Precise detecting method of target miss-distance for laser tracker

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Abstract: Laser tracker is an important optical instrument for precise geometric coordinate measurement in large scale. Position sensitive detector (PSD) is a core miss-distance detecting sensor in laser tracking system, which achieves precise position tracking of cooperation target. The detecting precision has remarkably direct influence on the performance of tracking and measurement. Firstly, one laser tracking measurement system was presented, and the working principle of the system′s tracking unit based on PSD was introduced. Then the miss-distance detecting module was designed and built based on PSD according to the actual demand. The module′s signal process circuit for weak signal detection was emphatically analysed, which met the requirements of PSD driving, I/V conversion, signal amplification, analogy signal filtering, parameter matching and efficient using of AD resources simultaneously. The output signal of PSD module was acquired by a four-channel and synchronous analogy to digital converter. The signal was processed by FPGA which worked in the form of finite state machine. A composite digital filtering algorithm revised from median and mean filtering method was proposed to reduce noise interfering. Based on FPGA an extended divider was put forward to improve accuracy of measurement. Through omitting the low-order byte of the numerator of coordinate formula, one two-step operation of the divider was used to extract effective decimal places. The experimental result shows that the stability of spot position is better than ±2.0 μm in the square effective area 4 mm×4 mm. The further tracking experiment indicates the miss-distance detection method can well meet the demand of the precise and fast target tracking.

Key words: miss-distance detecting; digital filtering; extended division operation; laser tracker
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激光跟踪仪目标脱靶量精密探测方法

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摘 要: PSD 是激光跟踪仪实现对合作目标精密跟踪的脱靶量传感器件,其探测精度直接影响跟踪测量性能。首先,简要介绍了基于 PSD 的激光跟踪测量系统,并根据系统需求提出了脱靶量精密探测方案;然后,重点讨论了信号调理、抗环境光干扰、参数匹配等硬件设计方法以提高 PSD 输出微弱电

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流信号的稳定性，研究提出了基于 FPGA 和有限状态机的去极值平均滤波算法和扩展除法运算算法以进一步提高测量精度;数据表明在 4 mm×4 mm 的区域内脱靶量探测稳定度优于±2 μm。采用该方法实现激光跟踪仪对合作目标的动态跟踪,很好地满足了激光跟踪仪的精密快速跟踪需要。

关键词: 脱靶量探测； 数字滤波； 扩展除法运算； 激光跟踪仪

0 Introduction

Laser tracker is a kind of high-precision optical coordinate measurement instrument, which is widely used in many fields such as dimension measurement and tolerance of position and shape measurement for large scale components, tooling and fixture measurement, large parts assembly, multi-degree-of-freedom tracking measurement for dynamic target[1-2]. Laser tracker is also known as laser tracking interferometer, just as the word implies, and distance interference measurement is based on the target′ s precise tracking. To achieve rapid and precise tracking, the servo control system must obtain in real time the high-precision target miss-distance information in two dimensions. Laser spot displacement detecting based on position sensitive detector (PSD) is one important miss-distance sensing method. Compared with four-quadrant detector, PSD has characteristics of more accuracy and no dead zone[3]; in contrast with camera, it has much more fast response and smaller size[4-5]. Hence it becomes one of the core miss-distance measurement elements in the laser tracking system. However, laser tracker is a complex opto-mechatronics integration instrument. On one hand, there are many factors influencing the PSD displacement detecting accuracy such as: stray light caused by multiple optical sources, complicated optical path and various optical devices; drive current impact caused by repeated and rapid start-stop of servo motors. These factors reduce the displacement detecting accuracy by their disturbing to the weak photocurrent signal. On the other hand, although PSD displacement has one-to-one match with target miss-distance, the relationship varies with opto-mechanical components poses and tracking state. For example, pose and installing location of PSD affect tracking zero point directly, and laser spot on PSD rotates with azimuth tracking motor rotation. These problems attract researcher to investigate effective and convenient calibration means to set up the analytical expression between target miss-distance and PSD displacement. Above all, research on precision detecting of spot displacement and tracking parameter calibration method is an important precondition to achieve good tracking performance of laser tracker.

1 Laser tracking measurement principle

The working principle of laser tracking interferometer system is shown as Fig.1 (a). The light beam emitted from laser is divided into two beams, one of which transfers to the interferometer directly, and the other of which is reflected by tracking mirror and heads to target. After the target reflection, the light beam returns beam splitter through tracking mirror and is divided into two new light beams. One is reflected to interferometer for distance measurement and the other one is reflected to PSD for target miss-distance detecting and tracking. When light beam locates on the centre of target, in theory the PSD unit´s output of target miss-distance is zero. Otherwise, the specific coordinate value representing the target deviating from target ball centre is calculated and outputted in real time. At this time the tracking system drives tracking mirror rotating around reflection base point, which reduces miss-distance to zero and realizes tracking measurement of the target[3]. Considering the precondition of interferometer continuously outputting right distance is the target miss-distance keeping below several millimetres in the wide distance range between tens of meters and one hundred meters. Hence the tracker´s effective field of view is very limited compared with the traditional opto-electronics tracking system, which requires PSD displacement detecting unit has the rapid, stable, and high accuracy detecting ability.

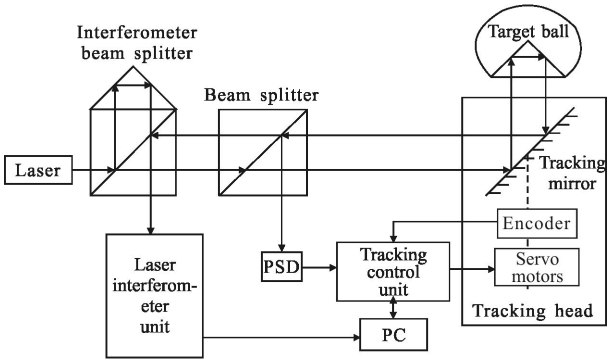


Fig.1 Laser tracking measurement system diagram

2 Hardware design of miss-distance detecting based on PSD

PSD which detects spot position based on lateral photoelectric effect, is a kind of photoelectric device. Due to the advantages such as small volume, high resolution, fast response, no dead-time etc., PSD is widely used in precision position detection of coordinates and posture [6-8]. It has gradually become one of the key position feedback elements in the tracking system[9-10].

2.1 Overall design of detecting unit

Target miss-distance detecting system based on PSD mainly includes PSD and its signal conditioning circuit, AD data acquisition module, data processing and communication unit etc. System′s block diagram is shown in Fig.2. Firstly optical signal from laser is incident on PSD′s active area through special optical path in laser tracker. It prompts PSD generating four current signals. Through I/V conversion, level shift and amplification, the four current signals are converted to proper voltage signals in the range from 0 to 10 V or −10 V to 0; after AD module′s synchronous parallel sampling and analogy-digital conversion, the voltage signals are sent to data processing unit based on FPGA, where the digital signals are conducted logic operation and digital filtering. Finally the spot position result is transferred to tracking control unit in the form of low voltage differential signal(LVDS).

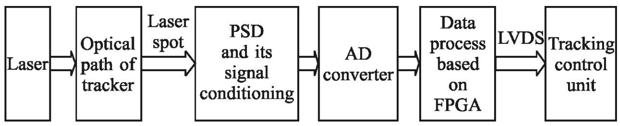


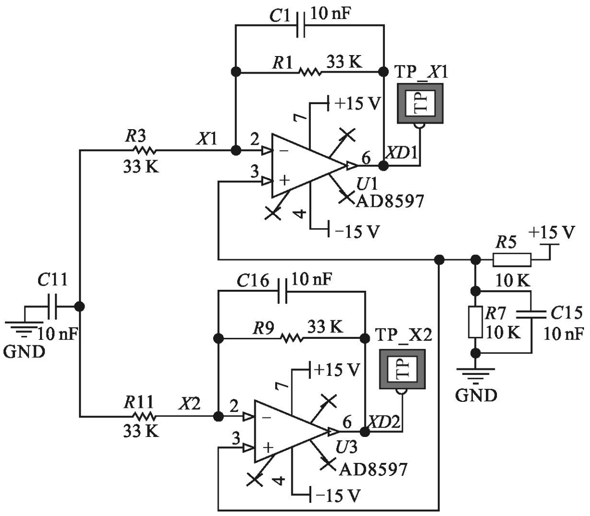
Fig.2 Overall concept of miss-distance detecting unit

2.2 PSD and its signal conditioning

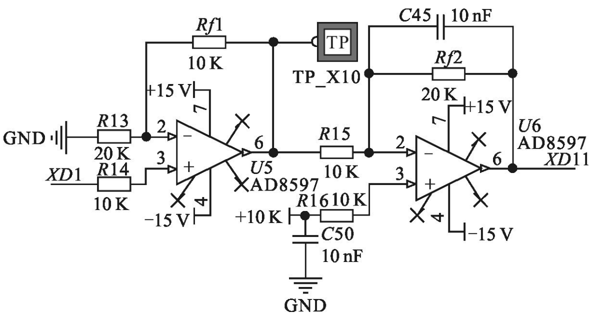
The two-dimensional PSD selects 2L10_SU7 with fast response (0.4 μs) and high-resolution (better than 0.1 μm) provided by Sweden SiTek Company. its active square area is 10 mm×10 mm; position non-linearity is within ±0.8% ; typical value of reverse voltage is 15 V; thermal drift is less than 200 ppm/℃, and the proper light intensity is set advisably between 200−300 μW.

In order to suppress multiple lights interfering caused by the complicated internal laser source and devices inside the tracker, a narrow band filter is fixed up in front of PSD, which only allows the light passing through whose wavelength is in the limited range. The output current of PSD is a kind of photocurrent, so the signal is very weak and only at μA level. In order to improve detecting precision of weak signal, on one hand, bypass filter capacitor of different orders of magnitude and magnetic beads are placed close to the power supply to suppress the interfering of the power ripple. On the other hand, the operational amplifier input is separated from other large voltage according to voltage gradient on the printed circuit board(PCB), meanwhile ensure that the connecting wires should be as short as possible.

The means discussed above ensure the quality of the current signal to some extent, but the PSD output current is only at μA level, which is difficult to detect precisely and process directly. So the signals should be converted from current to voltage and amplified further. As the PSD has no separate reverse-biased electrode, the reverse bias voltage should be supplied through signal lines. So the absolute value of four PSD signals are raised about 7.5 V at the same time, then the four signals are adjusted within ±7.5–±10 V through the first op-amp circuit. The circuit diagram is shown in Fig.3 (a), in which the $X1/X2$ is input current and $XD1/XD2$ is the output voltage.



(a) I/V conversion circuit $-X1/X2$



(b) Proportional difference operation circuit−X1

Fig.3 PSD and its signal conditioning circuit

Considering that the input voltage range of the selected 16-bit AD is ±10 V, which only makes use of 1/4 AD's resolution. So the proportional difference operation circuit with high input resistance difference is proposed to shift and amplify further the first op-amp signals, and the theory formula between the input $XD1$ and output $XD11$ of the circuit ($Rf1$, $Rf2$, $R13$, $R15$ is amplification operation resistance) showed as Fig.3(b), is expressed as:

$$XD11=\left(1+\frac{Rf2}{R15}\right)(10-XD1) \qquad (1)$$

Working conditions of Eq. (1) are $Rf1$ equal to $R15$ and $Rf2$ equal to R13 in Fig. 3(b). This circuit can realize the four analogy signals subtract from 10 V respectively, then the output voltage is adjusted within ±0–±2.5 V. The magnification of the second amplifier is set as 3 after comprehensive consideration. Finally the output voltage range of four PSD signals is conditioned within ±0–±7.5 V, and the AD converter is made more full use. The experimental result indicates that the precision of position detection stability is improved.

2.3 Analogy to digital converter and data acquisition

As the ADS8556 contains six low-power, 16-bit, successive approximation register based analogy to digital converters with true bipolar inputs. Each channel contains a sample-and-hold circuit that allows simultaneous high-speed multi-channel signal acquisition and supports data rates of up to 630 kSPS (PAR). In order to ensure the bandwidth of AD working at the maximum rate, the device OPA2211 is chosen as the input driver of the ADS8556. Using front-end circuit (shown as Fig.4) and pin configuration(shown as Fig.5), the input voltage of ADS8556 is configured is $\pm4V_{ref}$ in hardware mode and parallel interface, where V_{ref} is the internal reference voltage set as 2.5 V.

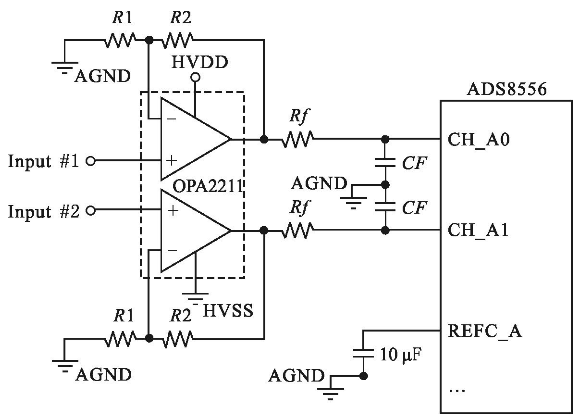


Fig.4 ADS8556 pre-conditioning circuit

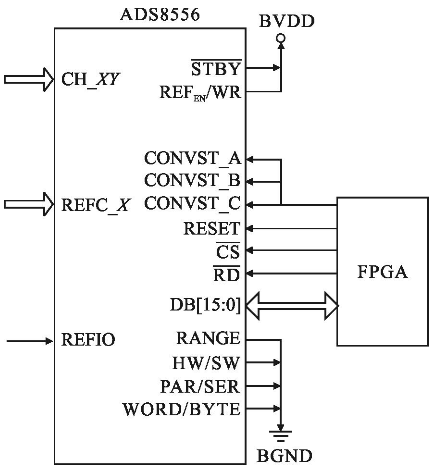


Fig.5 ADS8556 pin configuration

3 Software and algorithm design

Based on Spartan-3E series FPGA supplied by Xilinx, the system software are top-down designed and modularly programmed. AD conversion process, filtering algorithm and data processing method on spot centre coordinates is proposed and developed, and Verilog HDL and Melay finite state machines are applied. The program flow chart is shown as Fig.6.

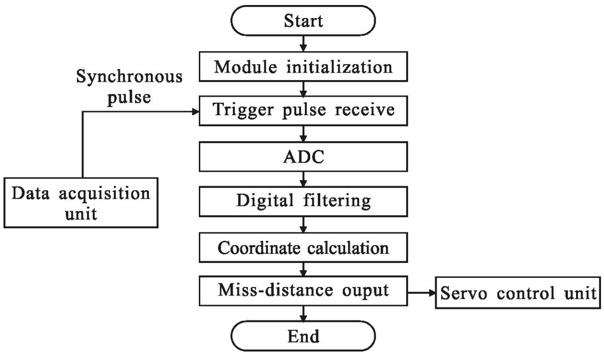


Fig.6 Flow chart of program

3.1 Filtering algorithm

To improve the filtering performance and reduce the influence of noise on sampling data, arithmetic average filtering and median filtering algorithms are combined. Firstly obvious noisy data is removed using median filters. Then inconspicuous noisy data (long-lasting interference signal) is taken out using arithmetic average filters. This method is named as anti-pulse-interfere median filtering or extremum-removing median filtering.

Anti-pulse-interfere median filtering is that sorting N sampling values from continuously acquisition data, removing the maximum and minimum value, and summing the remained $N-2$ sampling values as: $\sum_{i=2}^{N-1} X_{1.i}$, $\sum_{i=2}^{N-1} X_{2.i}$, $\sum_{i=2}^{N-1} Y_{1.i}$, $\sum_{i=2}^{N-1} Y_{2.i}$ (i is the sorted sequence number, $X_{1.i}$, $X_{2.i}$, $Y_{1.i}$, $Y_{2.i}$ are the sampling data of PSD output). To make use of AD sampling values as much as possible, the summation is calculated as a whole. So the computational formula of coordinate x and y of the light spot can be expressed as:

$$\begin{cases} x=k_x\dfrac{\sum_{i=2}^{N-1} X_{1.i}-\sum_{i=2}^{N-1} X_{2.i}}{\sum_{i=2}^{N-1} X_{1.i}+\sum_{i=2}^{N-1} X_{2.i}} \\ y=k_y\dfrac{\sum_{i=2}^{N-1} Y_{1.i}-\sum_{i=2}^{N-1} Y_{2.i}}{\sum_{i=2}^{N-1} Y_{1.i}+\sum_{i=2}^{N-1} Y_{2.i}} \end{cases} \tag{2}$$

3.2 Algorithm of the extended divider

In order to achieve a position detecting resolution of 0.2 μm, the coefficients k_x, k_y are between 4×10^4 and 5×10^4 according to PSD size, experiment and theory expression. As the AD converter is 16-bit and N is chosen as 10 (based on the experiment), during coordinates calculation the maximal absolute value of numerator is about 2.62×10^{10}($5\times10^4\times8\times65\,536$), which is greater than 2^{32} (but less than 2^{40}) and exceeds the numeric value limit of the divider (32 bit).

In order to solve this problem, an extended divider is designed based on parallel computations, which can accurately calculate coordinates of the light spot in real time. Firstly the numerator in Eq.(2) are expressed as Nr_x, Nr_y:

$$\begin{cases} Nr_x=k_x\sum_{i=2}^{N-1} X_{1.i}-\sum_{i=2}^{N-1} X_{2.i}=I1_x\times2^8+R1_x \\ Nr_y=k_y\sum_{i=2}^{N-1} Y_{1.i}-\sum_{i=2}^{N-1} Y_{2.i}=I1_y\times2^8+R1_y \end{cases} \tag{3}$$

In Eq.(3), $I1_x$, $I1_y$ are the quotient of $Nr_x/2^8$, $Nr_y/2^8$ respectively, and $R1_x$, $R1_y$ are the remainder.

The denominator in Eq.(2) are expressed as:

$$\begin{cases} D_x=\sum_{i=2}^{N-1} X_{1.i}+\sum_{i=2}^{N-1} X_{2.i} \\ D_y=\sum_{i=2}^{N-1} Y_{1.i}+\sum_{i=2}^{N-1} Y_{2.i} \end{cases} \tag{4}$$

Four output signals of PSD are within ±7.5 V, which are expressed as signed integer in AD converter. As the sum of two signals of coordinate x or y is 7.5 V or −7.5 V, which is defined as an integer value about 24 576. It's obvious that denominator is about 196 608 and is much larger than $R1_x$, $R1_y$ with a maximum of 255. So $R1_x$, $R1_y$ can be ignored respectively.

Supposed the numeric result of $I1_x$, $I1_y$ divide D_x, D_y is expressed as:

$$\begin{cases} \dfrac{I1_x}{D_x}=I2_x+R2_x \\ \dfrac{I1_y}{D_y}=I2_y+R2_y \end{cases} \tag{5}$$

where $I2_x$, $I2_y$ are quotients and $R2_x$, $R2_y$ are remainders.

To obtain the actual integer part of the position resolution from the remainders $R2_x$, $R2_y$, the second division step is carried out as follows:

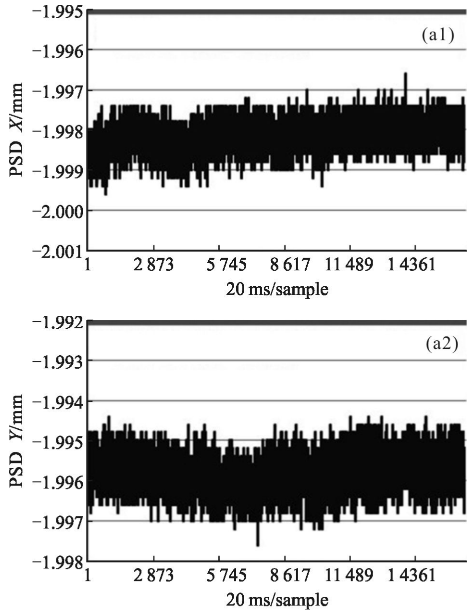
$$\begin{cases} \dfrac{R2_x\times 256}{D_x}=I3_x+R3_x \\ \dfrac{R2_y\times 256}{D_y}=I3_y+R3_y \end{cases} \tag{6}$$

where $I3_x$, $I3_y$ are integers and $R3_x$, $R3_y$ are remainders. Then computational formula of spot position with 0.2 μm resolution can be expressed as:

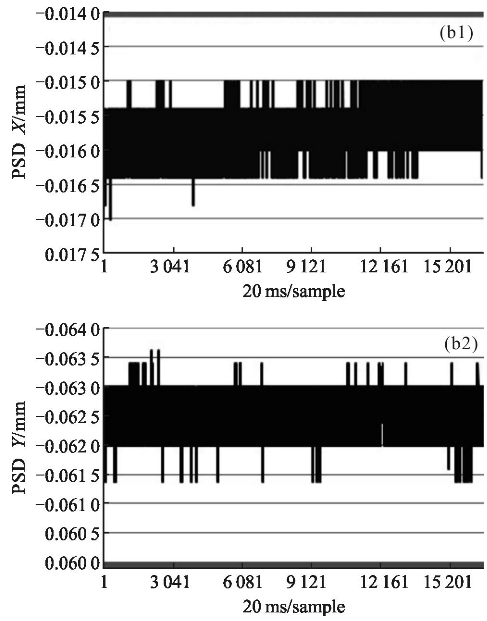
$$\begin{cases} x=I2_x\times 256+I3_x \\ y=I2_y\times 256+I3_y \end{cases} \tag{7}$$

4 Experimental results

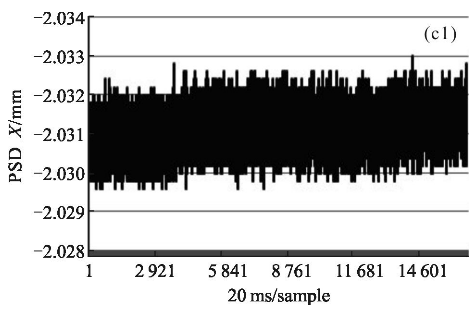
In the laser tracking system, considering the divergence angle and interference characteristic, the laser wavelength is chosen as 632.8 nm. In the detecting process, the detecting unit is interfering inevitably by the complicated internal laser source and devices inside the tracker, power supply as well as motor driving current. To examine the effectiveness of the hardware, filtering algorithm and extended operation method mentioned above and test the stability of measurement results, the experiment is carried out based on two-dimensional displacement platform. The results are shown as Fig.7.

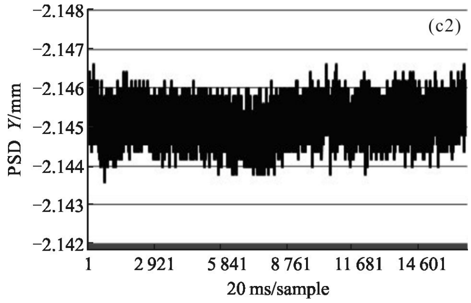


(a) Displacement fluctuation when light spot is around (−2, −2)



(b) Displacement fluctuation when light spot is around (0, 0)





(c) Displacement fluctuation when light spot is around (2, 2)

Fig.7 Experimental results of PSD displacement

From the Fig.7(a), it can been that the differences of peak value from bottom value of PSD X and PSD Y fluctuation are 3.0 μm and 3.2 μm respectively; and from Fig.7(c), the differences are 3.4 μm and 3.0 μm. While Fig.7(b) showed that the differences are no more than 2.0 μm. This is caused by the PSD′s inherent PIN structure and inhomogeneous distribution of P -type layer resistivity[11-12], that is, so called PSD bordering effect (when the spot goes on bordering, the detecting accuracy decrease gradually). Limit to the length of the paper, only the result of the above typical point in square detecting area of is presented. Actually, the stability is better than ±2 μm in the whole square area.

5 Conclusion

The working principle of the laser tracker is introduced and the important role of improving tracker′s tracking performance by precise target miss-distance detecting is analysed. Based on PSD, the miss-distance hardware solutions including opto-electronics filtering, signal fine conditioning, parallel AD data acquisition and so on are discussed; meanwhile based on the digital signal process platform FPGA one anti-pulse-interfere median filtering and an extend dividing method are proposed to obtain precise detecting performance. The experimental result indicates the spot displacement varies less than ±2 μm in the central square detecting zone (4 mm×4 mm), and is more stable and precise than the four-quadrant detector. Hence PSD could satisfy the tracker demand better. Then the precise detecting method was successfully applied in the laser tracking system and achieved satisfactory performance.

References:

[1] Soichi Ibaraki, Tomoya Kudo, Tomoaki Yano, et al. Estimation of three-dimensional volumetric errors of machining centers by a tracking interferometers [J]. ***Precision Engineering***, 2015, 39: 179-186.

[2] Shirinzadeh B, Teoh P L, Tian Y, et al. Laser interferometry-based guidance methodology for high precision positioning of mechanisms and robots [J]. ***Robotics and Computer-Integrated Manufacturing***, 2010, 26(1): 74-82.

[3] Zhou Peisong, Lu Rongsheng, Zhou Weihu, et al. Measurement system for laser tracker′ s target-missing quantity based on four-quadrant detector [J]. ***Electro-Optic Technology Application***, 2014, 29(1): 75-79.

[4] Su Yanzhao, Li Aihua, Wang Tao, et al. Visual tracking of moving objects based on piecewise fusion weight and multi-strategy[J]. ***Optics and Precision Engineering***, 2015, 22(12): 3409-3418.

[5] Song Lin, Cheng Yongmei, Liu Nan, et al. Algorithm of vision tracking for UAV navigation based on multi-constraint KLT [J]. ***Infrared and Laser Engineering***, 2013, 42(10): 2828-2835.

[6] Liu Jiaoyue, Yang Juqing, Dong Dengfeng, et al. Optoelectronic aiming and orientation system of laser tracker [J]. ***Optics and Precision Engineering***, 2015, 23 (6): 1558-1564.

[7] Song Dianyou, Liu Tiegen, Ding Xiaokun, et al. Precise PSD micro-displacement online measurement system [J]. ***Journal of Tianjin University (Science and Technology)***, 2013, 46(2): 168-173

[8] Ying Duan, Lan Qin, LianXue, et al. Multi-beam synchronous measurement based on PSD phase detection using frequency -domain multiplexing [C]//SPIE, Sixth International Symposium on Precision Mechanical Measurements, 2013, 8916: 89163C.

[9] Zhang Yajuan, Qiu Zurong, Li Xinghua, et al. Laser tracking coordinate measurement system based on PSD[J]. ***Transducer and Micro System Technologies***, 2011, 30(7): 116-119.

[10] Conte J, Santolaria J, Majarena A C, et al. Identification and kinematic calculation of Laser Tracker errors [C]//The Manufacturing Engineering Society International Conference, 2013, 63: 379-387.

[11] Zhang Min, Liang Yanbing. Experiment on two dimensional quadrilateral position sensing detector[J]. ***Infrared and Laser Engineering***, 2013, 42(2): 459-464.

[12] Toyomi Fujita. New types of semiconductor image position sensitive device[J]. ***Optical Engineering***, 2009, 48(9): 1-5.