A Novel Laser Tracking System Based on Optical Frequency Comb

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Content

1. Introduction of AOE and Laser measurement Technology division

2. Research on Traditional Laser Tracker

3. Laser tracker based on optical frequency comb Introduction of the laboratory

4. My research work
Founded in Dec. 2003

Dedicated in the research and development of optical remote sensing, laser and its application, space science & technology.
The headquarter of AOE (Beijing)
Division of Laser Measurement Technology

Employee:  20
Professor:  1
Research associate:  5
Postdoctor:  2
Students:  20
Doctor:  4
Postgraduate:  2
Laser measurement technology

- Traditional ranging technology
- Femtosecond laser ranging technology
- Angle measurement technology
- Precision tracking control technology
- Calibration and error compensation
- Software
Traditional Laser Tracker
Manufactures

Leica
Switzerland

API
USA

FARO
USA

PI
Germany
Prototype

- Measurement Range: 0 ~ 42m
- Horizontal Angle Range: ± 270°
- Vertical Angle Range: -45° ~ +60°
- Coordinate Uncertainty: 17ppm
- Tracking Speed: 2rad/s
- Tracking Acceleration: 2rad/s²
- Sampling Rate: 1000pts@1s
## Performance comparison

<table>
<thead>
<tr>
<th>Specification</th>
<th>Leica (AT402)</th>
<th>Our prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring scale</td>
<td>320m</td>
<td>42m</td>
</tr>
<tr>
<td>Horizontal angle Measuring scale</td>
<td>±360°</td>
<td>±270°</td>
</tr>
<tr>
<td>Horizontal angle Measuring scale</td>
<td>-145° ~+145°</td>
<td>45° ~+60°</td>
</tr>
<tr>
<td>Angle measuring accuracy</td>
<td>0.5&quot;</td>
<td>1&quot;</td>
</tr>
<tr>
<td>Distance measuring accuracy</td>
<td>±10μm</td>
<td>15μm/m</td>
</tr>
<tr>
<td>Coordinate measuring accuracy</td>
<td>±15μm+6μm/m</td>
<td>17μm/m</td>
</tr>
<tr>
<td>Data acquiring rate</td>
<td>3000pts/s</td>
<td>1000pts/s</td>
</tr>
<tr>
<td>Tracking speed</td>
<td>180° /s</td>
<td>2 rad/s</td>
</tr>
<tr>
<td>Acceleration</td>
<td>360° /s²</td>
<td>2 rad/s²</td>
</tr>
</tbody>
</table>
Development history and Orientation

2013
Prototype

2014~2017
Trial
Performance improvement
Stability improvement

Small batch production

……

industrialization

Continuous Financial support
Laser Tracker Based on Optical Frequency Comb

Supported by Ministry of Science and Technology of the People’s Republic of China
Goal of Project

(1) To develop Laser Trackers using Femto-second Laser Distance Measurement Technology. The function and performance of new tracker will reach the international level (Dist. resolution: 50nm, Accuracy: 0.5ppm);

(2) Break through the key technology of Femto-second Laser Source, Femto-second Laser Frequency Comb Distance Measurement, Air Refractive Index measurement and Compensation;

(3) Develop engineering prototype and study application technology of new generation laser tracker;

(4) Promote the advancement of metrology technology.
## Performance expected

<table>
<thead>
<tr>
<th>Title</th>
<th>Performance expected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coordinate uncertainty</td>
<td>10ppm (10μm/m)</td>
</tr>
<tr>
<td>Measuring scale</td>
<td>0-60m</td>
</tr>
<tr>
<td>Distance measuring accuracy</td>
<td>1μm + 0.5μm/m</td>
</tr>
<tr>
<td>Angle measurement accuracy</td>
<td>1.0&quot;</td>
</tr>
<tr>
<td>Tracking speed</td>
<td>2 rad/s</td>
</tr>
<tr>
<td>Tracking acceleration</td>
<td>1 rad/s²</td>
</tr>
</tbody>
</table>
Key Technology

◆ Distance Measurement
◆ Precision Angle Measurement
◆ Precision Tracking Control
◆ Model, Calibration and Error Compensation
◆ System Software
◆ Optical and Mechanical Integration
System Design

Distance Measurement Based on FOFC Module

Tracking and Detecting Module

Coarse Ranging Module

Femtosecond Optical Frequency Comb

Semiconductor laser

Target

Tracking mirror

Glass

Double wedge

Double wedge

45°DM
(R635nm, T775nm, T1550nm)

Corner reflector

PPLN1

ISO

f, 2f

PPLN2

DM1

Band-pass filter1

Band-pass filter2

PD1

PD2

Compensator

45°Mirror

45°Mirror

45°Mirror

BS1

BS2

QWP

PBS

Compensator

Interference filter

Interference filter

Compensator

45°Mirror

Focusing lens

Isolator

HWP

PD

PSD

Interference PD filter

PD
Dual-Comb

- Oscillator × 2
- Amplification and compression system × 2
- Temperature control module
- Coarse stabilization module of repetition rate
- Temperature control module
- Frequency synthesizer × 2
- Frequency counter
- Pump current source
- Phase locked loop
- Servo × 2
- Atomic clock
Stability of $f_{ceo}$

Carrier envelope offset frequency stability: $1.0 \times 10^{-10}/1S$
Distance measurement Setup By Dual-comb
Distance Measurement Result

Standard deviation is ±2.3 μm when target is moved from 8.7m to 9.9m.
Relative error: 0.1 ppm@9m
Air Refractive Index Compensation

\[ D_1 = n_1 D \quad \ldots \ldots \lambda_1 \]

\[ D_2 = n_2 D \quad \ldots \ldots \lambda_2 \]

\[ n_1 \text{ and } n_2: \text{ air refractive index} \]

\[ A \equiv \frac{n_1 - 1}{n_2 - n_1} \approx \text{const} \]

\[ D = D_1 - A(D_2 - D_1) \]

For 1.56 µm and 0.78 µm:

\[ A = 141 \]
Air Refractive Index Compensation

\[ f_{\text{AOM1}} = 160\text{MHz} \quad f_{\text{AOM2}} = 80\text{MHz} \]

320MHz

\( k^{\text{th}} \) mode \( (k+3)^{\text{th}} \) \( (k+6)^{\text{th}} \)

\[ f_{h1} = 4 \text{ MHz} \]
\[ f_{h2} = 2 \text{ MHz} \]

\[ D_1 = \phi_1/2\pi \times \lambda_1/2 \]
\[ D_2 = \phi_2/2\pi \times \lambda_2/2 \]

M_1-3: Mirror; BS: Beam splitter; DM_1-2: Dichroic mirror; PD_1-2: Photodetector; AOM: Acousto-optic modulator
Setup of Air Refractive Index Compensation

Experiment Result

Variation in relative distance (10^-6)

- One-color optical distance, $\Delta D_1/D$
- Two-color difference, $A \cdot \Delta (D_2 - D_1)/D$
- Corrected distance, $\{\Delta D_1 - A \cdot \Delta (D_2 - D_1)\}/D$

$\delta = 8.9 \times 10^{-8}$
Optical Design
Electronics Design

Power unit

Data acquisition unit

Clock synchronization unit
Electronic Control Box
Precision Angle Measurement

Multiple Reading Head → Self-Calibration

Metal circular grating with four reading head. Without comp.: 3.5” With comp.: 0.7”

Four Reading Head

Glass circular grating. Without comp.: 4” With comp.: 1.5”

Five Reading Head

Circular Grating

Reading Head

Error Mapping
Error Calibration and Compensation

Angle Precision

Before compensation: $\pm 1.2^\circ$
After compensation: $\pm 0.6^\circ$

Horizontal Angle Calibration

Vertical Angle Calibration
Error Calibration and Compensation

Tracking mirror tilt error

Tracking mirror offset error

Laser beam offset error

Transit axis tilt error
Software
System integration

Control box

Light source

Main frame
My research work

- Theodolite measurement system based on vision guidance
- Error Calibration and Compensation for laser tracker
- Software for measurement system
- Vision guided total station
- Photogrammetry
Theodolite measurement system based on vision guidance
Theodolite measurement system based on vision guidance

<table>
<thead>
<tr>
<th>Point index</th>
<th>The measured results of the manual operation (mm)</th>
<th>The measured results of automatic theodolite (mm)</th>
<th>Deviation (mm)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>x</td>
<td>y</td>
<td>z</td>
</tr>
<tr>
<td>1</td>
<td>760.083</td>
<td>370.834</td>
<td>5774.370</td>
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<tr>
<td>2</td>
<td>951.053</td>
<td>374.758</td>
<td>5788.259</td>
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<tr>
<td>3</td>
<td>1148.296</td>
<td>359.947</td>
<td>5808.436</td>
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<tr>
<td>4</td>
<td>652.664</td>
<td>389.054</td>
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<tr>
<td>5</td>
<td>750.394</td>
<td>390.547</td>
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<tr>
<td>6</td>
<td>1047.573</td>
<td>397.123</td>
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<td>7</td>
<td>698.130</td>
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<tr>
<td>8</td>
<td>849.731</td>
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<td>5797.828</td>
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<tr>
<td>9</td>
<td>1046.761</td>
<td>404.634</td>
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<tr>
<td>10</td>
<td>751.594</td>
<td>409.217</td>
<td>5783.970</td>
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</tbody>
</table>

The horizontal angles of the left theodolite
The vertical angles of the left theodolite
The horizontal angles of the right theodolite
The vertical angles of the right theodolite
Error Calibration and Compensation for laser tracker
Software of measurement system

Theodolite

Laser tracker

Antenna measurement system

Data analysis
Vision guided total station

<table>
<thead>
<tr>
<th>No.</th>
<th>X(mm)</th>
<th>Y(mm)</th>
<th>Z(mm)</th>
<th>Measured distance (mm)</th>
<th>Distance reference(mm)</th>
<th>Deviation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-58378.940</td>
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<td>-327.386</td>
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<td>3</td>
<td>-58398.894</td>
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<td>41.808</td>
<td>41.627</td>
<td>0.181</td>
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<td>4</td>
<td>-58405.762</td>
<td>-13675.406</td>
<td>-326.309</td>
<td>27.960</td>
<td>28.417</td>
<td>-0.457</td>
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<tr>
<td>5</td>
<td>-58413.977</td>
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<td>10</td>
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<td>-13514.690</td>
<td>-325.620</td>
<td>21.939</td>
<td>20.986</td>
<td>0.953</td>
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</tbody>
</table>
Photogrammetry

- Camera
- Target
- Experiment frame
- 3-DOF guide rail
- Spacecraft
- Precision rotating platform
- Vertical
- Horizontal
- Depth

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**Process:**

1. Stereo vision system
2. Camera calibration
3. Obtain image
4. Marker detection
5. Posture calculating
6. Coordinates transfer
7. Trajectory prediction
8. Accuracy evaluation

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**Components:**

- Camera
- Computer
- Adjustment mechanism
- Target
Contact information

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Add: No 9, Deng Zhuang South Road, HaiDian District, Beijing, 100094, China
Thank you for your attention!