Research article

Bogdan Wolski and Grzegorz Granek*

Functionality and reliability of horizontal control net (Poland)

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Abstract: Horizontal control networks established with monuments are functional if the conditions related to the number of control points, their density, condition and stability of coordinates are met. For functionality defined in those terms, deterministic accuracy characteristics are of little use. The subject matter discussed herein includes the two key features of geodetic control points, i.e., usability and stability. Due to the varying properties of those variables and the impact of the operating time of the system, there is no alternative to reliability-based approach in developing the functionality model. The measures of functionality and the procedures of data acquisition for developing the model of the control network destruction process have been defined. The solution presented herein is relevant for geodetic practice, providing a standard procedure for defining the time frame and the scope of the control network upgrading. The identified destruction process model optimizes this task assuming critical states expressed by the functionality probability. The applied approach is an example of the reliability theory-based approach typical for engineering. The issue of simulating the destruction process is illustrated with the results of the tests of class 3 control networks conducted in Kielce and Lodz regions in Poland. As a result of the tests, the characteristic properties of the control network destruction process have been identified. It was also shown how the patterns of usability and accuracy of the geodetic control points are relevant on the stage of implementing investment project tasks.

Keywords: class 3 horizontal control, operational reliability, condition criteria

*** Corresponding author: Grzegorz Granek,** Department of Geomatics, Kielce University of Technology, Aleja Tysiąclecia Państwa Polskiego, Kielce, Kielce Region, 25-314, Poland, e-mail: g.granek@tu.kielce.pl
Bogdan Wolski: Department of Geomatics, Kielce University of Technology, Aleja Tysiąclecia Państwa Polskiego, 25-314 Kielce, Poland, e-mail: bwolski@tu.kielce.pl

1 Introduction

The spatial correctness of any investment project depends on the quality of the control network. On the territory of Poland, in accordance with technical regulations in practice, class 3 control networks are usually used [1,2]. Geodetic control points are physically represented in the field by appropriate monuments that ensure the stability of their coordinates. The coordinates, recorded in the National Geodetic and Cartographic Database on the basis of the original measurement, are then used for years in the unchanged form. In terms of accuracy, class 3 control network is considered superior for all measurement tasks, including the cases when the investment project is implemented on more accurate autonomous networks. The issue of aligning control networks of variable accuracy is solved with the use of Hausbrandt's posttransformation correction [3–5]. It should also be noted here that any corrections of the coordinates of individual geodetic control points is only possible if the entire control network undergoes an upgrade or an update measurement [1].

Class 3 control network is functional if it meets the requirements related to the accuracy of coordinates of control points and the density of monuments in the field. According to the applicable technical regulations [1], the mean error of adjusted position of a class 3 network point for control formerly classified as class II should be $m_{\mathrm{p}} \leq 0.05\,\mathrm{m}$ and for control points formerly classified as class III, $m_{\mathrm{p}} \leq 0.10\,\mathrm{m}$. The coordinates of control points in PL-2000 coordinates system were determined by transforming the "1965" coordinates system. Due to local deformations and errors of the original system, as well as its operating time, the currently available data may be – and, as practice shows, frequently are – substandard.

The requirement on the density of monuments provided in the relevant technical regulations is imprecisely formulated. On the developed area, the density of class 3 control network points should be at least 1 point on 20 hectares [2]. In practice, control points are expected to be placed not further than 200–300 m from each other. The actual condition is verified as a part of the control network upgrades. The recommendation provided in the applicable technical regulations that the control network's condition should be inspected and the control points' coordinates should be updated on as-needed basis is correct from a factual and technical standpoint, but ambiguous. The lack of a clearly defined criterion is often exploited by the local authorities. The inspection intervals are extended for economic reasons.

The assessment of functionality of class 3 control networks requires

- formulating the measures of a global assessment of the control network functionality,
- standardizing the procedure of examining the control network degradation process, and
- developing a method of predicting the control network degradation process and planning the update measurements.

The model of assessment of control network functionality presented herein is based on the reliability approach. Only the reliability-based model allows combining variables of different properties. In the issue under consideration herein, accuracy is provided in metric units, while the technical condition and the availability of monuments are without unit. The theoretical background of the functionality model is provided in ref. [6]. An example of the application of the model in studying vertical control networks is provided in ref. [7]. In this study, the reliability model is used in the analysis of the horizontal controls degradation process. As in all considerations of reliability of a structure, an important element of the study is the statistical analysis of functionality of horizontal controls. The authors have been conducting this study since 2016 on control nets located in different parts of the Lodz and Kielce regions.

2 Data acquisition in horizontal control network functionality studies

In the proposed functionality analysis method, the control network "wear" process is described by two variables: usability and stability [6,7]. The geodetic control points stabilized in the field with monuments perform their task provided that they are in good working condition and the coordinates are stable. In practice, good working condition does not always qualify a control point as meeting the measurement requirements. This is the case for control points established close to the walls, in forests, shrubbery, marshes, restricted areas, on considerable depth, etc. It should be pointed out that in the case of doubt or the need to conduct additional measurements using traditional methods, a surveyor usually seeks another control point. In this context, usability is a more generalized feature than the working condition, as it provides for both the condition of the monument and the possibility of taking a measurement. Consequently, for the reliability-based approach, qualification is arbitrary and, in each case, binary.

Stability data are acquired from the results of the control measurement. This type of measurement is usually taken using kinematic techniques (RTK and RTN) on at least two geodetic control points located not farther than 5 km from the measured control points. The line vector of coordinate's difference f_{XY}, determined based on the control measurement, must not exceed 0.12 m [2]. The result of the control measurement is affected by the error or primary and current measurements and various other factors that are usually impossible to identify. In the study results presented herein, the impact of the measurement error was ignored, arguing that for the RTK GNSS measurement, the error does not exceed 1–3 cm, with the acceptable f_{XY} deviation of 0.12 m.

3 Theoretical background of the functionality study outcomes analysis

In the technical analysis, reliability is usually defined as the probability that an object meets specified criteria over a period of time $[t_0, t]$ of system operation [8–10]. The concision of assessment of the quality of the whole system with a single characteristic is one of the key advantages of the reliability-based model. A less advantageous feature of this approach is the need to gather data through research tests conducted on large sets.

The functionality model is defined by three functions, i.e., the reliability function $R(t)$, the failure risk function (hazard function) $\lambda(t)$ and the stability function $F(t)$. The reliability function $R(t)$ defines the probability of the correct operation of the object's system in the period of $\langle 0, t \rangle$, i.e., from the moment of handing over the object for operation.

$$R(t) = P\{t_N \geq t\} \quad \text{dla} \ t \geq 0 \tag{1}$$

Function $R(t)$ is related to function $F(t)$, which defines the random stability life of the object [6].

$$R(t) = 1 - P\{t_N < t\},$$
$$R(t) = 1 - F(t), \tag{2}$$

where t_N is the time of operation of the object. By definition, the function takes the following form:

$$R(t) = e^{-\lambda t}. \tag{3}$$

After transformation (3), the risk function $\lambda(t)$ is defined by the relation:

$$\lambda(t) = -\frac{\mathrm{d}}{\mathrm{d}t}[\ln R(t)] \ . \tag{4}$$

On the model identification stage, depending on the type and the properties of the available data, one of the functions above is applied, i.e., $R(t)$, $F(t)$ or $\lambda(t)$. The most frequently determined function is the risk function $\lambda(t)$, whereby in practice, it is usually assumed that:

$$\lambda(t) = \lambda = \text{const.} \tag{5}$$

The assumption that λ = const is a simplification, as the intensity of the destruction process varies in different periods of time. However, in the case of a study of the control network functionality, we have only one information, i.e., the total number of geodetic monuments that meet the usability and stability criteria in the period of time since the last upgrade. The value of variable λ is determined after transforming the survival function $R(t)$.

$$\lambda = -\frac{1}{t} \cdot \ln R(t). \tag{6}$$

The model is identified in two ways. In the first way, the functionality of the individual control points is assessed based on the statistical set in which each element is the resultant of usability and stability. In such cases, the value of risk λ is determined from the following relation:

$$\lambda = \frac{1}{T_p} \cdot \left(- \ln \frac{n_p}{N_p} \right), \tag{7}$$

where T_p is the period of study from baseline (no. of years), N_p is the number of geodetic control points according to the catalogue, and n_p is the number of control points that meet the requirement of both usability and stability.

An alternative method is based on separating the stability and usability tests [6,7]. In such case, the outcome of the test are two independent data sets and the probability of meeting the criteria of usability P_u and stability P_s determined on the basis thereof. Since the system is functional, if both conditions are met at the same time, the following equation is obtained [10]:

$$P_p = P_u \cdot P_s. \tag{8}$$

After taking the log of equation (8) and considering the relation (7), the resultant risk value λ_p is determined as the sum of the components λ_u (usability) and λ_p (stability).

$$\lambda_p = \lambda_u + \lambda_s. \tag{9}$$

In this case, the components λ_u and λ_s are determined separately based on the probabilities P_u and P_s.

$$P_u = \frac{n_u}{N_u} \quad P_s = \frac{n_s}{N_s}. \tag{10}$$

In practice, the method based on separate testing of usability and stability is less frequently used.

From a practical standpoint, the key element of the functionality analysis is the determination of the number of years T_{kr} after which the control network no longer meets the functionality criteria. In the authors' opinion, two critical functionality states should be distinguished, i.e., the first "warning" state when $R(T_{kr1}) = P_{kr1} = 75\%$ and the second when $R(T_{kr2}) = P_{kr2} = 50\%$. The value of T_{kr} is determined by the following relation:

$$T_{kr} = -\frac{1}{\lambda} R(T_{kr}). \tag{11}$$

4 Example of functionality analysis of the class 3 control network

4.1 Survey results

The analysis procedure was illustrated using the example of a class 3 control network located in the southern part of the Lodz Region. The upgrade and update measurement of the network were performed in 2007. The functionality analysis tests were performed in 2017 on 124 control points. The results of the survey for the purpose of the usability assessment are presented in Table 1.

On the geodetic control points, which were in good working condition, the control measurement of coordinates was performed using the RTK GNSS method and the VRSnet reference stations net. It was determined that a substantial portion of the control network, i.e., 26 control points, failed to meet the criterion of acceptable deviation $f_{XY} \leq 0.12$.

Table 1: Class 3 control network survey results

No. of points according to catalogue	Control points existing in the field			Destroyed control points
	Identified control points	Unavailable control points	Control points in good working condition	
124	90	0	90	34

Table 2: Destruction process prediction for the control network in question and the critical states of functionality thereof

	Initial state	Control measurement	Functionality prediction			Critical states	
	2007	2017	2022	2027	2032	P_{kr1}	P_{kr2}
	1	2	3	4	5	6	7
T [years]	0	10	15	20	25		
$R(t)$	0	0.532	0.388	0.283	0.207	0.75	0.50
Number of functional control points	124	66	48	35	26	93	62

4.2 Control network functionality prediction and critical states

Of the initial number of control points $N_p = 124$, the requirement of both usability and stability was met by 64 points. The risk value λ was determined from formula (7) for $T_p = 10$ years, $N_p = 124$, $n_p = 64$, $\lambda = 0.0631$/year.

Based on the survival function (3)

$$R(t) = \exp[-0.0631 \cdot t],$$

the prediction of the degradation process of the control network in question was determined for three subsequent 5 year operation periods (Table 2, columns 3–5).

Table 3: Summary of the mean values of azimuths and modules of linear deviations f_{XY}

Interval	Interval range (g)	Number of data points in an interval	Mean azimuth value (g)	Mean f_{XY} module (m)
1	2	3	4	5
1	0–49.9	4	31.4717	0.0562
2	50–99.9	5	78.7921	0.0774
3	100–149.9	6	123.4944	0.0704
4	150–199.9	6	176.8879	0.0595
5	200–249.9	19	219.5562	0.0774
6	250–299.9	26	272.7967	0.0754
7	300–349.9	22	318.4120	0.0603
8	350–399.9	2	358.7792	0.0750

4.3 Statistical interpretation of the control measurement results

The statistical analysis of the results of measurement of the coordinates of the control points is not an integral element of the functionality assessment. It is cognitive in nature, and its purpose is to identify the statistical properties in the set of deviations f_X, f_Y determined as the differences between the PL-2000 system coordinates and the results of the control measurement.

$$f_X = X_{sat} - X_{2000},$$

$$f_Y = Y_{sat} - Y_{2000},$$

$$f_{XY} = \sqrt{f_X^2 + f_Y^2}.$$

Conducting a statistical analysis is justified only for data meeting the requirement of $f_{XY} \leq 0.12$. The values that failed to meet the requirement were removed from the data set. Table 3 presents the frequency distribution of linear deviation f_l vectors after separating eight class intervals.

The data presented in Table 3 and the radar charts plotted on the basis thereof (Figure 1) show the distribution of the vectors of linear deviations f_{XY}. The distribution of linear deviations f_{XY} vectors is not even; the number of observations in the 200–300 G azimuths interval is much higher than in other sectors. Such a prominent difference in the number of data points indicates a systematic error. However, the conclusion of the significant impact of the systematic factor is not supported by the radar chart. The mean values of f_{XY}

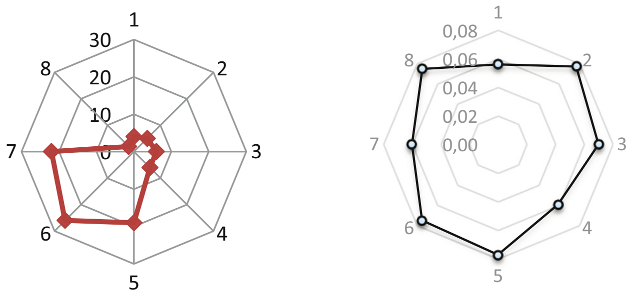

Figure 1: Histograms of azimuths of f_{XY} vectors and their mean values.

modules calculated for individual sectors do not show significant differences (Table 3, column 5).

To identify the statistical properties of the data set, a correlative dependence analysis was performed. The following were determined:

- mean values and standard deviations of variables f_X, f_Y,
- correlation coefficient from the value of variables f_X, f_Y,
- linear regression functions, and
- standard deviation ellipse.

The results of the analysis are presented in Table 4 and Figure 2.

The analysis shows that deviations f_X and f_Y are not correlated although the observations have a minor systematic error. Once the error has been filtered out, the data will have the properties of random variables. The standard deviation ellipses before and after transformation are virtually identical.

5 Class 3 control networks functionality studies in the Lodz and Kielce Regions

The class 3 control network functionality studies conducted by the authors aims, on the one hand, to determine the scale of the destruction issue, and, on the other hand, to identify the patterns of this process

Table 4: Statistical analysis of the results of the control measurement

Statistical value	f_X (m)	f_Y (m)
Mean value (m)	−0.012	−0.020
Standard deviation (m)	0.044	0.057
Linear regression function coefficients	0.0852	0.14445
Correlation coefficient	0.112	
Standard deviation ellipse (m)	b = 0.045, a = 0.055	

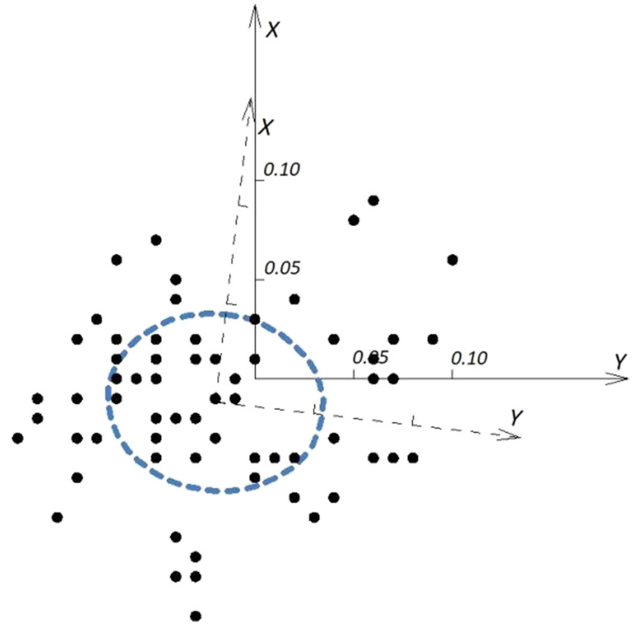

Figure 2: Standard deviation ellipse of f_X, f_Y vectors meeting the requirement of $f_{XY} \leq 0.12$.

relevant for surveying practice. The studies are conducted since 2017 in the Lodz and Kielce Regions (Figure 3) and follow a single program using a sample of 70–170 control points. Table 5 provides the basic information on the studied control networks, i.e., the object code (col. 1), measurement dates: initial and control measurement (col. 2), the number of control points: the number of points in the catalogue/number of points on which the control measurement was performed/the number of points meeting the requirements of $f_{XY} \leq 0.12$ (col. 3), the urbanization of the area in which the studied control

Figure 3: Positions of the objects in the Lodz and Kielce regions.

Table 5: Study objects

Object code	Dates of control network measurement	Number of control points	Area urbanization	Reference stations network
1	2	3	4	5
A	2012/2018	70/62/49	Municipal area	ASG-EUPOS
B	2007/2017	124/90/64	Rural area	VRSnet
C	1981/2016	169/67/50	Municipal area	TPI Net
D	2006/2018	107/66/59	Municipal area	ASG-EUPOS
E	1977/2016	149/84/76	Rural area	ASG-EUPOS
F	1998/2018	121/65/60	Municipal area	ASG-EUPOS
G	1997/2017	156/100/59	Rural area	VRSnet
H	2000/2017	158/80/65	Municipal area	VRSnet

network is located (col. 4) and the reference stations net (col. 5).

The control measurements were performed using the RTK GNSS method, referencing various reference stations networks, as per the recommendations provided in the technical regulations [2]. In the event of unfavorable conditions, which could affect the reception of satellite signals, the measurement session was extended as appropriate. Furthermore, for the study purposes, for a number of control points, measurements were taken with reference to the reference stations net other than provided in Table 5. Both in the case of extended measurement sessions and the use of different reference systems, the maximum discrepancies of the satellite measurement results did not exceed 0.03 m.

The observation results then underwent analysis identical in terms of scope and method as applied to object B presented in item 4. First, the observations exceeding the linear deviation of 0.12 m were excluded from the analyzed set. It should be emphasized that such deviations were found in all analyzed data sets. The number of control points provided in column 4 in Table 5, e.g., 149/84/76 ,means that the control measurement could be performed only on 76 points.

The analysis results summarized in Table 6 and shown in Figure 4 show a number of statistical patterns:

- In all cases, the mean values of deviations f_Y are negative. The data sets are shifted slightly westward. The result correlates with the size charts provided on the radar charts (Figure 4), whereby on the latter one, the systematic impact is much more prominent.
- The variables f_X and f_Y are not correlated. The correlation coefficient did not reach the value, indicating the presence of a correlative dependence in any of the analyzed samples.
- The standard error calculated for variables f_X and f_Y, and ellipse semi-axes show only minor differences.

6 Prediction of the functionality destruction process of the analyzed class 3 control networks

Table 7 summarizes the outcomes of the functionality prediction calculated for three subsequent 5 year operation periods and the years in which functionality

Table 6: Statistical analysis of the results of the control measurement

Object no.	Number of points	Mean values		Standard deviation		Correlation coefficient	Azimuth of semi-axis *A* (g)	Semi-axes of ellipses	
		f_X (m)	f_Y (m)	σ_{jX} (m)	σ_{jY} (m)			*A* (m)	*B* (m)
A	49	−0.005	−0.006	0.022	0.023	−0.12	−7.87	0.022	0.022
B	64	−0.012	−0.020	0.044	0.057	0.11	7.31	0.045	0.055
C	50	0.023	−0.014	0.054	0.049	0.165	10.46	0.055	0.048
D	59	0.013	−0.008	0.049	0.043	−0.19	−12.28	0.050	0.041
E	76	0.023	0.003	0.036	0.040	0.19	12.27	0.038	0.039
F	60	0.005	−0.029	0.035	0.039	−0.10	−6.07	0.035	0.038
G	59	0.006	−0.050	0.041	0.039	0.01	0.21	0.040	0.039
H	65	0.012	−0.030	0.039	0.038	0.12	7.48	0.040	0.037

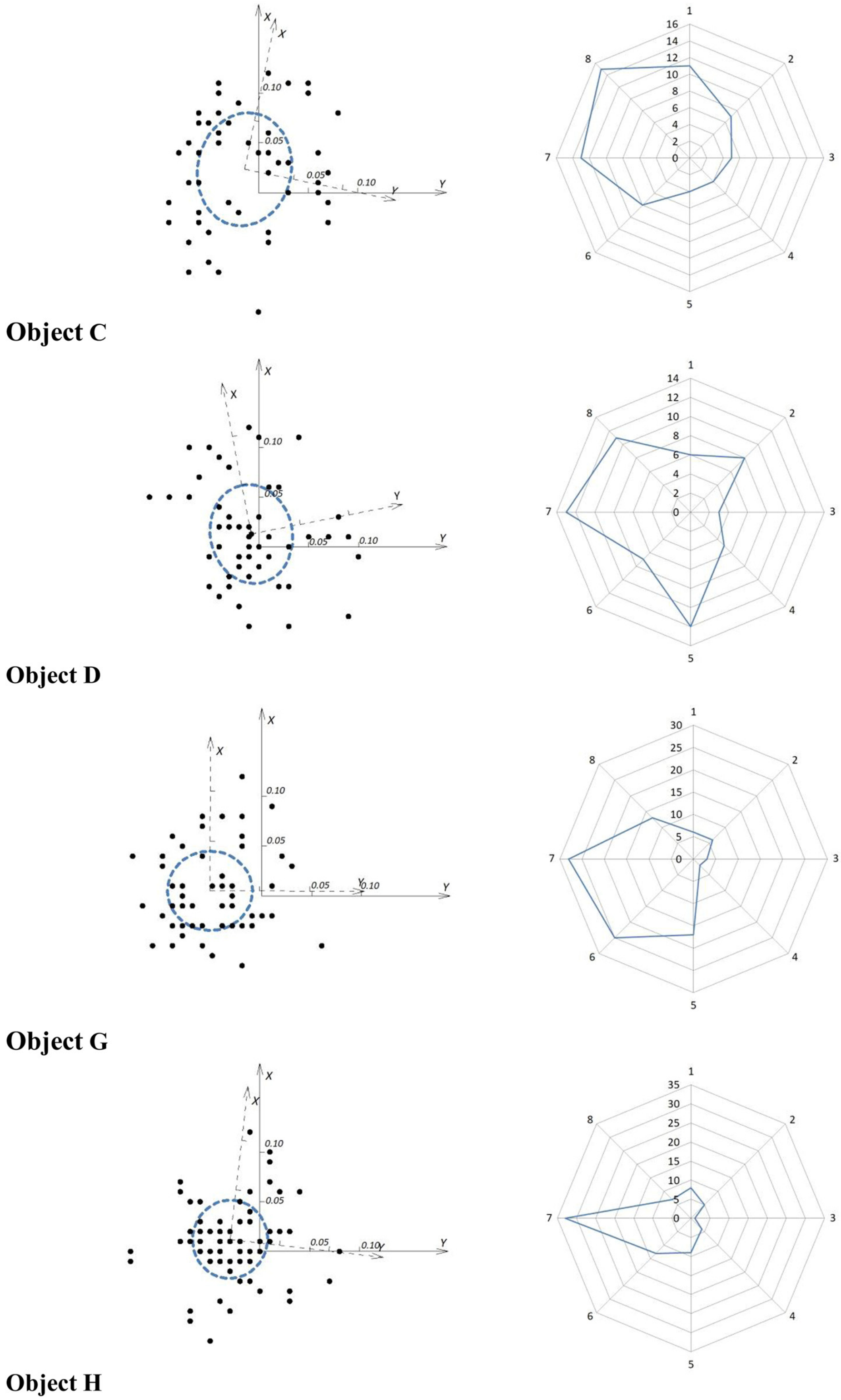

Figure 4: Examples of standard error ellipses and frequency radar charts.

reaches critical values (11). It should be noted that the first state, i.e., the alarm critical state, was not exceeded only for object A. The second critical state was exceeded for all analyzed data sets.

Table 7: Prediction of critical functionality states of analyzed objects

Object	λ	Initial measurement		Number of functional control points				Critical states	
		Date	Number	2018	2023	2028	2033	75%	50%
A	0.059	2012	70	49	37	24	18	2020	2024
B	0.063	2007	124	62	45	33	24	2015	2019
C	0.035	1981	169	46	39	32	27	1995	2002
D	0.056	2006	107	55	41	31	24	2015	2019
E	0.017	1977	149	74	68	63	58	2006	2021
F	0.056	1998	121	40	30	23	17	2007	2011
G	0.047	1997	156	58	46	36	29	2008	2013
H	0.054	2000	158	60	46	35	27	2009	2014

Based on the data in Table 6, a general conclusion can be drawn on the condition of the control networks and a detailed one on the intensity of the destruction process in different regions. The risk variable λ fluctuates around the mean value of 0.046 between the extreme values of 0.063 and 0.017. With the exception of the extreme values, the risk variable does not show significant variation. The significant deviation of object **E** can be explained by the exceptionally high local investment activity (central districts of Lodz city).

7 Final remarks and conclusions

7.1 Identification of the functionality model

The presented method of functionality assessment is a coherent solution in terms of the test purpose, an unambiguous criteria expressed in the form of probability interpreted according to the reliability engineering theory and data acquisition procedures as well. Only the reliability approach integrates different properties such as usability and stability in one model.

The critical state level is a questionable element of the method. The correct indication of critical probabilities provides a rational basis for the decision concerning the date of maintenance actions. The authors suggest introducing two critical functional states at the levels $P_{cr1} = 75\%$ and $P_{cr2} = 50\%$.

The destruction of the control network is influenced by two factors. The main one is the physical destruction of network benchmarks. Since the cause of destruction is the investment activity necessary for the functioning of the economy, therefore, the solution to this problem depends on decisions made by regional surveying departments and local administration. Technically, the problem is solved by supplementing the existing network and new measurements.

The presented method of evaluating functionality can be used regardless of the structure and the number of points. An optimal solution is to make an inventory and control check measurement for all control network points stabilized in a specified area, e.g., in the area of a commune. In case of significant number of points, the survey may be of statistical nature. Authors' experience has shown that achieving a reliable result requires testing a minimum of 100 points. The measurement should be carried out with a standard error $\sigma_p \leq 0.03\,\text{m}$, i.e., at least twice as high as the accuracy of the coordinates specified in technical regulation [1,2].

According to the authors, the scope and the detail of the research carried out entitles to conclude that the presented procedure can be adopted as a standard procedure, useful in the assessment of the quality of regional geodetic resource databases.

7.2 Statistical properties of the destruction process of the class 3 control networks

The problem of evaluation of horizontal control networks functionality in the article is presented on the example of class 3 control networks, which in Poland are stabilized by means of permanent markings. The local characteristics of these networks follow from the fact that the current coordinates of points in the “2,000” system are the result of the transformation of coordinates originally calculated in another reference system (“65”). The main conclusion is that the level of network destruction is significant and is dependent on the exploitation period. Changes in coordinate values exceeding the critical values usually affect some percentage of points. But the resultant value of the risk parameter λ is always significant, on average $\lambda = 0.046$.

The measurement results presented in Table 6 and Figure 3 indicate that the coordinates are influenced by a systematic factor. Asymmetry of the distribution of the number of deviations f_{XY} is visible in all test results. The direction of the translation vector is approximately consistent with the Y-axis. The value of translation and standard errors of the variables f_X, f_Y confirm the opinion that the accuracy of transformation of the primary system to the system "2,000" is within the limits of 0.05 m. Since it is impossible to indicate whether the observed coordinate differences are the result of an invalid primary measurement or due to unrecognized factors, it is optimal to update the network in larger areas. Currently, such corrections are carried out locally in accordance to the investment tasks.

In the analysis of the functionality issue, a research workshop is important. The coordinates of network points were determined using the GPS kinematic technique combined with ASG-EUPOS, VRSnet and TPInet reference station networks. To estimate the accuracy of the determined coordinates, some of the points were observed with extended observation time or in connection with another reference network. The standard error determined on this basis is similar for all objects, approximately 0.02 m.

7.3 Modernization of control networks by means of satellite measurement techniques

The high level of destruction and maintenance costs of networks on the one side and the effectiveness of satellite measurements on the other become rational arguments for the lack of acceptance for static control nets [11,12]. Currently, in the opinion of the authors, this is a premature opinion, although optimization of the methods of design and maintenance of class 3 control networks is necessary and possible taking into account local conditions. On the one hand, databases of class 3 control networks available in Polish regional documentation centers are components of the state surveying and cartographic resource [3,4]. These databases have an important role in the functioning of various segments of economy and administration. On the other hand, from a technical point of view, permanent signs are necessary in areas beyond the range of permanent reference stations, in densely built-up areas, in areas where it is not possible to effectively distribute GPS adjustment corrections via the GSM network or due to significant land surpluses also the UHF radio communication, etc.

The results of this study confirm the necessity to rethink the approach to the problem of networks' functioning and indicate the directions of these changes. In the opinion of the authors, the modified approach should be complementary, i.e., take into account the network structure, number of points and coordinate measurement methods. The main postulate of the proposed concept is to replace the network with a set of autonomous points. Local connections of adjacent points would be made by means of classical measurements, but the latter would only have a check character. The planning of location and number of points should take into account the process of destruction. The level of destruction can be assumed on the basis of the analysis of critical states determined by means of a functionality model. Such assumption will significantly increase the number of network points.

An important element of the proposed concept is to measure the coordinates of network points. Within this task it is possible to use differential GNSS positioning, precise point positioning (PPP), linear-angle measurements and hybrid methods integrating different techniques. The presented research results show that at the stage of control measurements sufficient accuracy is provided by the kinematic technique. When establishing a network, measurements should be carried out using static methods in accordance with the recommendations [1], but practice proves that under favorable conditions, kinematic techniques are also satisfactory. In Poland, measurements using differential GNSS method are possible thanks to several systems of reference stations, mainly the ASG-EUPOS system.

An alternative to differential measurements is technique of precise satellite positioning using a global fixed station infrastructure [13–15]. The advantage of the absolute PPP method is its autonomy. The measurement is performed without the need to relate to regional reference stations, while access to the GNSS (IGS) data on GNS and GLONASS is necessary. The PPP method is still a subject of research, and its accuracy depends on the length of the session and IGS data [16] The results in the range of 0.02–0.03 cm achieved with sessions of about 2–3 h can be assumed as sufficient for class 3 network measurements. The accuracy requirements for coordinate measurements are also met by Smart Station technology integrating satellite measurements with classical measurements [17]. It can be assumed that this technique will be particularly useful at the stage of control measurements, as it gives the possibility to control both the station and the adjacent points.

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