Innovative Assessment of Selected Properties of Industrial Floors

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Abstract -
The quality and precision of casted industrial floor is often a dispute between an investor and a contractor. Its geometrical and physical properties divert from values defined by the project and also often do not meet the criteria of National Standards requirements. The aim of this paper is to evaluate the practical use of the Terrestrial Laser Scanning (TLS) in non-destructive testing of selected industrial floors. Our focus is on the geometric flatness evaluation. With TLS technology we assess the surface quality and flatness more precisely, faster and moreover, investigate 100% of area. This may lead to better evaluation of the relative position of investigated areas, points and constructions. However, a further investigation, which would define the methodology for evaluation the geometric tolerance from point clouds is needed.

Keywords –
TLS; Non-destructive testing; Industrial floor

1 Introduction

Construction industry deals almost daily with various requirements for geometric accuracy of any structure or surface. As the ideal shape of any structure is technically not achievable in most of the cases, various standards define the limits for the deviations from projected shape. These geometric tolerance states how much an element, a structure or a surface can differ from its ideal, designed geometry and proposed location. All surfaces are usually defined as planes, cylinders, spheres, etc, so we are able to use common techniques to verify above mentioned parameters. Those techniques don´t reflect actual developments in digital age e.g. TLS and we assume that by setting a clear methodology, geometric tolerance verification may be easier, faster, more accurate and may also eventually leads to automation.

Further investigation may include BIM based evaluation of potential construction errors. Main benefit will include faster spatial coordination and better location determination and automatic evaluation especially if there is planned cross slope in order to drain water. Information from BIM model would speed up and ease the proces and provide precise information regarding the cause of possible construction or technological errors.

The spots with depression could be evaluated by destructive testing to determine cause of local inaccuracy. To evaluate the influence of fiber distribution CT scan of drilled cylinder may be used. This information could result in determination if the compression of floor or technological discipline failure has taken place.

For a purpose of this paper, only the geometric tolerance of finished surface of industrial floor is considered as this property is often a source of claims between Investor and Constructor in the construction industry.

2 Related work

2.1 Geometrical precision according actual standards

The challenge is to apply the standards and geometrical precision in construction practice. In doing so, it is still necessary to proceed in accordance with the standards and properly define the variables with which it comes into contact with only a small proportion of professionals in the construction industry. Within handover of the construction all structures and surfaces should be measured in accordance with prescribed procedures which describe data collection, evaluation and correct interpretation.

Standards that deal with geometric accuracy in the construction industry can be divided into following groups:

- *Standards for design*: STN 73 0205 Geometrical accuracy in construction. Designing geometric accuracy;

STN 01 3405 Construction drawings, labeling accuracy characteristics.

- *Standards for construction*: STN 73 0210-1 Geometrical accuracy in construction. Part 1: The accuracy of the placing; STN 73 0210-2 Geometrical accuracy in construction, Part 2: The accuracy of monolithic concrete structures (canceled after the release of STN EN 13 670 (73 2400) Execution of concrete structures).
- *Standards for verification and evaluation*: STN 73 0212-1 Geometrical accuracy in construction. Verification of accuracy. Part 1: Basic provisions; STN 73 0212-3 Geometrical accuracy in construction. Verification of accuracy. Part 3: Civil engineering objects; STN 73 0212-5 Geometrical accuracy in construction, Verification of accuracy, Part 5: Checking the accuracy of building components; STN 73 0212-6 Geometrical accuracy in building, Verification of accuracy, Part 6: Statistical analysis and handover; STN ISO 7737 Geometrical accuracy in construction. Tolerances in construction. Data logging for dimensional accuracy. STN ISO 7077 Geometrical accuracy in construction. Measurement methods in construction. General principles and procedures for verifying the accuracy of dimensions.

To assess local flatness of investigated industrial floor following standard has been used: STN 74 4505 Floors, Common provisions, Design and Execution. This standard specifies requirements for the design, execution and testing of floors both in internal and external environment of buildings. The standard defines maximum deviation values.

2.2 Terrestrial Laser Scanning

The technology of Terrestrial Laser Scanning (TLS) is a non-selective method of spatial data acquisition. TLS determines the 3D coordinates of the measured points on the surface of the measured object in a grid, which is defined by regular angular spacing in the horizontal and vertical directions [1]. The result of TLS is an irregular raster of measured points, the so-called point cloud, which documents the measured object (fig. 1). The difference between TLS and conventional surveying methods is that the coordinates of characteristic points are obtained by modelling, respectively by generalization of the main elements of 3D models or the resulting point cloud [2].

Most of the current TLS works on the principle of spatial polar method. The spatial position of measured points are calculated from the measured horizontal and vertical angles and from the measured slope distance (fig.2 left).

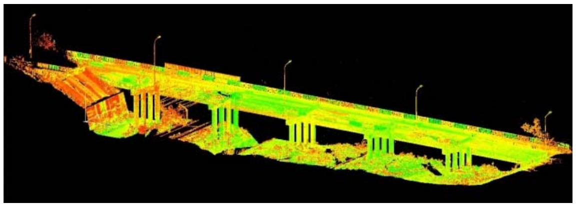


Figure 1 The point cloud of The bridge No. 137, Bojnicka street in Bratislava

The optimal source of radiation of electromagnetic waves for scanning systems are lasers. These are used for contactless measuring of distances. Laser beams are highly monochromatic and have a narrow spectral line width compared to other sources of radiation.

The deflection of the laser beams is provided by oscillating mirrors, rotating prism, by rotation of the laser source around horizontal and vertical axis of the instrument or by fiber optics, resp. by combination of the methods above mentioned [1]. The most common used is the combination of rotation of instrument around the vertical axis, and an oscillating mirror.

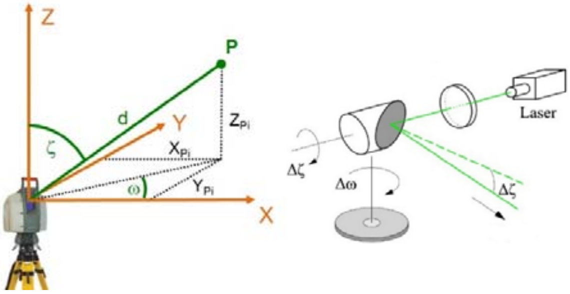


Figure 2 The principle of spatial polar method (left), and the combination of rotating source and oscillating mirror (right)

The process of data acquisition and the modelling using TLS can be divided into three main steps. The first one is the preparation for the measurement (for scanning), recognition of the measured object, the choice of positions for the instrument, signalization of the control points. The second step is the process of scanning and the third one is the processing of data obtained by TLS. The data processing contains:

- Preparation of the point cloud for data processing. This includes initial adjustments of point cloud: error elimination, filtering and data reduction, transformation (between different coordinate systems), elimination of unnecessary points, and coloring of points (assigning the colors according to the intensity of measuring signal or from photographs).
- Processing of data obtained by TLS. Spatial model creation of the measured object or its parts,

determination of geometric parameters (e.g. dimensions) and deformations of chosen parts of the measured object.

- Visualization. Rendering of the created model, and creation of animations.

2.3 Determination of the quality of as-build state of structures

Common mistakes and faults occurring on industrial floors are cracking, flatness deviation, failure of surface inclination, incorrect execution of expansion joints and delamination. As stated above, flatness and surface inclination can be easily evaluated by TLS.

The determination of the flatness of structures from laser scanning data is relatively simple when the flatness is represented by mesh surfaces (complex meshing or TIN), or by measuring the coordinate difference between discrete measured points. In both cases the accuracy of the results depending on the accuracy of the position of scanned points (several millimetres). To increase the accuracy of the results, the measured points (monitored parts of the scanned structure) have to be modelled using regression. Using regression models the noise of the point cloud can be significantly reduced.

The flatness of industrial floors can be determined as the difference between the height of measured points (lying on the surface of the floor) and a horizontal plane. It also allows to check the slope of the floor surface. The height of the points can be calculated by modelling small planes using orthogonal regression. The position of the measured points in the XY plane can be defined by their coordinates in the plane (in a regular grid) (fig. 3).

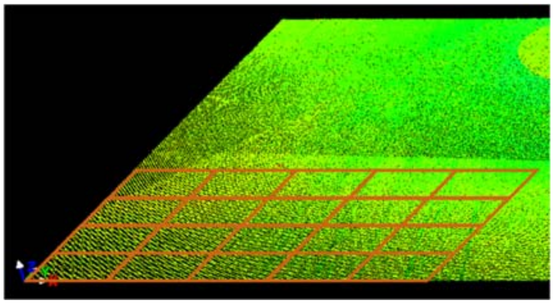


Figure 3 Modelling the position of the measured point using small planar surfaces

In this case the position of the measured points is calculated from tens or hundreds of scanned points, which increasing the accuracy of the results.

The deviation of the measured surface from a horizontal plane can be represented by isolines (contours) or by mesh, where the deviation is drawn on the Z axis of the figure.

Orthogonal regression is calculated from the general equation of a plane:

$$a \cdot X + b \cdot Y + c \cdot Z + d = 0 \tag{1}$$

where: a, b and c are the parameters of the normal vector of the plane,

X, Y and Z are the coordinates of the point lying in the plane,

d is the scalar product of the normal vector of the plane and the position vector of any point of the plane.

The orthogonal distance of a point from the plane is calculated by:

$$d_{P,\rho} = \frac{\left|a \cdot X_P + b \cdot Y_p + c \cdot Z_P + d\right|}{\sqrt{a^2 + b^2 + c^2}} \tag{2}$$

The requirement of orthogonal regression is that the sum of the squares of orthogonal distances have to be minimal, so:

$$\sum_{i=1}^{n} \frac{\left|a \cdot X_i + b \cdot Y_i + c \cdot Z_i + d\right|^2}{a^2 + b^2 + c^2} = \min \tag{3}$$

where: *n* is the number of points used for the calculation of the plane.

Partial derivation of (3) with respect to *d* leads to:

$$2 \cdot \sum_{i=1}^{n} \frac{\left|a \cdot X_i + b \cdot Y_i + c \cdot Z_i + d\right|}{a^2 + b^2 + c^2} = 0 \tag{4}$$

According to the previous formula, the parameter *d* can be formulated as:

$$d = -(a \cdot X_0 + b \cdot Y_0 + c \cdot Z_0) \tag{5}$$

And the formula for the general equation of a plane becomes:

$$a \cdot (X_i - X_0) + b \cdot (Y_i - Y_0) + c \cdot (Z_i - Z_0) = 0 \tag{6}$$

where: $(X_i - X_0)$, $(Y_i - Y_0)$ and $(Z_i - Z_0)$ are the coordinates of the point cloud reduced to a centroid.

For each point of point cloud is possible to write a formula according to (6),then the design matrix of the system of equations has the form:

$$\mathbf{A} = \begin{pmatrix} (X_1 - X_0) & (Y_1 - Y_0) & (Z_1 - Z_0) \\ (X_2 - X_0) & (Y_2 - Y_0) & (Z_2 - Z_0) \\ \vdots & \vdots & \vdots \\ (X_n - X_0) & (Y_n - Y_0) & (Z_n - Z_0) \end{pmatrix} \tag{7}$$

Orthogonal regression is calculated by applying Singular Value Decomposition:

$$\mathbf{A} = \mathbf{U\Sigma V}^{T} \tag{8}$$

where: **A** is the design matrix, with dimensions *nx3*, and *n* is the number of points used for the calculation. The column vectors of $\mathbf{U}^{nxn}$ are normalized eigenvectors of matrix $\mathbf{AA}^{T}$. The column vectors of $\mathbf{V}^{3x3}$ are normalized eigenvectors of $\mathbf{A}^{T}\mathbf{A}$. The matrix $\mathbf{\Sigma}^{nx3}$ contains eigenvalues on the diagonals. Then the normal vector of regression plane is the column vector of **V** corresponding to the smallest eigenvalue from **Σ** [3], [4].

The position of the observed points in XY plane is defined as fixed in a defined grid (e.g. 100 m x 100 m). The Z coordinates (heights) of the measured points are calculated by projecting the points onto regression planes (fig.4) using formula:

$$Z_P = -\frac{a \cdot X + b \cdot Y + d}{c} \tag{9}$$

In case of large floor surfaces, when it is not possible to scan the whole floor from a single position of the instrument, the transformation of the point clouds from each instrument position is needed to obtain data in a common coordinate system.

The standard deviation of the results is calculated using uncertainty propagation law, from the standard deviation of the vertical component of the transformation error and the standard deviation of the regression planes:

$$\sigma_{Z_P} = \sqrt{\sigma_{T_Z}^2 + \sigma_\rho^2} \tag{10}$$

where: σ_{T_Z} is the vertical component of the error of the data transformation and σ_ρ is the standard deviation of the calculated regression plane.

The accuracy of the transformation is given by the differences (ΔX, ΔY, ΔZ) between the identical reference points after the transformation of the scanned point cloud from each instrument position into a common coordinate system. The standard deviation of the regression planes is calculated from the orthogonal distance of the points of point cloud from these planes. Dispersion of the points around the plane reflects the random error (noise) of the distance measurement by TLS (coordinate determination) mainly.

An application based on software MATLAB® was developed for automated data processing. The above mentioned computational procedure is performed and controlled with help of this application. The application was created as a standalone app; however, the Matlab Runtime is necessary to be installed. The work with the app is as follows: In the first step the user can choose a work directory in which the resulting files will be saved. The second step is the point cloud file loading in *.txt or *.xyz file format which contains the coordinates of scanned points. The position of measured points is defined by the step of a grid in XY plane. The deviation of measured points from the horizontal plane (Z coordinates) is calculated in the points defined by the mentioned grid definition.

According to the dimensions of the grid the application defines fencing boxes (selects part of the point cloud around the grid points). Using the above mentioned calculation procedure, calculates the Z coordinates and their standard deviation for each measured point using the uncertainty propagation rule. The results are saved into an *.xlsx file in the work directory. Flatness is represented by isolines and by mesh surface. Both are created and saved into a *.png file.

The accuracy of the results is defined by the standard deviation of the flatness determination. Actually it is difficult to define one scalar value for the whole floor, but it can be calculated from the standard deviation of the Z coordinates of measured points (grid points) using quadratic mean.

3 Case study

Precision of works was evaluated on selected type of industrial floor located in Bratislava, Slovakia.
Within this case study, we have measured two dilatation units, A and B (see Figure 4). They were further evaluated according to above mentioned methodology. The dimensions of A and B are equal, length is 6,0m and width is 6,0m. To eliminate imperfection of works, we have selected internal dilatation units.

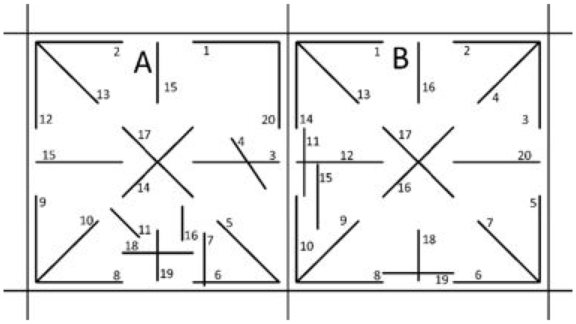


Figure 4 Measured area of industrial floor

Due the fact that investigated industrial floor was recently finished and has not been handed over for use, data collected by TLS are stored and might be used in future for comparison and further investigation of deformations caused in time.

3.1 Standard Measurement

The standard allows maximum deviation of 5 mm for industrial floors. Measurement was carried out using a standard pads at the ends of the measuring spirit level meter. Defined height was 10 mm.

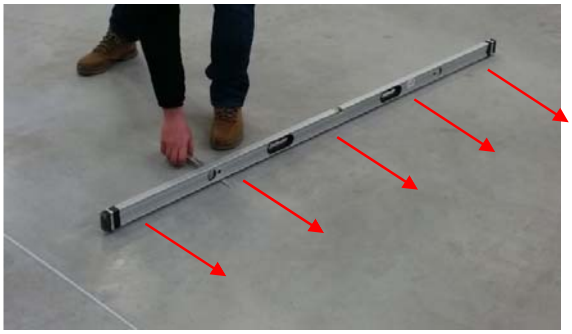


Figure 5 Local flatness measurement showing the position measurement

Measurements were performed on two expansion sections, the two-meter spirit level within the meaning of the abovementioned standard was used. The method of measurement is captured in the image below. Number of sets and locations on the floor was 20 times per section. Each spot was measured by spirit level measure and calibrated wedge in five positions. The measurement result is a set of 100 measurements which are in accordance with the standard STN 73 0212-6 Geometrical accuracy in building. Control accuracy. Part 6: Statistical analysis and thinning, - Table No. 10, when considering the same risk of the investor and the contractor with a set of permitted levels.

Evaluation for a set of measurements n = 100 is then the result for section No. 1 is shown in Table 1 below. In the evaluation, it is therefore considered PR = CR = 5%, PRQ = 1.5%, CRQ = 5%, n = 100, and k = 1.91.

Table 1 Evaluation of Section n.1

n.	Deviation +10mm	Measured deviation abs(x_n)	$x_n - x$	$(x_n - x)^2$
1	10,5	0,5	-0,265000	0,0702250
2	9,0	1,0	0,235000	0,0552250
3	8,5	1,5	0,735000	0,5402250
4	10,0	0,0	-0,765000	0,5852250
100	10,5	0,5	-0,265000	0,0702250

Σx_n	76,5
x	0,765
$\Sigma(X_n - X)^2$	50,05705
x_m	0,505626
s	0,711074
x + k . s	2,123152

n	100
k	1,91
PRQ	1,50%
RQ	5%

According to the standard, calculated deviation is at section no. 1 equal to 2.12 mm and the deviation of section no. 2 equals 1.7 mm.

In search of extremes according to STN 74 4505, as well as statistical analysis and handover according to 730212-6, evaluated industrial floor is within 5 mm tolerance for the category of manufacturing warehouses and garages.

Table 2 Evaluation of Section n.2

n.	Deviation +10mm	Measured deviation abs(x_n)	$x_n - x$	$(x_n - x)^2$
1	10,5	0,5	-0,180000	0,0324000
2	10,0	0,0	-0,680000	0,4624000
3	10,0	0,0	-0,680000	0,4624000
98	10,5	0,5	-0,180000	0,0324000
99	10,5	0,5	-0,180000	0,0324000
100	10,0	0,0	-0,680000	0,4624000

Σx_n	68
x	0,68
$\Sigma(X_n - X)^2$	28,2600
x_m	0,28545
s	0,53427
x + k . s	1,7004737

n	100
k	1,91
PRQ	1,50%
RQ	5%

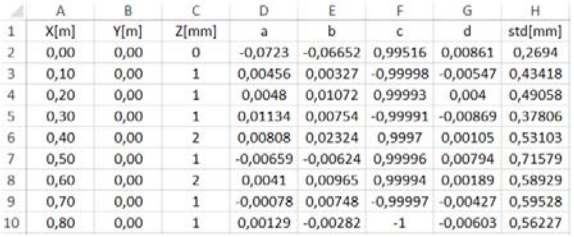
3.2 TLS Measurement

TLS was performed from two positions by Leica ScanStation2 device to cover the area underneath the device. The device was directly connected to the Notebook. Data from point cloud were then processed using specialized software tool developed by our research team.

Figure 6 Laser scanner Leica ScanStation2

The point cloud file was loaded into the software in order to obtain the coordinates of scanned points. The extracted position of measured points is shown in the Table 3 below. The deviation of measured points from the horizontal plane (Z coordinates) is calculated using the uncertainty propagation law.

Table 3 Data output after processing



	A	B	C	D	E	F	G	H
1	X[m]	Y[m]	Z[mm]	a	b	c	d	std[mm]
2	0,00	0,00	0	-0,0723	-0,06652	0,99516	0,00861	0,2694
3	0,10	0,00	1	0,00456	0,00327	-0,99998	-0,00547	0,43418
4	0,20	0,00	1	0,0048	0,01072	0,99993	0,004	0,49058
5	0,30	0,00	1	0,01134	0,00754	-0,99991	-0,00869	0,37806
6	0,40	0,00	2	0,00808	0,02324	0,9997	0,00105	0,53103
7	0,50	0,00	1	-0,00659	-0,00624	0,99996	0,00794	0,71579
8	0,60	0,00	2	0,0041	0,00965	0,99994	0,00189	0,58929
9	0,70	0,00	1	-0,00078	0,00748	-0,99997	-0,00427	0,59528
10	0,80	0,00	1	0,00129	-0,00282	-1	-0,00603	0,56227

Column A – defined coordinate X [m], Column B – defined coordinate Y [m], Column C – computed height, coordinate Z [m]. Columns A, B define the grid.

The accuracy of the results in this case study defined by the standard deviation of the flatness determination calculated from the standard deviation of the Z coordinates of measured grid points using quadratic mean is represented by the value 0.7 mm.

Graphical representation based on output data is presented on the Figure 7 where overall flatness is represented by isolines and on the Figure 8 where by the flatness is represented by mesh surface.

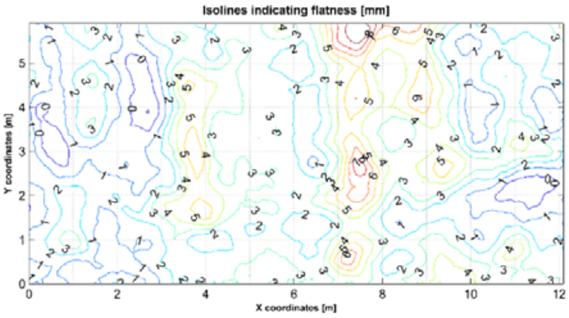


Figure 7 Isolines indicating flatness

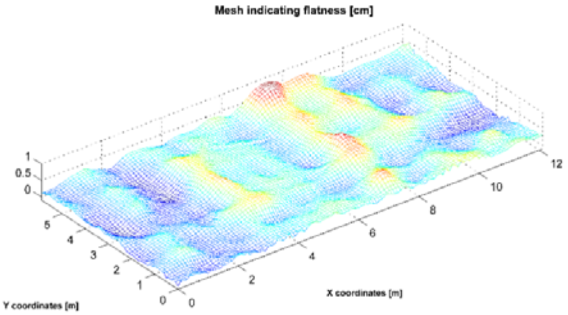


Figure 8 Mesh indicating flatness

3.3 Comparation of two methods

Comparation of mentioned methods for flatness evaluation (standard methodology and non-standard methodology using TLS) provided several facts and factors to be taken into account developing the process of new methodology.

<u>Evaluation according to actual standards</u> could provide information about local flatness without the possibility of including individual points from wider area than 2m. Total deviation of individual points of industrial floor from defined plane is not possible neither the verification of inclination nor declination defined by project. Moreover, this process is very laborious, time consuming and it requires a high degree of attention. This may lead to significant errors in reading of measures and result in inaccurate records.

The measurement is directly dependent on the choice of places where the spirit level was placed and also the direction in which the spirit level is placed on floor, therefore different interpretation of the results are possible. Under certain circumstances, the very same floor can be evaluated both to meet and not to meet the criteria of standards for flatness. On the Figure 9 are shown various positions of spirit level and influence to measurement. By placing spirit level in position A and B measured data provide an information that floor has almost no deviation from plane and local defects. By placing the spirit level into position C, data obtained from a measure proves significant deviations.

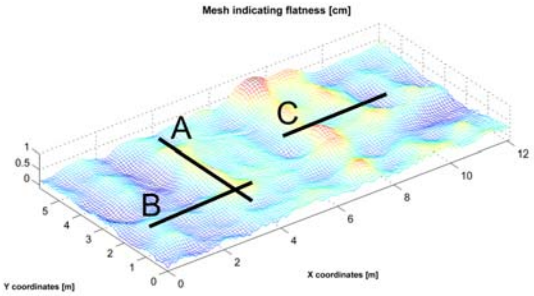


Figure 9 Various positions of spirit level meter

One of major disadvantage is the fact that the measurement cannot be automated.

<u>Measurement using TLS</u> can be evaluated from perspective of the local flatness and at a same time total deviation from the plane or verification of inclination nor declination defined by project can be assessed. The measurement by TLS is very accurate and fast. Measurements record exact data in defined grid, i.e. it could be used also for the evaluation of the data in accordance with standard methodology.

Proposed methodology is able to provide clear answer what degree of the flatness of the floor has been reached.

Significant advantage is that the measurement and evaluation can be automated and therefore will not depend on personal judgement of evaluator.

3.4 Prospective future research

Destructive tests were not allowed on this case study as the deviations were not significant and investor has not raised a claim. Local defects might be better assessed by drilling cylinders and performing tests e.g. determining the number of fibres in this spot by CT scan. The declined spot may be a result of less fibres or improper distribution of fibres.

By providing 3D BIM model of a project, other possible causes of defects may by easily evaluated and rejected or confirmed. By comparing the planned 3D model vs model obtained from actual measurements, differential models will be automatically generated (processed). Analysis of difference models will be the part of new tools and the final assessment of the quality of the work, its correct location in space, as well as the fulfilment of quality requirements (construction deviations), will be determined in the BIM environment.

These data could be easily used to discover local defect that can be caused by failure of underfloor horizontal piping system (leakage, inadequate compaction, etc.). Without having precise and complete data, technological uncertainty is higher, investigation is more complicated, time consuming and the result is ambiguous.

By continuing on this research we assume that more complex testing will be included into methodology.

CONCLUSION

Geometric accuracy measurement of flatness of industrial floors is rather time consuming activity and the quality of works cause many legal disputes between investor and contractor. Standards that are currently in use don´t reflect to actual digital technology developments and advanced technologies as many of processes are manual which leads to significant errors e.g. error in measuring, error in evaluation, error caused by low complexity of operation. Moreover, such a manual process cannot be automated. Proposed methodology by our research team is able to provide clear answer what degree of the flatness of the floor has been reached.

Methodology could result in new standards but further study and research in this field needs to be performed.

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[18]STN 73 0212-6 Geometrical accuracy in construction, Verification of accuracy, Part 6: Statistical analysis and thinning

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