

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