Exploration of polar crane geometric parameters with the use of modern geodetic electronic gauges

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Abstract. The paper presents recent explorations of polar crane parameters with the use of the latest geodetic electronic gauges, instead of conventional devices recommended by normative documents for measuring instruments. A set of basic geometric conditions for polar cranes was specified with required precision, namely: convergence of diagonals at the specified points, inside rolling radius of the wheels, lateral sliding of the wheels, longitudinal sliding of the wheels, position of wheels at a given radius, position of wheels at a given diameter, rolling radius of virtual wheels in small balancers, transverse slippage of bridge virtual wheels in small balancers. All basic parameters are shown not to surpass theoretical (design) parameters. The findings illustrate that the main operational characteristics of the polar crane explored herewith are permissible.

1. Introduction
Polar crane parameters were explored using the following geodetic gauges and instruments:
- high-precision Zeiss ELTA S10 total station No. 400396;
- high-precision GTS-102N total station No. 6G0051;
- high-precision DINI 0.3 digital level No. 731249;
- LD 11 Nedo Trimble leveling staff No. 50523;
- RK-2-30 measuring tape No. 04.

The measuring instruments were duly verified and had metrological certificates.

The following geometric parameters were determined:
- bridge parameters, including sizing along the length of the end trucks and idler girders fixed by specified points K and F on the diagonals, the idler cambers;
- parameters of the wheel base, including the parameters of the travel wheels, the parameters for the travel wheels to be installed on the rails (radii, diameters of the travel wheels).

The main operational criteria that determine the effective geometric conditions enabled in the wheels and the wheel base are longitudinal and cross slip as well as longitudinal stability of the crane.

Geodetic accuracy was measured in line with mechanical tolerances given in the design and detailed documentation through the accuracy assurance factors

\[ M_{geo} = C \times \delta_{mech} \]
where $m_{geo}$ is the root-mean square error (RMS) of geodetic measurements;

$C$ is the accuracy assurance factor (in this case, it was taken equal to $C = 0.2$);

$\delta_{mech}$ is the mechanical deviation (tolerance).

Measured and processed values are presented below. The findings are provided in tabular and graphical forms.

2. Problem Statement
The paper examines the geometric parameters of polar cranes in order to determine the possibility and timeline for further operation. A review of scientific and technical literature [1–12, etc.] shows that the parameters were most commonly investigated using standard measuring instruments, namely, string, string-optical, optical and beam gauges and other technical means. This task can be simplified by using the latest electronic geodetic gauges. Hence, it is vital to call for electronic means for addressing it.

3. Research Questions
The target issue is high-precision determination of the geometric parameters of polar cranes using the latest electronic geodetic gauges.

4. Purpose of the Study
The paper aims to pilot a high-precision algorithm for determining the polar crane parameters using the latest electronic geodetic gauges.

5. Research Methods
The methods involve observation, system analysis, comparative analysis, simulation.

6. Findings
When the geometric parameters of the polar crane bridge were checked, the sides and diagonals of the rectangles formed by the points $K$ and $F$ were determined. The geometric determinations are shown in Table 1 and Table 2.

![Figure1. Schematic for the monitored crane bridge dimensions](image-url)
### Table 1. Geometric determinations

|       | theor. | D1–D2 | theor. | ±5   |
|-------|--------|--------|--------|------|
| K1–K4 | 40798  | 40795.4| pract. | 3.1  |
| K2–K3 | 40798  | K1–K2  | theor. | 7600 |
| K1–K3 (D1) | 41500 | K3–K4  | theor. | 7600 |
| K2–K4 (D2) | 41499.9| pract. | 7604.9|
|       | theor. |        |        |      |
|       | 41500  |        |        |      |
|       |        |        |        |      |
|       | 41496.8|        |        |      |

### Table 2. Geometric determinations

|       | theor. | F1–F2 | theor. |       |
|-------|--------|--------|--------|-------|
| F1–F4 | 40587.8| pract. | 8589.5|
| F1–F2 | theor. |        |        |       |
| F2–F3 | 40588.9| pract. | 8604.1|

In addition, the idler cambers were determined. The measurements are shown in Table 3.

### Table 3. Bridge idler cambers

| No. | Travel, m | Markings, mm | Exceedances, mm | No. | Travel, m | Markings, mm | Exceedances, mm |
|-----|-----------|--------------|-----------------|-----|-----------|--------------|-----------------|
| 1   | 0.0       | 0            | 1               | 24  | 21.4      | 56           | 54              |
| 2   | 0.9       | 6            | 7               | 25  | 22.3      | 55           | 56              |
| 3   | 1.9       | 9            | 12              | 26  | 23.2      | 57           | 57              |
| 4   | 2.8       | 15           | 17              | 27  | 24.2      | 54           | 57              |
| 5   | 3.7       | 18           | 21              | 28  | 25.1      | 52           | 56              |
| 6   | 4.6       | 21           | 26              | 29  | 26.0      | 52           | 54              |
| 7   | 5.6       | 26           | 28              | 30  | 27.0      | 50           | 52              |
| 8   | 6.5       | 28           | 31              | 31  | 27.9      | 47           | 51              |
| 9   | 7.4       | 33           | 32              | 32  | 28.8      | 46           | 49              |
| 10  | 8.4       | 37           | 38              | 33  | 29.7      | 45           | 48              |
| 11  | 9.3       | 39           | 39              | 34  | 30.7      | 43           | 47              |
| 12  | 10.2      | 42           | 41              | 35  | 31.6      | 42           | 43              |
| 13  | 11.2      | 46           | 43              | 36  | 32.5      | 39           | 42              |
| 14  | 12.1      | 47           | 43              | 37  | 33.5      | 37           | 39              |
| 15  | 13.0      | 48           | 44              | 38  | 34.4      | 34           | 35              |
| 16  | 13.9      | 50           | 46              | 39  | 35.3      | 30           | 29              |
| 17  | 14.9      | 51           | 48              | 40  | 36.3      | 27           | 27              |
| 18  | 15.8      | 53           | 48              | 41  | 37.2      | 24           | 23              |
| 19  | 16.7      | 54           | 49              | 42  | 38.1      | 18           | 18              |
| 20  | 17.7      | 56           | 52              | 43  | 39.0      | 15           | 14              |
| 21  | 18.6      | 57           | 52              | 44  | 40.0      | 11           | 8               |
| 22  | 19.5      | 57           | 53              | 45  | 40.9      | 7            | 2               |
| 23  | 20.5      | 55           | 54              | 46  | 41.8      | 1            |                 |
Figure 2. Schematic for theoretical geometric parameters of the wheel

Table 4. Theoretical geometric parameters of the wheel

| No. | runway track | Wheel diameters Inside, mm | Outside, mm | Wheel traveling radii, mm | One turn, mm | Relative slip coefficient | Full circle slip, mm | One turn, mm | Relative slip coefficient | Full circle slip, mm |
|-----|--------------|----------------------------|-------------|--------------------------|--------------|--------------------------|---------------------|--------------|--------------------------|---------------------|
| K1  | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K2  | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K3  | 737.43       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K4  | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K5  | 737.99       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K6  | 737.43       | 744.58                     | 21752.79    | 6.0132689                | 0.0025831    | 336.774                  | 0.166761            | 2.4106E-06  | 9.338593                 |
| K7  | 737.43       | 744.58                     | 21752.79    | 6.0132689                | 0.0025831    | 336.774                  | 0.166761            | 2.4106E-06  | 9.338593                 |
| K8  | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K9  | 737.99       | 745.15                     | 21760.17    | 6.0647837                | 0.0026032    | 339.3969                 | 0.167974            | 2.4273E-06  | 9.406563                 |
| K10 | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K11 | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K12 | 737.99       | 744.87                     | 22664.91    | 11.032931                | 0.0047366    | 617.5435                 | 0.295668            | 4.10398E-06 | 16.55738                 |
| K13 | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K14 | 737.43       | 744.87                     | 21752.79    | 6.0132689                | 0.0025831    | 336.774                  | 0.166761            | 2.4106E-06  | 9.338593                 |
| K15 | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| K16 | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| Av. | 737.71       | 744.87                     | 21756.48    | 6.0390115                | 0.0025932    | 338.0852                 | 0.167367            | 2.41895E-06 | 9.37257                  |
| Design | 737.694     | 744.849                    | 21756.25    | 6.0374018                | 0.0025925    | 338.0032                 | 0.167329            | 2.41484E-06 | 9.370446                 |

Note: the wheel radii error (outer $r_{\text{out}}$ and inner $r_{\text{in}}$) is equal to the value of $m_w = \pm 0.25$ mm.
Sliding is a continuous interaction between the wheel and the rail where the length of the track calculated along the railhead is not equal to the length of the track calculated along the wheel.

Slippage is an instantaneous change in the mutual position of the wheel and the rail with the unloading of accumulated forces in the crane metal structures.

In this case the sliding can be formed both in the longitudinal direction (coinciding with the motion direction) and in the transverse direction (perpendicular to the motion direction). Slippage occurs only in the lateral direction. The consequence of sliding and slippage is the actuation of the railhead on one side and the loss of stability when the crane moves. These parameters are the main operational characteristics which should be normalized and should be minimal in absolute terms.

The calculated longitudinal and lateral slips are presented in Table 5.

![Figure 3. Schematic for mutual arrangement of runway circumference and transverse slip circumference](image)

When the crane is travelling, given that $R_{\text{runway}}$ is not equal to $R_{\text{wheel rolling}}$, then the wheel tends to move along its circumference corresponding to its geometric parameters. However, riding along a crane rail, the target wheel remains on the circumference of the crane runway. Thus, the wheel slides in the radial direction by the value of $\Delta x$ when it slips at each full turn $C_w$.

$$
\Delta_x = \left[ R_{\text{runway}}^2 + 4 \cdot \sin^2 \left( \frac{R_{\text{runway}} \cdot \gamma}{R_{\text{runway}}} \right) \left( R_{\text{runway}}^2 - R_{\text{runway}} \cdot R_{\text{wheel}} \right) \right]^{1/2} - R_{\text{runway}};
$$

(2)

The coefficient of relative lateral slip is calculated by the formula

$$
K_{\Delta x} = \frac{\Delta_x}{C_{\text{runway}}};
$$

(3)
When the wheel is installed on the rail, a so-called “contact patch” is formed in the zone of their interaction, the shape of which depends on the shape of the wheel and the shape of the upper surface of the railhead. Given that the rail has a radial shape, then when the wheel travels on this rail, the process of longitudinal sliding $\Delta s$ is observed in the contact patch. Given that the wheel is conical and $R_{\text{runway}} = R_{\text{(wheel rolling)}}$ then $\Delta_s = 0$. In any other case, a process of longitudinal sliding is observed in the contact patch.

The coefficient of relative longitudinal slip is calculated by the formula

$$
\Delta_c = 2 \cdot \pi \cdot \left( \frac{d_{\text{ailias}}}{2} - d_i \right) \cdot \left( \frac{d_{\text{ailias}}}{R_\varepsilon} + \frac{R_\varepsilon}{R_\varepsilon} \cdot \tan (\beta) \right); 
$$

(4)

The coefficient of relative longitudinal slip is calculated by the formula

$$
K_{\Delta s} = \frac{\Delta_c}{C_\varepsilon}. 
$$

(5)

Table 6 shows the geometric parameters for travel wheels to be installed along the circumference.

The principal geometric parameters of the crane runway are the mutual arrangement of the travel wheels in small balancers. The mutual arrangement of the wheels determines the movement of the crane along the circumference. Moreover, if tapered wheels with a motion radius corresponding to the crane runway radius are used and the tops of these wheels are aligned in a single center, the wheel-wheel interaction forces are equal to zero $f_w = 0$.

The angles of the mutual arrangement of the travel wheels are given in Table 7.

The angles of mutual rotation of symmetrical travel wheels in the main balancers and the angles of mutual rotation of symmetric travel wheels in adjacent main balancers are also determined.
### Table 6. Position of travel wheels

| Radius No. | Radius, mm | Deviation from design radius, mm | Diameter No. | Diameter, mm | Deviation from design diameter, mm |
|------------|------------|---------------------------------|--------------|--------------|-----------------------------------|
| 1          | 20752.0    | 2.0                             | 1–9          | 41499.0      | –1.0                              |
| 2          | 20752.4    | 2.4                             | 2–10         | 41500.9      | 0.9                               |
| 3          | 20751.5    | 1.5                             | 3–11         | 41502.5      | 2.5                               |
| 4          | 20752.8    | 2.8                             | 4–12         | 41504.3      | 4.3                               |
| 5          | 20749.9    | –0.1                            | 5–13         | 41501.0      | 1.0                               |
| 6          | 20750.6    | 0.6                             | 6–14         | 41501.6      | 1.6                               |
| 7          | 20749.8    | –0.2                            | 6–15         | 41499.5      | –0.5                              |
| 8          | 20751.4    | 1.4                             | 8–16         | 41500.5      | 0.5                               |
| 9          | 20747.0    | –3.0                            |              |              |                                   |
| 10         | 20748.5    | –1.5                            |              |              |                                   |
| 11         | 20751.0    | 1.0                             |              |              |                                   |
| 12         | 20751.5    | 1.5                             |              |              |                                   |
| 13         | 20751.1    | 1.1                             |              |              |                                   |
| 14         | 20751.0    | 1.0                             |              |              |                                   |
| 15         | 20749.7    | –0.3                            |              |              |                                   |
| 16         | 20749.1    | –0.9                            |              |              |                                   |
| **Design values** | **20750.0 ±2.5** | **41500.0 ±5.0** |              |              |                                   |

Note: the radii error is equal to $m_R = ± 2$ mm; diameters $m_D = ± 3$ mm

### Table 7. Angles of wheel-wheel rotation in pairs

| No of pairs of wheels | Angle of mutual rotation ° ′ ″ | Angle of wheel-wheel rotation ° |
|-----------------------|--------------------------------|--------------------------------|
| 1–2                   | 2° 53’ 55"                     | 2.89861111°                    |
| 3–4                   | 2° 40’ 24"                     | 2.67333333                     |
| 5–6                   | 2° 38’ 29"                     | 2.64138889                     |
| 7–8                   | 2° 55’ 12"                     | 2.92000000                     |
| 9–10                  | 2° 44’ 41"                     | 2.74472222                     |
| 11–12                 | 2° 41’ 42"                     | 2.69500000                     |
| 13–14                 | 2° 40’ 22"                     | 2.67277778                     |
| 15–16                 | 2° 53’ 14"                     | 2.88722222                     |
| **Average value**     |                                | 2.76663194                     |
The crane, with no efforts in auxiliary balancers, moves along the calculated circumference where $R_{runway}$. In any other case, when the radius of the tapered wheels are not equal to the calculated $R_{runway}$ or their tops are not aligned in a single center, there are wheel-wheel interaction forces $f_w$ in auxiliary balancers, which characterize the conditions for movement around the circumference ($R_i$ is not equal to $R_{runway}$), the geometric parameters of which are determined by the values of these forces. Without considering the theoretical foundations of these provisions in detail, ultimately, any pair of wheels united in small balancers can be replaced with a virtual tapered wheel. The parameters of this wheel are similar to the parameters of real cylindrical wheels except for the fact that there is no concept of longitudinal slip for a virtual wheel. The virtual wheel only generates a lateral slip on the rail.

In addition, the geometric parameters of small balancers (sliding of virtual wheels formed by small balancers), geometric parameters of the main balancers (sliding of virtual wheels formed by the main balancers) and geometric parameters of the sides of the crane bridge (sliding of virtual wheels formed by the main balancers on each side of the crane) were determined.

7. **Conclusion**

1. The convergence of diagonals along the specified points $K = 3.1 \text{ mm}$, $F = 4.3 \text{ mm}$ is less than the design value of the parameter $\pm 5$.
2. The idler cambers: side $2-3$, mm = $47 \text{ mm}$, side $1-4$, mm = $47 \text{ mm}$ is less than the design value of the parameter equal to $46\text{ mm} \pm 20\%$.
3. Internal rolling radius of wheels min = $20917.93 \text{ mm}$, max = $22664.91 \text{ mm}$, av. = $21756.25$ is less than the design value of $20645 (+1606) \text{ mm}$.
4. Cross slip of wheels: min=0.0004499, max=0.0047366 less than the design value $-0.00029$.
5. Longitudinal wheel slip: min = $5.87402E-07$, max = $4.10398E-06$ is less than the design value $1.97E-07$.
6. Position of wheels at a given radius: min = $20747.0 \text{ mm}$, max = $20752.8 \text{ mm}$ less than the design value $20750 (\pm 2.5)$.
7. Position of wheels at a given diameter: min, mm = $41499.0$, max, mm = $41504.3$ less than the design value $41500 (\pm 5.0)$. 

![Figure 5. Schematic for mutual arrangement of travel wheels in small equalizers](image)
8. The rolling radius of virtual wheels in small balancers \( m = 20.29865422 \) m, max, \( m = 21.4700352 \) m, average, \( = 21.01657214 \) m is less than the design value of 21.500000 m.

9. The lateral sliding of virtual wheels in small balancers \( \text{min} = 0.000387, \text{max} = 0.003566 \) is less than the design value.

Thus, all parameters correspond to the design (calculated) requirements.

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