Modeling of temperature distribution of engineering objects on the basis of data obtained from a thermal imaging camera and geodetic instruments

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Abstract. In the modern world, collections of various types of data have become the most valuable commodity. Data is obtained automatically or manually and comes from various measuring techniques, monitoring systems, sensors or methods of tracking human activity on the Internet. This combined with the idea of intelligent devices, which can automatically exchange data (Internet of Things), creates unimaginably large sets of data that seem to be unrelated to each other. Only the application of advanced Big data analysis can detect connections that are not visible at first glance. A common desire to integrate various types of measurement data also applies to engineering facilities. In the case of modeling temperature distribution, the integration of data from terrestrial laser scanning and thermovision, i.e. mapping of thermal images on point clouds, is very popular. This provides a three-dimensional representation of the tested object enriched with information about temperature. These types of models are used to identify damaged parts of the object, determine the size of leaks (e.g. heat and/or air leaks) or perform thermal analyses. In the classic approach, modeling of temperature distribution is performed in two-dimensional space using a set of quasi-continuous thermographic images with a colored scale or a set of point data with temperature values measured at a specific time. In the latter case, we can talk about the integration of spatial data (regarding the location of points, obtained by geodetic techniques) with the results of point measurements of temperature made by physical techniques (e.g. contactless pyrometer). The combined data sets can be further analyzed, e.g. using geostatistical methods, enabling continuous temperature distribution model to be obtained. This article presents the three-dimensional integration of data from two measurement techniques and methods to model the temperature distribution in two-dimensional space. Three-dimensional spatial integration concerned the point cloud acquired by terrestrial laser scanning and thermal imaging. The measurement object was a fragment of the ventilation system in the underground car park. Modeling of temperature distribution in two-dimensional space uses an unusual data source, which are temperature readings from a precision level, obtained during measurements of vertical displacements of a multi-level underground parking structure. These data, combined with images from a thermal imaging camera, enabled performing thematic maps of temperature distribution to be made using the IDW method and ordinary kriging. These maps can help in the future to interpret the values of vertical displacements of the parking structure.
1. Introduction

Temperature is one of the most important environmental factors that affect building structures and their surroundings. Temperature fluctuations can cause geometric and structural changes in the tested objects, as well as affect the operation of measuring instruments. Ensuring the reliability of the obtained measurement results usually requires considering information on the environment, especially about temperature.

Until recently, the research on the influence of temperature on engineering facilities was based on direct temperature measurements with contact or non-contact devices [1]. Modern geodetic instruments during measurements also record temperature values of the tested object or its surroundings. An example of such a device may be a digital precise level, which during the registration of each invar leveling staff reading also measures the ambient temperature of the instrument. As follows from the available literature, this type of data is usually omitted, but could be used for further analyzes of the tested object, e.g. assessment of the influence of temperature on the values of recorded settlements of buildings.

The current technological progress and the emergence of modern measurement solutions, such as terrestrial laser scanners, have increased the popularity and the availability of research that allows assessing the effect of temperature on buildings and engineering structures. The combination of terrestrial laser scanners and thermal imaging cameras [2] allows creating models of temperature distribution in three-dimensional (3D) space. In addition, the increase in computing power and the development of computer procedures for the reconstruction of 3D models, allow the creation of 3D models based on digital and thermal images only.

The main purpose of the research presented below was to model the temperature distribution that prevailed during geodetic measurements of vertical displacements of a multi-level underground car park, based on data from a precise level and a thermal imaging camera. The second aim was to visualize the spatial temperature distribution of the parking technical infrastructure element (a ventilation duct) based on integrated measurement data obtained by a terrestrial laser scanner and a thermal imaging camera.

2. Methods

The issue of measuring and modeling the temperature distribution of the object or the air inside the object can be considered in two- and three-dimensional space, considering the specificity of the measurement methods and modeling algorithms used. The most important of them are described below.

2.1. Thermography

Thermography, also known as thermovision, is a method based on assessing the temperature distribution on the surface of the analyzed object in a non-contact and remote way [3]. The measurement is performed with a thermal imaging camera, whose operation is based on the process of converting the infrared radiation reflected by the analyzed object into an electric signal. This signal is converted into a thermal image visible on the screen of the device [4], [5].

Depending on the intended use of thermal images, the measurement methods are different. For example, the measurements involving small areas of the test object can be performed stereoscopically. More modern measuring methods, emphasizing the collection of large amounts of data, are based on automatic or semi-automatic processes for obtaining thermograms. For such methods could be include measurement with thermal imaging cameras mounted on car roofs or unmanned aerial vehicles, in which a large number of overlapping thermal imaging is generated. However, the main field of thermovision applications is still industry and construction, where non-space-oriented thermograms
are obtained or the thermograms are combined with other measurement techniques, most often with Terrestrial Laser Scanning (TLS). The thermal imaging camera can be integrated with the laser scanner, which allows direct coloring of the point clouds, or the thermal imaging is performed separately. Then it requires thermograms processing based on control points and subsequent coloring of point clouds [6].

2.2. Terrestrial Laser Scanning (TLS)
The TLS is a method of obtaining data about the geometry and properties of the measured object based on the measurement of angles and the distance between the surface of the tested object and the instrument (scanner), which is mounted on a stationary tripod (scan station). The scanner emits a laser beam at a given frequency, which is reflected from the object and returns to the instrument. Each reflection is recorded as the spatial location of the point for which the coordinates are determined. The final result of the measurement is a point cloud and each point has X, Y, Z coordinates and parameters characterizing the laser beam reflection properties (e.g. intensity, reflectance, RGB color).

Typical processing of acquired data includes: registration of scans, filtration and 3D modeling. The registration consists in transforming point clouds (scans) into the coordinate system of one chosen scan station (relative orientation) or a specific coordinate system (absolute orientation) [7]. The filtration involves the initial elimination of interference (so-called noise, e.g. scanned raindrops) and unnecessarily scanned objects. After filtration, the data can be modeled. One of the popular modeling methods is the construction of MESH, i.e. the approximation of the object's surface using a triangle network with vertices located in a point cloud [8]. Another popular modeling method is to fit geometrical solids into the appropriate sub-areas of the point cloud. There are many computer programs on the market for 3D modeling of point clouds offering original algorithms.

2.3. Modeling of temperature distribution
Modeling of temperature distribution is performed in two-dimensional (2D) or three-dimensional (3D) space. The simplest form of representation of models of temperature distribution in 2D space is a set of thermograms with a color scale, showing the temperature values assigned to the individual colors. Another way of visualization can be to show the points with the value of the measured temperature recorded at a specific time on appropriate surfaces. Due to the poor readability of this method of presentation, usually continuous temperature field interpolation is performed using geostatistical methods. In the literature, temperature modeling is discussed primarily in the context of climatological research (e.g. [9], [10]). The most commonly used interpolation methods include various types of kriging, Inverse Distance Weighting (IDW), Thiessen polygons, etc. With the use of temperature distribution models from several periods, their gradient can be determined [11].

Modeling of temperature distribution in 3D space is performed primarily on the basis of thermal images or by integrating point clouds obtained from TLS with thermography. The first method is based on automatic or semi-automatic processes for generating 3D models from disordered collections of infrared images. In work [12], the output data was thermovision and digital imaging. The images were combined in the Photomodeler Scanner software and the final 3D model was prepared using the DMS algorithm. It is a complex modeling and data processing technique that searches for corresponding surfaces in a regular grid. In the article [13], thermograms matching was performed using the ASIFT (Affine Scale Invariant Feature Transform) algorithm in PW (Photogrammetry Workbench) software, which also generated a 3D surface model. The second method of modeling thermal data in 3D space is presented, among others in [6]. There the authors proposed to obtain data from: 1) the proprietary two-camera system "Bi-camera" (consisting of a digital camera and a thermal imaging camera), 2) a terrestrial laser scanner on which the NIR (near-infrared) camera was mounted and 3) an independent digital camera. The 3D thermal model was reconstructed in Rieg's Riscan Pro software. Another example is presented in [14], where the data was obtained from an “Irma3D” robot.
(designed and made by the authors of this publication), which consisted of a laser scanner, a web camera and a thermal imaging camera.

In this work, modeling of temperature distribution in 2D space was made based on geostatistical methods. There is no universal method for temperature distribution modeling in the available literature, especially for engineering facilities. For this reason, it was decided to conduct a preliminary analysis of three selected geostatistical methods for the data sample, and then choose the best method and apply it to the rest of the data being developed. For testing, the following methods were selected: kriging (ordinary and simple) and the IDW method, which are briefly characterized below.

Kriging is a stochastic interpolation method that studies the isotropic distribution of a phenomenon. It is used for data for which the spatial relationship between the direction or distance was found. Forecasts are based on certain weighted averages of data [15]:

$$z^*(x_0) = \sum_{i=1}^{N} \lambda_i \cdot z(x_i)$$

where:

- $z^*(x_0)$ is the predicted value,
- $x_0$ is a target point for which we search for a value,
- $z(x_i)$ are measured data and the $\lambda_i$ are unknown weights of the sample value. Due to the applied calculation algorithm, a number of kriging methods are distinguished: simple kriging, ordinary kriging, universal kriging, kriging with a trend, co-kriging, etc.

The second tested IDW method is a deterministic method in which the values of the variable at the interpolation point $Z$ are determined on the basis of the weighted arithmetic mean of the surrounding measurement points [16]:

$$Z = \frac{\sum_{i} p_i z_i}{\sum_{i} p_i}$$

where:

- $z_i$ is the value of the variable at the measuring point, and $p_i$ is the weight factor of points, which is taken as the inverse of the square of the distance between interpolated and measuring points.

In the case of modeling the temperature distribution in 3D space, the source data most often comes from laser scanners with an integrated thermal imaging camera ([6], [14]). In the case of separately obtained data (as in this work), thermograms are superimposed on the processed point cloud as a consequence of the transformation of raster images based on known coordinates of characteristic points (identified in the thermal image and the point cloud).

3. Results and discussions

3.1. Description of research objects

The study uses two research objects marked with letters A and B. Object A is a five-level underground car park next to the public building (figure 1a), where individual floors/levels are designated as: 0.5, 1.0, 1.5, 2.0, 2.5, 3.0. Object B is a fragment of a one-level underground car park belonging to the Wrocław University of Science and Technology. The measurement covered three cavity walls and the technical installations suspended to the ceiling (figure 1b).
3.2. Modeling of temperature distribution in 2D space – object A

The following data were used to develop 2D temperature distribution models: 1) files from the Trimble DiNi 0.3 precision level in the native format *.dat covering three measurement campaigns (no. 16 from August 2017, no. 20 from December 2017 and no. 23 from March 2018), 2) thermal imaging taken during measurements in March 2018, and 3) sketches of the interior structure of the parking levels. In the scientific literature, no examples of the use of temperature data obtained from the precision level were found, so it is an innovative method, gathering the data source that has been omitted until now.

The first stage of the study involved data preparation. The precision level records the temperature during each reading of the invar leveling staff. The precision leveling network for testing the vertical displacements of the object A consisted of 140 leveling stations forming 20 polygons measured twice in the main and return directions. For 115 leveling stations, temperature averaging (from four readings BFFB: backward, forward, forward, backward) was made for the return direction of each measured leveling line. The x,y coordinates of the level stations were determined by the method of linear resection on the basis of measured distances from the stations to controlled points, which are also recorded by the instrument.

The next step was to choose the geostatistical method to develop 2D models of the temperature distribution prevailing at a given parking level. A preliminary analysis was made for two measurement campaigns no. 16 and no. 20 and three parking levels: 0.5, 1.5 and 2.5. A comparison of three interpolation methods: ordinary kriging, simple kriging and IDW was performed in ESRI’s ArcGIS software. Sample results for level 1.5 are presented in figure 2.

To choose the best method of temperature data interpolation for each of tested methods the following error values were calculated: 1) mean prediction error (ME), 2) root mean square prediction error (RMSE), 3) root mean square standardized prediction error (RMSSE), 4) mean standardized prediction error (MSE) and 5) average kriging standard error (ASE). The obtained results were summarized in the form of a table, and then each error was analyzed by giving appropriate weights, as recommended by the software manufacturer. An example of interpretation for RMS error is given in Table 1.

Analyzes proved that the best method is ordinary kriging. According to the literature [10], this method should be used for spatial analyzes of large amounts of source data. The IDW method is recommended for small data sets. In order to reconcile the empirical results of the performed preliminary analysis with the theoretical approach, it was decided to prepare models of temperature distribution by both methods. Distribution maps have been prepared for three measurement campaigns and all parking levels. Figure 3 shows the exemplary results for level 1.5.
Table 1. Comparison of three interpolation methods based on the RMS error values – the exemplary results of the preliminary analysis (object A).

| CAMPAIGN | LEVEL 0.5 | LEVEL 1.5 | LEVEL 2.5 | ERROR VALUE INDICATOR |
|----------|-----------|-----------|-----------|-----------------------|
| IDW      | 3 3 3 2 2 | 2 3 3 2 2 | 1 3 3 1 1 | 16                    |
| ordinary kriging | 2 1 1 1 1 | 1 2 1 1 2 | 8         |
| simple kriging | 1 2 2 3 3 | 3 1 3 2 2 | 12        |

Designations: 1 - the lowest error value; 3 - the largest error value.

Figure 2. Comparison of three interpolation methods: IDW, ordinary kriging and simple kriging for measured temperature values by precise level – exemplary result of the preliminary analysis for parking level 1.5 (object A).

The next stage of spatial analysis included the preparation of temperature distribution maps, considering additional points such as: fire fan, industrial air conditioner, ticket machines, etc., which may affect the spatial distribution of air temperature. Data on temperature values at these points were read from thermovision images (figure 4a), which were taken during campaign no. 23 for levels 0.5 and 1.5. The IDW method was chosen to make the temperature distribution map (figure 4b) as a method providing more vivid visualization compared to ordinary kriging. The prepared maps were juxtaposed with maps developed only on the basis of data from level (figure 4c), and then maps of differences (figure 4d) were performed to emphasize the impact of parking infrastructure devices on the temperature distribution.
Figure 3. A collection of temperature distribution maps for parking level 1.5 made using the IDW method (left) and ordinary kriging (right).

Figure 4. An example of thermograms and digital image for parking level 1.5 (a) and temperature distribution maps: including thermovision data (b), based only on measurements from the level (c) and a differential map (d).
3.3. Modeling of temperature distribution in 3D space – object B

Field work began with the establishment of a geodetic network consisting of 5 tie-points stabilized with retro-reflective sheet targets and 4 instrument positions (stations) marked with a marker on the floor. Angular-linear measurements of the geodetic network were made in two series with the use of the Trimble S3 motorized total station. All visible tie-points and adjacent instrument stations were measured from each station. The TLS measurement was performed with the Riegl VZ-400i pulse laser scanner from 12 free stations. The scanning density was set to 40 mdeg in 1200 kHz mode. Finally, about 40 thermal images were made with the FLIR T640 non-integrated thermal imaging camera.

Data processing began with the establishment of a local coordinate system. The results of angle-linear measurements were adjusted using the least squares method in Softline's C-GEO software. The mean error of the horizontal position for the worst point did not exceed ±1.5 mm. Pre-registration of point clouds was done directly in the scanner software. Next, the point clouds were aligned in the Riscan Pro software based on common plane elements of the neighboring point clouds. In order to give the cloud appropriate georeferencing, the coordinates of the tie-points after network adjustment were used. In the next stage, the point cloud was colored based on images taken by the integrated RGB camera. An important stage in the processing of point cloud is filtration, aimed at removing points representing false signal reflections from the measured surfaces and objects unnecessary for further development. Filtration was performed based on the reflectance parameter. The processed point cloud was exported to Leica Cyclone software, in which the point cloud was colored based on infrared images. The texturing consisted of fitting the thermogram to the point cloud using at least 7 homologous points. A similar way of connecting the point cloud with thermal imaging is presented in the paper [11]. The obtained models of temperature distribution for the fragment of the ventilation duct are presented in the pictures below (figures 5, 6).

![Figure 5. Three-dimensional model of temperature distribution for the surface of the ventilation duct (side view – object B)](image-url)
4. Conclusions
This article presents examples of modeling temperature distribution in two-dimensional and three-dimensional space based on data obtained from a precision level, a laser scanner and a thermal imaging camera.

The task of modeling the temperature distribution in 2D space for object A was quite unusual because the temperature data came from the precise code level and was recorded in an auxiliary way during the measurement of vertical displacements. In the preliminary analysis of methods of modeling temperature distribution, three geostatistical methods were used: ordinary kriging, simple kriging and inverse distance weighting (IDW). The value analysis of five types of interpolation errors (using the adopted criteria for interpretation of these errors) showed that the best method for modeling this type of data is ordinary kriging. However, this method is not recommended for a small amount of measurement data. In the analyzed object, there were from 14 to 22 points per one parking level. For this reason, the IDW method, which has no quantitative restrictions for the developed point data, was also used (apart from ordinary kriging). As a result of the calculation, the set of 36 maps for all three measurement campaigns and all six parking levels was created. After considering the results of thermal imaging of the car park’s technical infrastructure more detailed maps were created. The impact of additional information about the temperature obtained from thermovision images was visualized in the form of differential maps. The local temperature distribution at a given parking level 1.5 has changed by up to 12°C, which is a significant value. The practical use of developed maps of temperature distribution prevailing during leveling measurements could be the analysis of the relationship between the thermal elongation of parking structure elements (columns) and the values of vertical displacements of structures recorded at individual parking levels. In further studies, it would be worth adding further sensors or performing point measurements of the structure temperature using thermometers, as well as considering the impact of internal partitions (walls) in the model.

For object B the three-dimensional model of temperature distribution was made. Data covering a fragment of the ventilation duct was obtained from two non-integrated measurement sources: the terrestrial laser scanner and the thermal imaging camera. The point cloud was processed in Riscan Pro software, and then the thermal images were textured in Cyclone software. Due to the low
resolution of the images and the associated blurry outlines and edges of the objects, the process of applying thermograms using tie-point was difficult. Additional information appearing on the thermograms limits the effective range of the texturing. Nevertheless, the obtained temperature distribution model provides valuable information about places of heat loss and potential places of material discontinuity of the analyzed infrastructure element.

The integration of various measurement techniques provides valuable thermal information about buildings and infrastructure elements. Thermal images are a universal source of data that can be combined with data obtained from precision levels as well as with the point cloud obtained from TLS in the process of two- and three-dimensional modeling of temperature distribution.

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