RESEARCH ON HYDROSTATIC LEVELING SYSTEM TO PROVIDE ELEVATION CONSTRAINTS FOR CONTROL NETWORK ADJUSTMENT*

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Abstract
As the precise sensor system for monitoring the relative altitude changes among multiple points, the capacity hydrostatic leveling system (HLS) is widely used in particle accelerators. To expand its application in providing the elevation constraint for the control network adjustment, the research on the issue of the HLS for altitude difference measurement between multiple points is carried out. Based on the working principle of the HLS sensor, a comparison system composed of dual-frequency laser interferometer, high-precision Z stage, HLS sensors and others is designed and manufactured. The system is used to control multiple sensors to observe the same liquid level in the same coordinate system. The zero-position difference among sensors can be obtained by comparison. Then the altitude difference measurement can be realized, and it is verified that the measurement accuracy is better than 5 μm. In addition, a simulation experiment for 3D control network measurement is run, in which the HLS system provides the elevation constraint for the adjustment processing. The results show that for the 100m linear tunnel, the errors accumulation in the elevation direction is significantly improved compared to the classics adjustment.

INTRODUCTION
In recent years, the 4th generation synchrotron radiation light sources have gradually emerged. Their engineering scales are significantly larger and alignment accuracy requirements are stricter than those of 3rd generation. For example, the perimeter of the storage ring of the Hefei Advanced Light Source is about 480 m, and that of the Beijing High Energy Photon Source is 1400 m. They both require the alignment error among the pre-alignment girders to be less than 50 μm [1-3]. To achieve such high alignment accuracy in a large spatial scale, the control network is usually needed to be the reference of equipment installation and alignment[4]. It is widely used in control network measurement to define the coordinates of unknown points by setting free-station of Laser Tracker. However, the accumulated errors in multi-station measurements make it challenging to meet the alignment accuracy requirements of the four generations light sources, especially in the direction of elevation [5-8].

To address this issue, the HLS is considered to provide a distance constraint in the elevation direction for control network adjustment. Currently, the HLS is widely used for real-time monitoring of the relative elevation changes between several different positions in accelerator, and can achieve a measurement accuracy of 5 μm [9-11]. However, when the zero-position difference among different sensors are unknown, the HLS cannot acquire the altitude differences between different points.

In summary, this paper is structured as follows. First, a comparison system is described in detail, including its structural components and how it acquires the zero-position difference between HLS sensors. Then, a calibration platform was designed to verify the measurement accuracy of the altitude differences based on HLS sensors. Finally, how to use the HLS system to suppress the error accumulation for the control network measurement is analyzed, and the feasibility of this method is validated by simulated data.

COMPARISON SYSTEM
In order to make the HLS available for measuring altitude differences between different points, a comparison system in Fig. 1 is built to obtain the measured values of a group of sensors observing the same liquid level in the same coordinate system. As shown in Fig. 2, let \( \mathbf{d}_n \) present the distance of the measured level relative to the zero-position of the sensor numbered \( n \). Since the distance a of measuring level relative to the coordinate system is always constant, the zero-position difference between the two sensors and the corresponding difference of \( \mathbf{d} \) is the opposite of each other. Combined with the HLS sensor measurement principle, in practical engineering applications, assuming that the reading No. \( n \) sensor is \( \mathbf{l}_n \) and its coordinate system elevation is \( \mathbf{h}_n \), the elevation difference between any two sensor coordinate systems can be calculate by:

\[
\mathbf{h}_i - \mathbf{h}_j = (\mathbf{l}_i - \mathbf{l}_j) + (\mathbf{d}_i - \mathbf{d}_j) \tag{1}
\]

To ensure the system stability during the experiment, it is installed on a marble platform to avoid relative displacement between the fixed components. The system can be divided into two modules, one of that verifies the repeatability accuracy of the reference sensor which keep the liquid level consistent. The results are shown in Fig. 3, for 12 repeated measurements, the standard deviation is 0.66 μm. Another one is used for the comparison of the zero-position difference among sensors in which mechanical construction and two-axis inclination sensor ensure consistent relative position between the coordinate system of reference sensor and of which will be compared. Detailed steps are listed below:
1) The liquid level is adjusted using a high-precision Z stage so that the reference sensor reading is any specific value (7500 μm in this paper);
2) The readings of the compared sensor are recorded, that is the average of 3 repeated measurements;
3) The readings of the inclination sensor are recorded. And the formulate used to correct the relative position relationship is as follow:
\[ \gamma = 0.32 \times \theta \text{ (mm)} \] (2)
Where \( \gamma \) is the value to be corrected, 0.32 is the center distance between the coordinate system of reference sensor and the compared sensor, in m, and \( \theta \) is the inclination sensor reading, in mrad;
4) Calculate the value of \( d \) by correction data minus 1500 which is defined as the zero-position reading;
5) Replace the compared sensor and repeat the above steps.
All readings in step 2 are shown in Table 1. The inclination sensor readings, the correction reading in step 3, and the \( d \) values in step 4 are shown in Table 2.

### Table 1: Values of the HLS Sensors Reading

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>33</td>
<td>7527.2</td>
<td>7527.1</td>
<td>7525.3</td>
<td>7526.5</td>
</tr>
<tr>
<td>36</td>
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<td>7536.5</td>
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<tr>
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<tr>
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<td>7528.2</td>
<td>7529.3</td>
<td>7528.6</td>
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</tbody>
</table>

### Table 2: Values of the Inclination Sensors Reading And d

<table>
<thead>
<tr>
<th>Sensor numbers</th>
<th>Title [mrad]</th>
<th>Correction [μm]</th>
<th>d [μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>33</td>
<td>0.000</td>
<td>7526.5</td>
<td>-26.5</td>
</tr>
<tr>
<td>36</td>
<td>0.000</td>
<td>7526.2</td>
<td>-26.2</td>
</tr>
<tr>
<td>32</td>
<td>0.001</td>
<td>7536.2</td>
<td>-36.2</td>
</tr>
<tr>
<td>38</td>
<td>0.004</td>
<td>7531.7</td>
<td>-31.7</td>
</tr>
<tr>
<td>44</td>
<td>0.001</td>
<td>7528.3</td>
<td>-28.3</td>
</tr>
</tbody>
</table>

### ACCURACY ESTIMATION

Among the above sensors, seven pairs were randomly selected to measure the altitude differences between two points. The measurement value of the coordinate measuring machine (CMM) is used as the standard value, whose measurement accuracy was better than 3 μm. The data before correction are the difference of sensor readings and then, as described above, the correction data are calculated by compensating the zero-position difference.

As shown in Fig. 4, let \( \delta_0 \) be the deviations between the reading difference before corrections and the standard value. Let \( \theta \) be the deviations between the corrected data and the standard value. For the seven measurements, the maximum absolute value of \( \delta_0 \) is 10.59 μm and the average absolute value is 4.89 μm, the maximum absolute value of \( \theta \) is 2.41 μm and the average absolute value is 0.78 μm.
ELEVATION CONSTRAINT

We carried out a simulation and analysis in order to verify the feasibility of using the HLS to suppress the error accumulation in 3D control network adjustment. Firstly, the theoretical coordinates of the accelerator alignment network were obtained for common control network layout. We set 104 control points, 12 Laser Tracker stations and 13 HLS sensors in a 100 linear tunnel as Fig. 5. The interval between two adjoining sets of control points is 5 m, and the laser tracker measures six sets of control points and two HLS sensors forward and backward along the tunnel.

Data adjustment is executed by the USMN module in Leica’s laser tracker measurement software SA. The classical method determine the instrument position by measuring a number of common points station-by-station, which results in the accumulation of errors especially in the direction of elevation, as shown in Fig. 6. However, the accuracy of HLS system is almost independent of distance. In combination with the above, when the position of the first sensor in the global coordinate system is known, all position of the system are precisely known. Then the elevation positions of the Laser Trackers are inverse calculated by the measurement values of the targets on these sensors, the adjustment result is shown in Fig. 7. It is obvious that the accumulation of positional errors in elevation direction is improved.

CONCLUSION

In this paper, a comparison system is designed and built based on the principle of capacitive HLS sensor measurement. This system can be used to calculate the zero-position difference between HLS sensors. Based on the comparison results, seven pairs of HLS sensors were selected to measure the height difference between two fixed points, and the measurement deviation was calculated relative to the CMM measurement value. The results show that the maximum absolute value of deviation is 2.41 μm and the average absolute value is 0.78 μm, which meets the accuracy requirement for providing the elevation constraint for the control network adjustment. In addition, the simulation indicate that the laser tracker gives a significant improvement in absolute positional precision in elevation direction with the new method.

REFERENCES


