Measurement Station Planning of Single Laser Tracker based on PSO

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Abstract—The laser tracker owns large measuring range, high precision and is easy to carry, which makes it widely used in large scale measurement. For a specific measurement task, however, it is hard to locate a laser tracker measurement station. In view of this situation, this paper advances a new planning method, which combines optimization engine with computer virtual laser tracker measurement (VLTM). A design case constructed by particle swarm optimization (PSO), SpatialAnalyzer(SA) virtual measurement and a high-precision marble plane is studied to illustrate and demonstrate the feasibility of the proposed method. The result shows that this method is able to find out the feasible solution which meets the uncertainty requirements in the given area automatically and exactly.

Keywords-laser tracker; Planning of Measurement field; Flatness Measurement; SpatialAnalyzer virtual measurement; PSO

I. INTRODUCTION

Laser tracker system is high-precision and its measuring range is large. It is widely used in industrial measurement and fits to large piece assembly measuring, heavy machinery manufacturing, large parts detection and reverse engineering. Because of the uncertainty, the measuring result cannot determine the product is qualified or not directly. Therefore, a good measurement result contains measurement values, confidence level and confidence interval in modern error theory [1].

The planning of laser tracker measurement field is about the layout of measurement stations, common points and enhanced reference points. The confidence level and confidence interval are related to measurement field layout. Up to the present, the study on planning of measurement field get some guiding principles only; in large piece manufacturing, making a coordinate measurement plan is always depends on experience and experiments, which is inefficient. Unfortunately, sometimes, for example, with sophisticated measurement environment or demanding accuracy requirements, it is impossible to get a feasible solution. The traditional methods and computer technology are not close, which is detrimental to optimization and improvement.

This paper focuses on the study of automatic planning techniques of locating a single laser tracker measurement station. For planning the layout of laser trackers automatically, the optimization combines with virtual laser tracker measurement (VLTM), and sets the preselected area of space as constraints and measurement uncertainty requirements as target. In this paper, the measurement of high-precision marble surface flatness is as an example for verification. The result shows that the planning method is high efficiency and accurate-planning, and can plan the measurement field layout automatically.

II. PLANNING METHOD OVERVIEW

The planning of locating a single laser tracker measurement station is contained in laser tracker measurement field planning. While doing coordinate measurement with laser trackers, if all the targets are under the vision of a single laser tracker without any obscured points, one measurement station will suffice. In this case, to meet the measurement accuracy is the only constraint, and at the same time, the difficult to study reduced and significance clear.

Figure 1. Design of optimization engine

The implementation approach of locating a single laser tracker measurement station is: taking the optimization engine as main part, and the uncertainty of VLTM as the input of
optimization engine; and then, calculating the lower direction of measurement uncertainty for re-planning the new VTLM station. As a result, the best position and its uncertainty are output. Fig.1 shows the implementation approach of the optimization engine.

In this paper, the optimization engine is PSO, and SA provides VLTM, and the goal is to get the best station or that meets the uncertainty requirements.

III. COMPUTER VIRTUAL MEASUREMENT

A. SA Simulation Introduction

Without linking to a real instrument, SA gains the measurement data by simulating the behavior of laser tracker with certified algorithms. The measurement errors follow a normal distribution, and setting up the instrument precision parameters and environmental parameters can make it roughly the same as the real one’s, which makes the results of simulation believable.

Document [1] achieved the target of doing the large-scale measurements automatically with SA, VCMM method and MonteCarlo method, which is used to simulate the sources of uncertainty in the measurement process. Because of the complicating factors in measurement process and the difficulty to establish precise measurement model, the MonteCarlo method is the most effective way to evaluate the laser tracking measurement uncertainty in object oriented measuring.

In this paper, MonteCarlo method combined with SA simulation is used to evaluate the uncertainty.

B. Simulation Design

The simulation input is from a SA file, which contains the geometric model of measured object. By clicking the surface, a series of points are generated for output.

The simulation process is as follows:

1) After the program starts, select a point data file via dialog box, and read it with prescribed format and save it into memory.
2) Through the measure plan (MP) interface, the program links to SA, and it can manipulate SA automatically. Close auto event creation.
3) Add an API Tracker III into an empty SA file and set up the instrument precision parameters and environmental parameters to fit in with the real one.
4) Locate the instrument with the data from PSO, then loop simulation.
5) Read points data from memory and construct points in SA through functions. Make fabricate observations on these points with instrument error.
6) Fit plane to the measured points by using SA functions, and get the flatness at the same time, then save it into memory.
7) Delete all data except the instrument to improve running efficiency.
8) Loop 5)-7) until uncertainty converges
9) Read simulation results from memory and compute uncertainty for PSO

The process is as Fig.2:

![SA simulation process](image)

IV. PSO AND ITS IMPROVEMENT

A. Basic PSO

Particle Swarm Optimization (PSO) is a kind of global optimization method based on swarm intelligence theory. Its swarm intelligence is generated by the cooperation and competition among the particles, which guides the optimal search [2]. The particles update speeds and positions according to their own best positions $p_{best}$ and the global best position $g_{best}$.

$$v_{i,j}^{k+1} = \omega v_{i,j}^{k} + c_1 r_1 (p_{best}^{i} - x_{i,j}^{k}) + c_2 r_2 (g_{best}^{i} - x_{i,j}^{k})$$

(1)

$$x_{i,j}^{k+1} = x_{i,j}^{k} + v_{i,j}^{k+1}$$

(2)

In the formulas, subscript $i$ is particle number, subscript $j$ is dimension number, superscript $k$ is iterative algebra; the particles’ position and speed are in a given range; $c_1$ and $c_2$ are non-negative learning factors, $r_1$ and $r_2$ are random number in [0, 1], $\omega$ is inertia factor and $\alpha$ is constraint factor; $p_{best}^{i}$ is the $j$th dimension of particle $P_i$’s best position; $g_{best}^{i}$ is the $j$th position dimension of the global best one. Equation (1) and (2) make up the basic PSO.

B. Improve PSO with SA Simulation

PSO combined with SA simulation is different from the basic one. For the former one, its range of activities is discrete, and the fitness is from SA simulation.
It always takes a long time to simulate at a position. And the influence of the error of locating the laser tracker measurement station to measurement accuracy is not obvious in a small range. Considering the previously mentioned, introduce discrete layout can narrow the range of activities and avoid doing simulation at the same place. It can improve simulation efficiency. For discretization, upper and lower bounds(Xup, Xdown), the degree of dispersion Step and the next position X' provided by PSO are needed. Then calculate the spacing between one point and another in all directions by (3).

\[
X_{\text{step}} = (X_{\text{up}} - X_{\text{down}}) / \text{Step}
\]  

(3)

After getting the spacing, calculate new position X by (4) or (5).

\[
X = \left[ X' / X_{\text{step}} \right] \times X_{\text{step}}
\]  

(4)

\[
X = \left[ X' / X_{\text{step}} \right] \times X_{\text{step}}
\]  

(5)

The discretization process is as Fig.3:

Do simulation after locating the new position and record it.

The fitness is SA simulation measurement uncertainty. The uncertainty is smaller, that is closer to the optimal solution. The objective function of simulation is

\[
\min U = \text{Simu} (\text{InstID}, P(x_i, y_i, U(r, \theta, \phi)), U(r, \theta, \phi))
\]

\[
(x_i, y_i) \in [X, Y],
\]

\[
-25000 \leq x_i \leq 25000,
\]

\[
-25000 \leq y_i \leq 25000.
\]  

(6)

\[
\min U \text{ represents the target is the smallest uncertainty, Simu( ) is the simulation process, InstID is the ID of the instrument, } P(x_i, y_i) \text{is the instrument’s position which is included in the discrete plane}[X, Y], \text{ its unit is mm, } U(r, \theta, \phi) \text{ is the uncertainty of instrument.}
\]

The algorithm implementation process is as Fig.4, proceed as follows:

1) Particle swarm initialization: Randomly initialize each particle’s position and velocity, set of particles’ size n

2) Calculate the fitness: first of all, search record to tell whether the current position has been reached before, if it has, read the fitness from the record; otherwise, do simulation there and record the current position and its fitness.

3) For the first generation of particles, pbest is current position. And find out the gbest from them. For subsequent generations of particles, if the current position is better than pbest, then update the pbest as the current one. For each particle in the entire population, compare its pbest with gbest, if it is better than gbest, then update the gbest.

4) Update speed and position according to (1) and (2).

5) Check the termination condition: determine whether the algorithm achieves fitness requirements or the best fitness value. If it does, terminate the program, otherwise go to 3).

Figure 3. Discretization process

Figure 4. Algorithm process

V. FLATNESS MEASUREMENT SIMULATION AND EXPERIMENTAL RESULT DISCUSSION

A. Definition of flatness

The mathematical definition of flatness [3] is: two parallel planes with spacing equal to the tolerance t of the defined area. It can be expressed as a set of points satisfying (7):
In (7), $\hat{T}$ is the normal vector of two parallel planes which defines the tolerance zone, $\vec{A}$ is the position vector of the median plane between two parallel planes.

To evaluate the flatness, there are several methods such as minimum zone method least squares method. In this paper, SA provides the flatness, and its algorithm is certified least squares methods.

### B. Simulation design

The MonteCarlo method is used to simulate the sources of uncertainty in the measurement process. It requires multiple measurement process through computer simulation. However, it’s hard to know how many times after the simulation results can be convergent. For using the SA to get the uncertainty, document [4] verified the credibility of 10,000 times simulation results, and drew figures to analyze the convergence of uncertainty. Fig.6 shows the uncertainty change trend of $D_x$, $D_y$, $D_z$, $R_x$, $R_y$, $R_z$, in a specific measurement plan. It shows that there is a convergent uncertainty after 3000 times simulation.

While planning measurement field by PSO, it is unavoidable to measure the same object repeatedly. So, it requires greater simulation efficiency. Based on the literature’s conclusion, the simulation time is set to 3000. It can not only guarantee the accuracy of the simulation, but also needs the minimum resource.

The basic parameters of the algorithm are set as follows:

- **a)** Particle size $n$: Generally set to 20~40, and $n=20$ in this paper;
- **b)** Particle dimension $D$: determined by the number of the objective optimization function’s arguments, and $D=2$ in this paper;
- **c)** Range of activities: determined by the distribution of measuring points; in this paper, the measured object is set to the origin, and the range is $\pm 25$m, and there are 1000 points in each direction.
- **d)** Maximum speed $V_{\text{max}}$: due to the large measuring range, set $V_{\text{max}}=0.1\Delta$, $\Delta=X_{\text{up}}-X_{\text{down}}=50$m.
- **e)** Termination condition: gbest meets the fitness requirements or gbest is unchanged in the latest 200 times.

After analyze the data from experiment, the uncertainty of the instrument [5] is

$$
\begin{align*}
    u_{\rho} & = 0.483 \\
    u_{\theta} & = 0.246 \\
    u_{\phi} & = -0.0013 \\
    u_{\text{pme}} & = 1.18.
\end{align*}
$$

In a simulation, the positions experienced by the laser tracker are shown in Fig.7:

As is shown in Fig.7, there is high efficiency by using PSO to find the right position, and it experienced less than 1% among the whole points.
As is shown in Fig.8, the particles evolve fast, and get the optimal solution in several generations. The optimal position is (1400, 500).

Fig.9 up is in the range of 0-9m, and the step equals 1m, Fig.9 down is in the range of 0-3m, the step is 0.1m. As is shown in Fig.9 that the optimal position is distributed at 1.4m in this interval, which is basically the same as the PSO’s conclusion. The result of the algorithm is credible.

C. Experimental design and processing

A high-precision marble flat is used in this experiment, and its flatness equals 5μm. Fundamentally, laser tracker station layout planning is to get the relative position of the plane and the laser tracker. Because moving the plane is more convenient, in this experiment, the laser tracker is stationary and the plane moves, which equals to moving the laser tracker.

Fit the 10 sets of data measured at (1.29, 0.48) to plane by SA, and display the flatness in table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flatness</td>
<td>0.0101</td>
<td>0.0058</td>
<td>0.0072</td>
<td>0.0064</td>
<td>0.0061</td>
</tr>
<tr>
<td>No.</td>
<td>6</td>
<td>7</td>
<td>8</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Flatness</td>
<td>0.0061</td>
<td>0.0053</td>
<td>0.0104</td>
<td>0.0057</td>
<td>0.0048</td>
</tr>
</tbody>
</table>
Because the 1st, 8th data are larger than others apparently, consider the possibility of gross error. Use the Grubbs discriminate for testing two outliers [6] to determine.

Arrange the above data in order by size to order statistic.

\[ x_{(1)} \leq x_{(2)} \leq \ldots \leq x_{(n)} \]

\[ s_0^2 = \frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 = 3.3488 \times 10^{-4} \]

\[ \bar{x}_{n-1,0} = \frac{1}{n-1} \sum_{i=1}^{n-1} x_i = 0.0060 \]

\[ s_{n-1,0}^2 = \frac{1}{n-2} \sum_{i=1}^{n-2} (x_i - \bar{x}_{n-1,0})^2 = 2.8759 \times 10^{-5} \]

\[ \bar{x}_{1,2} = \frac{1}{n-2} \sum_{i=3}^{n} x_i = 0.0073 \]

\[ s_{1,2}^2 = \frac{1}{n-3} \sum_{i=3}^{n} (x_i - \bar{x}_{1,2})^2 = 2.0694 \times 10^{-4} \]

Computing high and low Grubbs test statistics

\[ g_b = \frac{s_{n-1,0}}{s_0} = 0.0859 \]

\[ g_* = \frac{s_{1,2}}{s_0} = 0.6180 \]

Look-up table, find out the value corresponding to \( n=10 \), \( \alpha=0.05 \), the critical value \( G_b(0.05,10)=0.1864 \).

Because of \( g_b < g_* \)

\[ g_b < G_b(0.05,10), \]

the maximum \( x_{(10)}=0.0104 \) and \( x_{(9)}=0.0102 \) may have gross error.

Redetermination the data after excluding the two maxima

\[ g_b = \frac{s_{n-2,0}^2}{s_0^2} = 0.2621 \]

\[ g_* = \frac{s_{1,0}^2}{s_0^2} = 0.3088 \]

Because of \( g_b < g_* \)

and

\[ g_b > G_b(0.05,8) = 0.1101, \]

there is no gross error in the set. The variance of new data is 0.007mm. Other data are also processed by the way for a single outlier or more, the results are shown in Table 2.

<table>
<thead>
<tr>
<th>Position (m)</th>
<th>Distance (m)</th>
<th>Uncertainty (measured)</th>
<th>Uncertainty (simulated)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1.29, 0.48)</td>
<td>1.4</td>
<td>0.0007</td>
<td>0.0008</td>
</tr>
<tr>
<td>(3.44, -1.54)</td>
<td>3.7</td>
<td>0.0037</td>
<td>0.0035</td>
</tr>
<tr>
<td>(0.00, -4.20)</td>
<td>4.2</td>
<td>0.0012</td>
<td>0.0035</td>
</tr>
<tr>
<td>(3.73, -6.14)</td>
<td>7.1</td>
<td>0.0069</td>
<td>0.0064</td>
</tr>
<tr>
<td>(3.73, -6.14)</td>
<td>7.1</td>
<td>0.0069</td>
<td>0.0064</td>
</tr>
</tbody>
</table>

As is shown in the table, by comparing the measured data and the simulation one, the uncertainty of measurement and simulation are substantially similar. And at (1400, -500) which provided by PSO, the uncertainty is smaller than other locations significantly. Thus, the conclusion is credible.

VI. CONCLUSION

In this paper, the stations layout planning for laser tracker measurement field is conducted according to the measurement uncertainty requirements of flatness. SA simulation and location query are introduced to PSO, and gets good results. The improved PSO is computationally efficient, and the error distribution of SA simulation is close to that of real laser tracker. In fact, the method proposed in this paper is not only limited to the PSO, SA, and flatness measurement. It applies to different optimization and virtual laser tracker measurement methods. For other measured objects exposed to a single laser tracker station, it applies, too. It greatly increases the versatility of the method. This paper have not considered some other problems such as the convergence of uncertainty, the blocked light path and the tasks which needs two stations at least. These will be the future research directions of this subject.


