Studia Geotechnica et Mechanica, Vol. 39, No. 4, 2017
DOI: 10.1515/sgem-2017-0035

APPLICATION OF TERRESTRIAL LASER SCANNER WITH AN INTEGRATED THERMAL CAMERA IN NON-DESTRUCTIVE EVALUATION OF CONCRETE SURFACE OF HYDROTECHNICAL OBJECTS

MARIA KOWALSKA, JANINA ZACZEK-PEPLINSKA

Warsaw University of Technology, Faculty of Geodesy and Cartography,
Chair of Surveying Engineering, Measuring and Control Systems, pl. Politechniki 1, room 310, 00-661 Warsaw, Poland,
e-mail: m.kowalska@gik.pw.edu.pl, jzaczek@gik.pw.edu.pl

Abstract: The authors present possible applications of thermal data as an additional source of information on an object's behaviour during the technical assessment of the condition of a concrete surface. For the study one of the most recent propositions introduced by Zoller + Fröhlich company was used, which is an integration of a thermal camera with a terrestrial laser scanner. This solution enables an acquisition of geometric and spectral data on the surveyed object and also provides information on the surface's temperature in the selected points. A section of the dam's downstream concrete wall was selected as the subject of the study for which a number of scans were carried out and a number of thermal images were taken at different times of the day. The obtained thermal data was confronted with the acquired spectral information for the specified points. This made it possible to carry out broader analysis of the surface and an inspection of the revealed fissure. The thermal analysis of said fissure indicated that the temperature changes within it are slower, which may affect the way the concrete works and may require further elaboration by the appropriate experts. Through the integration of a thermal camera with a terrestrial laser scanner one can not only analyse changes of temperature in the discretely selected points but on the whole surface as well. Moreover, it is also possible to accurately determine the range and the area of the change affecting the surface. The authors note the limitations of the presented solution like, *inter alia*, the resolution of the thermal camera.

Key words: *terrestrial laser scanning, thermal camera, concrete surface, intensity*

1. INTRODUCTION

For many years thermal imaging has been widely used in road building, construction, spatial planning or in natural studies [4], [9], [11], [12]. Images used in those kinds of projects are usually registered using handheld thermal cameras or obtained through satellites. A new era of utilisation of thermal data has been sparked by Zoller + Fröhlich (Z+F) company, who introduced a thermal camera integrated with terrestrial laser scanner. This solution enables not only to acquire geometric information in the form of a spatial *XYZ* point cloud and spectral information as registered Intensity (I) value for each of the surveyed points but also a "fifth coordinate" is obtained, that is the temperature of the measured point.

Primary application of a thermal camera integrated with a terrestrial laser scanner can be found in construction industry as a mean to detect and evaluate thermal leakage of a building [2]. Thermographic analyses are an important tool in the aspect of integrated energy saving policy. Creation of thermograms of building's external walls and their analysis allow for a non-invasive identification of insulation layer defects and detection of contractor's errors [3], [6], [12]. Thermal images used up to now only provided information on the differences in temperature occurring on the surface of the object. In order to carry out a metric evaluation of the estimated wastage area, additional inventory measurements were necessary [10]. Independent analysis of single images was also in sufficient. Images had to be mapped and mosaicked on the surfaces to be analyzed. In the literature on the subject there are examples of integration of 3D metric models and thermal images, which seems a great improvement of this investigation technique, because it can overcome the lack of reliable surveys and assessments [1], [6], [13].

A terrestrial laser scanner with an integrated thermal camera can, as a part of surface measurement, provide one with a temperature-coloured point cloud, which will enable carrying out precise geometric measurements. The data acquired in such fashion may complement existing thermograms and temperature profiles. Through relevant point cloud processing metric thermal model of the object can be obtained. The undoubted advantage of integrating a terrestrial laser scanner and thermal camera is the reduction of time and cost of measurement. However, the biggest advantage of this solution is the elimination of the need to combine using photogrammetric methods, such as independently obtained thermal images and point clouds that are troublesome, because of the need to designate a sufficient number of common points for mutual data orientation.

Evaluation of thermal properties of buildings is not the sole application of the solution offered by Z+F company. The authors would like to present possible applications of the data acquired this way in assessment of technical condition of concrete surfaces, especially downstream walls of large hydrotechnical objects (e.g., water dams).

2. THERMAL MEASUREMENT (THERMOGRAPHIC)

The concept of integrating a thermal camera with a terrestrial laser scanner is comparable to commonly known integration of a photographic camera with a scanner or a total station. The measurement sequence involves a scan, which creates a point cloud (*XYZ* and *I*), then the thermal camera is used to take pictures that, through the firmware, are combined into a panorama. Based on common distinctive points which are identified either manually or automatically, LaserControl V8.8.0 colours the point clouds using the data from thermal panorama as reference. During thermal image processing the material from which the surveyed surface is made is defined. The final product takes the form of a point cloud, where each point is

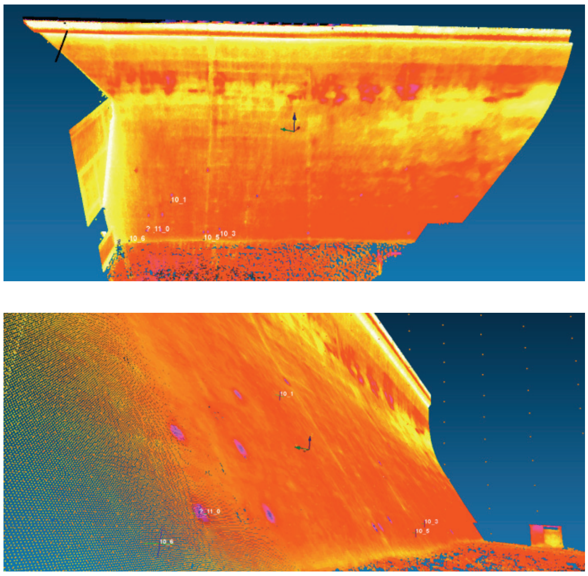

Fig. 1. Point Cloud coloured using the registered temperature (pictures present fragments of the central part of the downstream wall of a water dam in Rożnów)

Table 1. T-Cam thermal camera characteristics

Camera	
Resolution	382 × 288 pixel
Infrared spectrum	7.5–13 µm
Working temperature	0 °C–50 °C
Storage temperature	–20 °C – + 60 °C
Lens	
Fields of View	62° × 49°
Temperature accuracies	
Temperature resolution	4096 increments (12 Bit)
Noise Equivalent Temperature Difference (NETD)	0.08 K
System accuracy / absolute temperature accuracy [1]	+/– 2 °C
Number of images for full panorama >1.6 m (4.8 ft)	32 (4 rows)
Recording time for full panorama	1:45 min
Pixel thermo-panorama (is scaled to scan resolution)	2500 pixel / 360°
Working range	>1.6 m
Vertical[2] and Horizontal field of view	284° and 360°

1. The temperature accuracy depends on the emissivity of the material. With the above information, it is assumed that the emissivity of the material to be measured is known.

2. The vertical field of view depends on the height of the tripod, in this case 1.80 m.

defined not only by its coordinates but also Intensity and Temperature values (Fig. 1).

Accuracy of the obtained study depends on the scan's parameters, type and characteristics of the thermal camera and its calibration. Table 1 presents the characteristics of the utilised T-Cam thermal camera.

The results of thermographic measurements (acquired using a thermal camera equipped with infrared radiation detector) are presented in a digital thermographic picture (thermogram), where each temperature value is presented by a colour. During the measurement and thermogram analysis one has to take into consideration the emissivity coefficient of the material from which the object is made as well as the ambient conditions that may distort the thermogram. Only a detailed knowledge of the emissivity of the inspected surface provides the means to determine its absolute temperature value [14]. Table 2 presents the values used to determine relative and differential surface temperatures using Z+F's T-Cam thermal camera.

The acquired thermal images are influenced by the object's surroundings. Thus, one has to take into consideration factors such as beam's incidence angle, surfaces inclination angle and external lighting. These types of corrections are introduced, i.a., during satellite image processing [8]. Acquisition of integrated thermal and geometric data (point clouds) may be an ideal opportunity to introduce these kind of corrections. This issue will be the topic of further publications.

3. APPLICATION OF THERMAL DATA IN ASSESSING THE CONDITION OF CONCRETE SURFACES

The experimental research presented in the further part of the paper was carried out in Rożnów – scan of the central fragment of the concrete downstream wall of the water dam was carried out at the end of September 2015 and it was performed from two sites:

1) Site 1 was located in the middle of the downstream wall in the distance of 50 m. 3 measurements at a different time of day were performed. Each time a point cloud corresponding to the whole surveyed surface was obtained.
2) Site 2 was located in front of the left part of the downstream wall in the distance of 15 m. 2 measurements were performed at a different time of day.

Table 2. The values used to determine relative and differential surface temperatures captured by Z+F T-Cam

Material	e-Emissivity	Temperature [°F]	Temperature [°C]
Asphalt	0.93	100	38
Concrete	0.94	32–2000	0–1093
Brick (red rough)	0.93	70	21
Wood (oak)	0.91	100	38
Steel (oxidized)	0.80	77	25
Steel (polished)	0.07	100	38
Aluminium (oxidized)	0.09	75	24

Fig. 2. View of the inspected downstream wall of water dam in Rożnów with circled example fragments affected by surface change

All scans were transformed to a uniform coordinate system defined by the signalised merge points. Those points were measured using a total station and their coordinates were defined in the object's local system.

Figure 3 presents the results of a scan of the downstream wall's surface from site 1. Based on the thermal data superimposed on the point cloud it is easy to notice how the surveyed surface heats up during the day. Uneven heating of the surface can be observed. The upper part of the surveyed surface as well as the edges adjacent to the power plant (to the left) and upper spillways (to the right) are significantly warmer. The early morning measurement was carried out in foggy and overcast weather conditions which delayed concrete surface's exposure to the sun. Data on atmospheric conditions on the days of the survey are presented in Table 3. Temperature of the concrete registered on the level of 2nd control gallery located inside the building was constant throughout the day and equal to 8.2 °C.

In the upper part of scans (Fig. 3) distinguishable irregular "spherical" areas can be observed. The said areas are characterised by properties different than those of concrete (calcium carbonate leakage). They are clearly visible in optical RGB image (Fig. 2).

The presented example does not fully utilise the potential of the data acquired through terrestrial laser scanning. It is only based on analysis of thermal data

Table 3. Atmospheric conditions – data from ASTKZ ZEW Rożnów–Czchów sensors

Time	Air temperature [°C]	Air humidity [%]	Dew point [°C]	Concrete temperature [°C]	Humidity of the concrete surface [%]
10.00	8.0	–	–	–	88–0
11.00	9.9	67.5	4.7	–	70.5
12.00	14.6	64.0	5.8	13.2	–
14.00	19.4	42.6	7.2	17.3	–
18.00	12.0	–	–	–	–

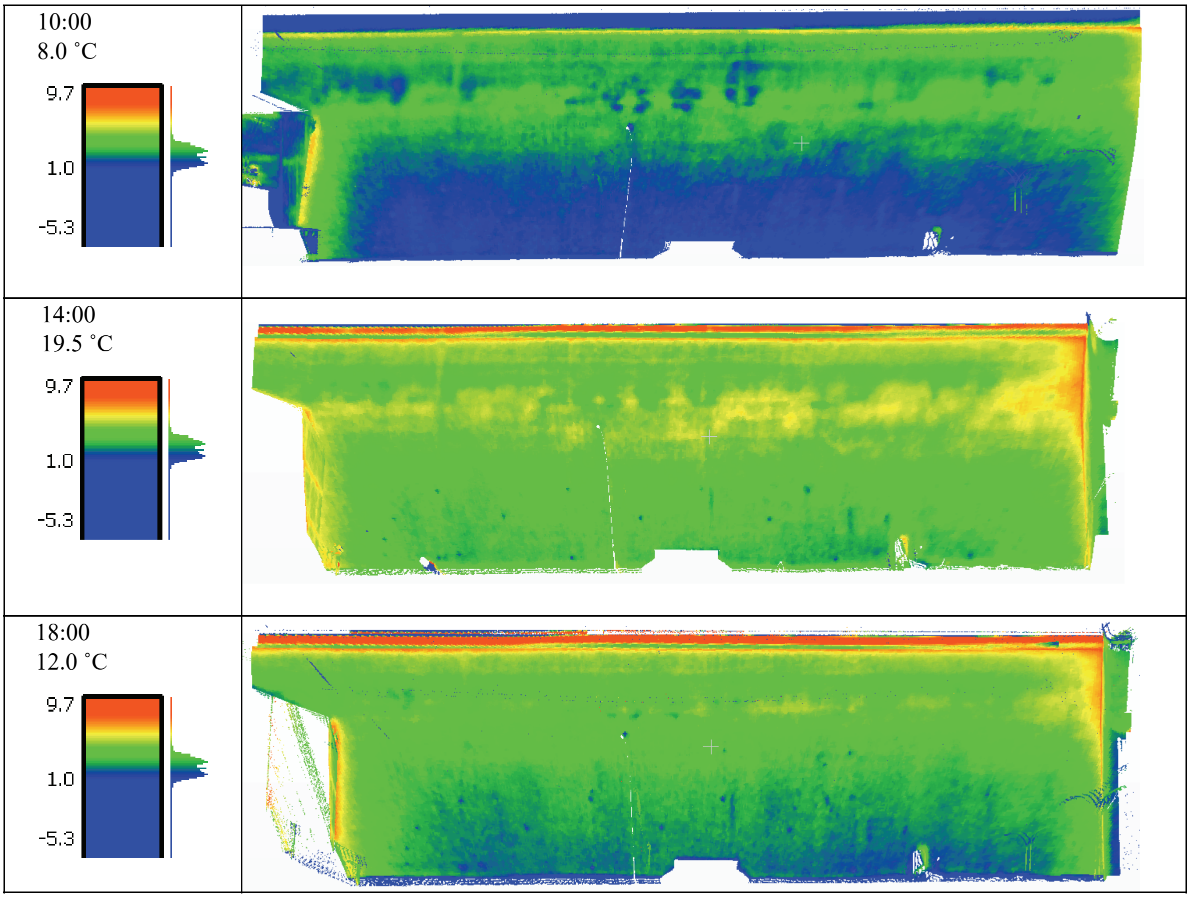

Fig. 3. Juxtaposition of scans coloured using thermal data acquired from the same site at different times of day (pictures taken subsequently, over one day, at 10:00, 14:00 and 18:00)

with omission of point cloud geometry. In this case the geometric data could be used to calibrate the image, in order to eliminate the influence of the previously mentioned external factors on the acquired thermal data. After geometric calibration it is possible to perform analyses aimed at providing details on the genesis of the diversification of the registered temperature differences between selected areas (e.g., top and bottom of the construction). Identification of the level of influence of the surface inclination, thereby, illumination angle, will enable the analysis of the condition of the surface based on the corrected data. This, in turn, will increase reliability of the acquired thermal data and condition assessment. Another possible example of application of this method is evaluation of thermal insulation and by that identification of cracked and overgrown areas characterised by changeable, reduced surface properties of the material.

As mentioned in the introduction, data from terrestrial laser scanning provides geometric information as well as information on the intensity of the reflected laser beam from the surveyed surface (Intensity). It is possible to perform evaluation of technical condition of selected surfaces created from various construction materials using the registered intensity values. Thus, it is possible to remotely (without any direct contact with the object) identify areas in need of conservation, cleaning or those that were repaired or infilled with seemingly same material but characterised by different spectral properties [15], [16].

Through the integration of the data from terrestrial laser scanning with thermal data it is possible to directly, without any distortions, compare thermal and intensity images. Figure 4 clearly shows that both images contain information that can supplement one another. Using only intensity image it would be impossible to notice that the area around point 1 possesses locally different surface thermal properties, which can indicate an existence of a crevice, crack or increased filtration. Using thermal data as basis it is also possible to note that the leakages present in the vicinity of point 2 and 3 heat up much more slowly than the rest of the surface, which diametrically changes the way the material works and, in turn, may result in increased surface erosion. One can observe thermal dilatation between closed sections of the dam. With appropriate selection of the analysed temperature and colour range one can highlight the analysed aspects. Thanks to a geometrically uniform data layout it is possible to compare registered data and analyse it in differential aspect.

Thermal data can also be used in order to study the behaviour of crevices and cracks. Using data from the second measurement site a comparison of thermal data registered at 14:00 and 18:00 in area 1 of Fig. 4 was made. Figure 5 presents a point cloud coloured with intensity value corresponding to the analysed crevice. Figure 6, in turn, presents the same fragment of the clouds registered at two times of day, coloured using temperature values. For the purposes of thermal data analysis 8 *XYZ* points were selected,

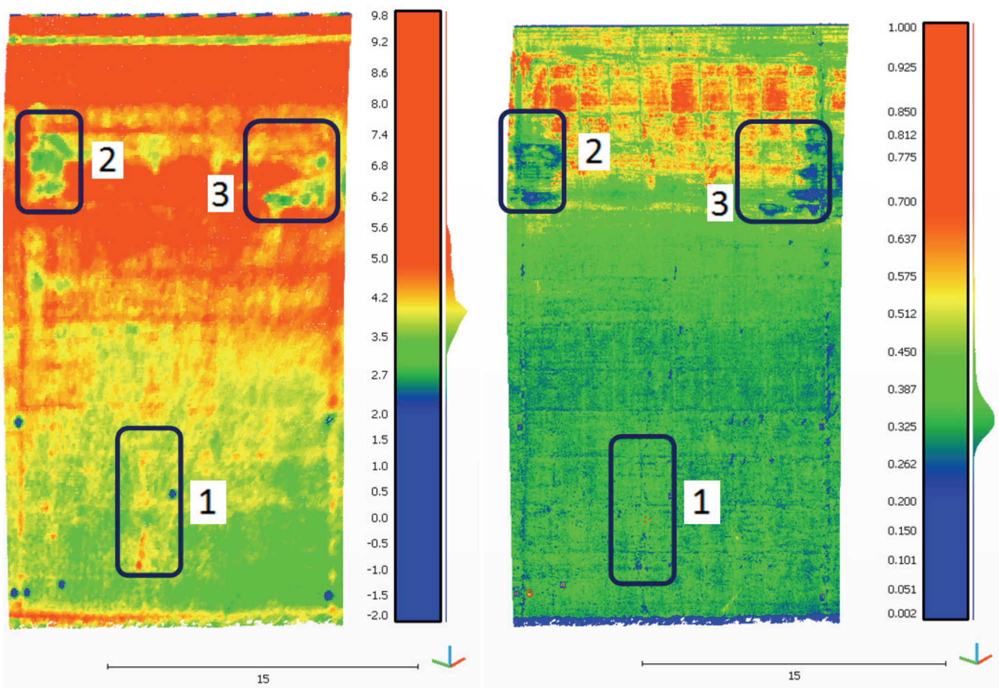

Fig. 4. Juxtaposition of a thermal image (on the left) and intensity image (on the right) for a selected fragment of a downstream wall belonging to a dam in Rożnów

for which the temperature was measured for both clouds.

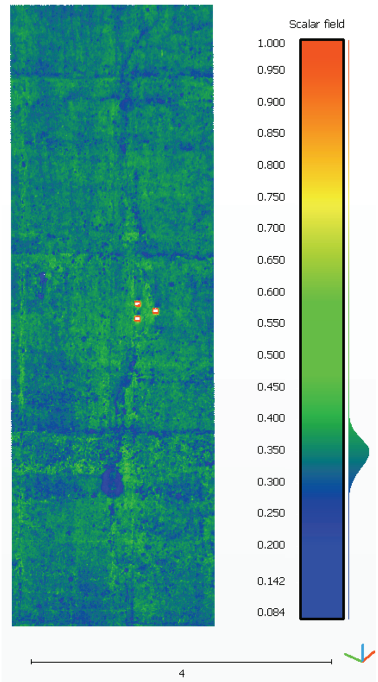

Fig. 5. Registered intensity values for the selected fragment

Points 1, 2, 4, 6, 7 and 8 were placed in the area where cracks were located – in the immediate range of the analysed crack, whereas point 3 and 5 were selected as reference points located outside the cracked area. By analysing the calculated temperature differences in Table 4, a faster increase in temperature can be noticed on the surface surrounding the crack than in the crack itself (changes equal to 0.9 °C and 0.5 °C accordingly). A temperature drop was registered for point 8. This may result from the resolution of the thermal image. For the selected fragment of the thermal image the pixel size equals to 5 × 5 cm. In the case of points selected on the edges of the crack, the obtained temperature was measured as a mean value for an area of 25 cm^2.

Point clouds acquired through terrestrial laser scanning may be used, apart from thermal analysis, for geometric analysis of the selected crack. One can determine geometric characteristics of the crack, like width or depth, in the selected sections by fitting appropriate planes into the selected fragment of the point cloud.

Figure 7 presents the distances of each point from the fitted plane visualised in colour range. Points located on the surface are marked in bright green colour.

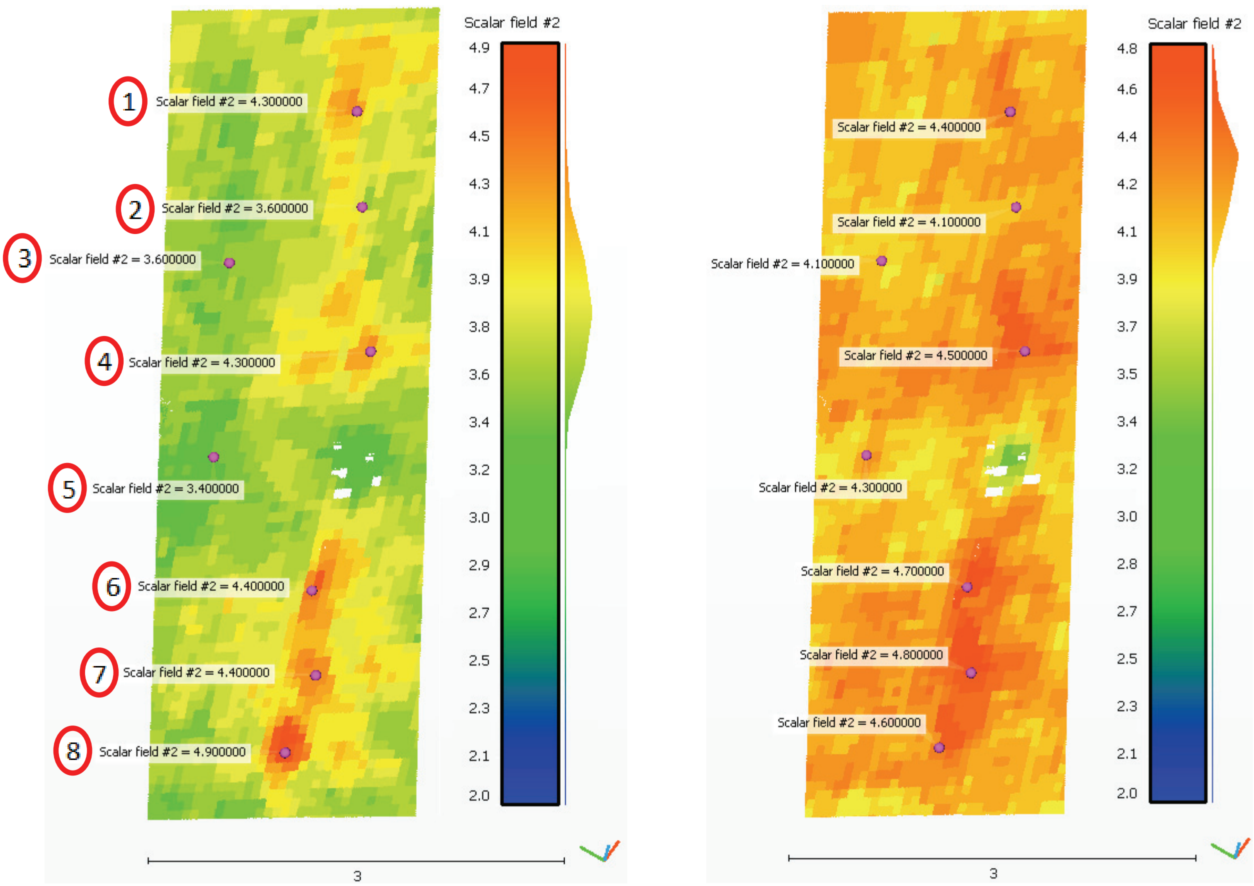

Fig. 6. Registered thermal values at 14:00 (on the left) and at 18:00 (on the right) for a selected fragment of the downstream wall of the water dam in Rożnów

It was assumed that points marked with warm colours (towards red colour) are located above the surface whereas cool colours (towards blue colour) are located beneath the exterior surface of the wall.

Table 4. Juxtaposition of temperature values in points 1 to 8 at 14:00 and 18:00 and their differences

Point number	Temperature [°C] time 14.00	Temperature [°C] time 18.00	Temperature difference [°C]
1	4.3	4.4	0.1
2	3.6	4.1	0.5
3	3.6	4.1	0.5
4	4.3	4.5	0.2
5	3.4	4.3	0.9
6	4.4	4.7	0.3
7	4.4	4.8	0.4
8	4.9	4.6	–0.3

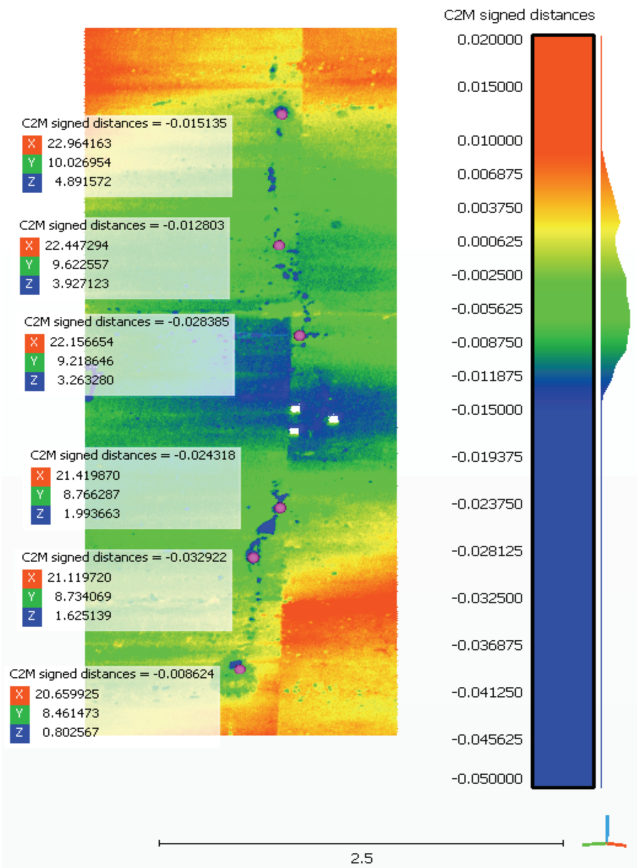

Fig. 7. Determined distances of points on the wall's surface from the fitted inclined plane (fitting using least squares method)

A combination of thermal and geometric data shows, that the crack (cavity) is significantly less prone to air temperature changes (heating) and direct exposure to sunlight. However, due to an incomparably large pixel size (low resolution of thermal data) in relation to the resolution of geometric data, these types of analyses can only be used for guidance purposes to indicate existence of a phenomenon and not for its accurate evaluation.

4. SUMMARY

The article analysed the results of scanning of a concrete downstream wall belonging to a dam wall in Rożnów. The scans were carried out using Z+F Imager 5010 terrestrial laser scanner (laser in near infrared range) with an integrated T-Cam Rev1.0 thermal camera registering temperature of an object in the range from –20 °C to +60 °C in resolution of 382 × 288 pixels. Scans of a 44-meter-high wall were performed at a different time of day and different air temperature. All scans were transformed to a uniform coordinate system defined by merging points signalised on the object. The points were measured using a total station.

The registered temperature and intensity values of the reflected laser beam were used to formulate the following statements:

- low, and insignificant due to the resolution of thermal data, influence of the air temperature, concrete and intensity of sun operation on the values of the surveyed coordinates X, Y, Z (differences below scan's accuracy estimated at 0.005 m),
- significant influence of changes in insolation and concrete temperature on the registered laser beam's intensity value, especially in brightly coloured areas (upper part of scans of the wall from site 2) – the changes may be important when evaluating surface condition using spectral image classification method, which indicates the appropriateness of integrating data from different sources such as, for example, thermal camera and use of multispectral classification with regard to time lapse between consecutive measurements,
- in the aspect of scanning effectiveness no deterioration of scan quality was observed with the number of registered scans.

Terrestrial laser scanning enables creation of complex publications and analyses that have not been available to any of the surveying methods used in the fields of construction and hydrotechnics. Preparation of studies of almost any fragment of an object without the necessity to carry out additional field works is possible due to the method of data registration that results in the creation of a point cloud representing the geometry of the scanned objects. The metric location of thermal anomalies that should be further investigated with destructive tests is crucial for reducing of the size and number of samples needed as much as possible. Also one of the significant advantages of this method lies in the speed at which huge amounts of data are being registered. Thanks to the integrated thermal camera, additional information is obtained through joint analysis of the registered intensity of the reflected laser beam from the surveyed surface and its temperature. Thermograms can be analysed for any projection and section based on once registered data for any part of a building if/when such needs arise. Moreover, the surveys can be easily repeated, compared and their results are easy to present.

One has to remember, that digitalisation of phenomena and objects carried out during the measurement, that is point cloud registration, and subsequently visualisation of the data in the form of spectral images: intensity and temperature, imposes the method of preliminary data processing, calculation, result analysis and their visualisation. The obtained scans and thermograms differ in terms of resolution. Intensity and thermal images generated during measurement are acquired through data averaging for the selected window. However, the resolution of thermal data is limited to max. 5 × 5 cm. Selection of points and areas subject to surveying and evaluation should be performed after consultation with specialists or based on geodesists' work experience. The results of surveys carried out using laser scanning technique have to be consulted with construction engineers. One cannot assume that the results are comprehensive and not burdened with various instrumental and environmental errors.

Analysis of integrated data enables a quick identification of changes in the material's surface that are often not registered by visual methods. Differences in the registered temperature and intensity values, especially in reference to periodic surveys performed in different weather and environment conditions (e.g., changes in water damming level in the reservoir) may indicate uneven construction work, local weakening of the material, soiling or surface erosion. Geometric analysis of the obtained scans helps to determine wall deformations and movement of object's characteristic construction elements. Data integration allows for multidimensional evaluation of the object's technical condition.

REFERENCES

[1] ALBA M.I., BARAZZETTI L., SCAIONI M., ROSINA E., PREVITALI M., *Mapping infrared data on terrestrial laser scanning 3D models of buildings*, Remote Sensing, 2011, 3(9), 1847–1870.

[2] COSTANZO A., MINASI M., CASULA G., MUSACCHIO M., BUONGIORNO M.F., *Combined use of terrestrial laser scanning and IR thermography applied to a historical building*, Sensors, 2015, 15(1), 194–213.

[3] GONZÁLEZ-AGUILERA D., LAGÜELA S., RODRÍGUEZ-GONZÁLVEZ P., HERNÁNDEZ-LÓPEZ D., *Image-based thermographic modeling for assessing energy efficiency of buildings façades*, Energy and Buildings, 2013, 65, 29–36.

[4] HERNÁNDEZ P.A., CALVARI S., RAMOS A., PÉREZ N.M., MÁRQUEZ A., QUEVEDO R., BARRANCOSA J., PADRÓNA E., PADILLAA G.D., LÓPEZB, D., SANTANAB A.R., MELIÁNA G.V., DIONIS S., RODRÍGUEZ F., CALVO D., SANTANA Á.R., *Magma emission rates from shallow submarine eruptions using airborne thermal imaging*, Remote Sensing of Environment, 2014, 154, 219–225.

[5] LAGÜELA S., MARTÍNEZ J., ARMESTO J., ARIAS P., *Energy efficiency studies through 3D laser scanning and thermographic technologies*, Energy and Buildings, 2011, 43(6), 1216–1221.

[6] LAGÜELA S., DÍAZ-VILARIÑO L., ARMESTO J., ARIAS P., *Non-destructive approach for the generation and thermal characterization of an as-built BIM*, Construction and Building Materials, 2014, 51, 55–61.

[7] MALINOWSKI M., SIKORA J., *Termograficzna analiza wybranych przegród budowlanych w aspekcie ich termoizolacyjności* (*Thermographic analysis of selected building partitions in the context of their thermal insulation properties*), Infrastruktura i Ekologia Terenów Wiejskich, 2013, 3/IV, (in Polish).

[8] OSIŃSKA-SKOTAK K., *Znaczenie korekcji radiometrycznej w procesie przetwarzania zdjęć satelitarnych* (*The importance of radiometric correction in satellite images processing*, Archiwum Fotogrametrii, Kartografii i Teledetekcji, 2007, 17, (in Polish).

[9] PASCUCCI S., BASSANI C., PALOMBO A., POSCOLIERI M., CAVALLI R., *Road asphalt pavements analyzed by airborne thermal remote sensing: Preliminary results of the venice highway*, Sensors, 2008, 8(2), 1278–1296.

[10] RUTKOWSKA G., KLEPAK O., PODAWCA K., *Problemy strat ciepła w istniejących budynkach jednorodzinnych w kontekście błędów wykonawczych* (*Problems of Heat Loss in Existing Single-family Buildings in the Context of Construction Errors*), Annual Set the Environment Protection, 2013, 2625–2639, (in Polish).

[11] SAARONI H., BEN-DOR E., BITAN A., POTCHTER O., *Spatial distribution and microscale characteristics of the urban heat island in Tel-Aviv, Israel*, Landscape and Urban Planning, 2000, 48(1), 1–18.

[12] TITMAN D.J., *Applications of thermography in non-destructive testing of structures*, NDT & e International, 2001, 34(2), 149–154.

[13] WANG C., CHO Y.K., GAI M., *As-is 3D thermal modeling for existing building envelopes using a hybrid LIDAR system*, Journal of Computing in Civil Engineering, 2012, 27(6), 645–656.

[14] WRÓBEL A., *Termografia w pomiarach inwentarskich obiektów budowlanych* (*Thermography in the measurement of building objects* (Postdoctoral Thesis), Monografie 209, AGH, Kraków 2010, (in Polish).

[15] ZACZEK-PEPLINSKA J., OSIŃSKA-SKOTAK K., WUJANZ D., KOŁAKOWSKA M., *Analysis of the possibility for using the results of terrestrial laser scanning (TLS) measurements and classification algorithms of images for the engineering struc-*

ture surface condition assessment, [in:] F. Humair, B. Matasci, M. Jaboyedoff, A. Abellan, D. Carrea, M.-H. Derron, M. Wyser (Eds.), *Vertical geology, from remote sensing to 3D geological modelling*, Proceedings of the first Vertical Geology Conference, (pp. 227–232). University of Lausanne, 2014.

[16] Zaczek-Peplinska J., Kowalska M., Nowak E., Osińska--Skotak K., *Metodyka wykonania oceny stanu powierzchni masywnej konstrukcji betonowej na podstawie klasyfikacji obszarów jednorodnych chmur punktów (TLS)* (*Methodology of large concrete structure surface condition evaluation based on classification of uniform areas within point clouds (TLS)*), [in:] J. Winter, A. Wita (Eds.), *Eksploatacja budowli piętrzących – diagnostyka i zapobieganie zagrożeniom*, (pp. 373–384), Instytut Meteorologii i Gospodarki Wodnej, Państwowy Instytut Badawczy, 2015, (in Polish).

[17] Internet sources: http://www.zf-laser.com/fileadmin/editor/Datenblaetter/ Datasheet_TCam_e.pdf (online access: 23.11.2016).