Research on OEF geometry control algorithm in dual-galvanometric laser scanning manufacturing

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For the dual-galvanometric laser scanning manufacturing, the traditional geometry algorithm-$f\theta$ only considered the distance between the two swaying mirrors, the distance between the swaying mirror and the convex lens, the mirror swaying angle, and the lens focal length. And it could not correctly express the manufacturing track which was made geometry distorted. Based on analysis, a creative geometry control algorithm — optical entire factors (OEF) was brought forward. From the creative algorithm it can be known that OEF geometry control algorithm was concerned with not only the distance of the two swaying mirrors, distance between the swaying mirror and the convex lens, mirror swaying angle, and lens focal length, but also the lens central height, lens convex radius, and medium refractive index. The manufacturing system can manufacture satisfied geometry with the creative double ends approach (DEA) control model based on OEF in the experiments.

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In laser manufacturing the requirement of manufacturing geometry quality is more and more. In the dual-galvanometric laser scanning manufacturing, the manufacturing quality is more important[1,2]. However the traditional geometry control algorithm-$f\theta$ made the manufacturing track geometry distorted. The errors were come from two aspects: one was that $f\theta$ adopted the equation $\tan\theta = \theta$; the other was that $f\theta$ omitted the convex lens central thickness, the lens convex radius, and refracting rate. The remedies of distorted geometry commonly adopted table-remedying[3], soft-remedying[4], and least squares curve-fitting remedying[5]. Based on the analyzing the reasons of geometry distorted and refraction law of light, a creative OEF (optical entire factors, also called $f\theta trn$ algorithm) geometry control algorithm was brought forward. The geometry based on the OEF algorithm was satisfied with the manufacturing requirement. And a creative control model — double ends approach (DEA) was brought forward based on the OEF algorithm. The optical principle of dual-galvanometric laser scanning manufacturing was shown in Fig. 1. X-Y is the
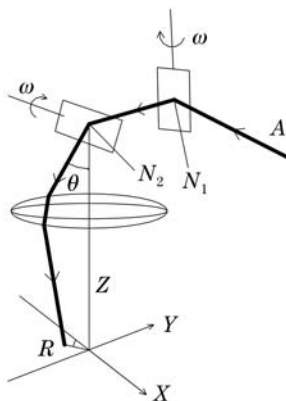

Fig. 1. Optical principle dual-galvanometer scanning manufacturing.

laser scanning plane. X-axis is parallel to the rotating axis of mirror y. Z-axis is parallel to the rotating axis of mirror x. And the Z-axis is also main optical axis.

Hypothesis: the distance between two swinging mirrors was a; the distance between swaying mirror y and convex lens was b; the unit vectors of x, y, z were $\vec{i}$, $\vec{j}$, and $\vec{k}$; the angle of the swaying mirrors were ω_x, ω_y, and the reflected angles were $2\omega_x$, $2\omega_y$; the incident light was $\vec{A}$ that was defined vector $-\vec{i}$.

The incident light $\vec{A}$ was reflected through swaying mirror x and the reflected light was named $\vec{A}_1$, it is known by the refracted law of light. The vector $\vec{N}_2$ was the normal of the swing mirror y turned clockwise ω_y. Turn the vectors $\vec{N}_2$ and $\vec{A}_1$ reverse clockwise ψ ($= 45° + \omega_y$) degree to make the vector $\vec{N}_2$ and Y-axis to be superposition; and the $\vec{A}_{1Z}$ was the vector after $\vec{A}_1$ was turned. The vector $\vec{A}_{1d}$ was the symmetry vector of $\vec{A}_{1Z}$ to Y-axis. $\vec{A}_{1s}$ was that the vector $\vec{A}_{1d}$ turned clockwise ψ degree around the X-axis, and then was symmetrized to origin point to obtain the unit vector $\vec{A}_2$. And then $\vec{A}_{1s}$ was symmetrized to origin point to obtain the unit vector $\vec{A}_2$.

$$\vec{A}_2 = \vec{A}\vec{A}_R\vec{A}_\psi\vec{A}_y\vec{A}_{-\psi}\vec{A}_O, \tag{1}$$

where $\vec{A}_R$ is the matrix of $\vec{A}$ reflected through swaying mirror; $\vec{A}_\psi$ is the matrix of turn clockwise ψ; $\vec{A}_y$ is the matrix symmetrizing to Y-axis; $\vec{A}_{-\psi}$ is the matrix of turn reverse clockwise ψ; $\vec{A}_O$ is the matrix symmetrizing to origin point. So,

$$\vec{A}_2 = (-\sin 2\omega_x)\vec{i} + (-\cos 2\omega_x \sin 2\omega_y)\vec{j}$$
$$+ (-\cos 2\omega_x \cos 2\omega_y)\vec{k}. \tag{2}$$

θ was the angle between reflected light $\vec{A}_2$ and the Z-axis; R was the distance between the origin point and the point

that light $\vec{A}_2$ and scanning manufacturing plane were intersected; Φ was the angular coordinates of the point that light $\vec{A}_2$ and scanning manufacturing planes were intersected. So from the Eq. (2) we can obtain[4]

$$\tan\theta = \left[\frac{\tan^2 2\omega_x}{\cos^2 2\omega_y} + \tan^2 2\omega_y\right]^{\frac{1}{2}}, \qquad (3)$$

$$\tan\Phi = \cos 2\omega_x \sin 2\omega_y / \sin 2\omega_x. \qquad (4)$$

In the process of traditional laser scanning manufacturing, the $f\theta$ algorithm was adopted, and some geometry distorted was brought. During analyzing the geometry distorted, two reasons were come from two aspects: one is that the equation $\tan\theta = \theta$ was adopted in $f\theta$ algorithm; the other is that the convex lens central thickness, the lens convex radius, and refractive index were omitted in the $f\theta$ algorithm. For the first reason the equation $\tan\theta = \theta$ is valid when θ is very small, and the error barely comes into view[3]. For the second reason the analysis is shown in the follows. And a creative geometry control algorithm-OEF was brought forward.

During analyzing the optical system, sticking point of geometry distorted is at the convex focusing. The convex-focusing analysis was as follows. The former of OEF algorithm adopted the former of $f\theta$ algorithm. The convex-focusing principle is shown in Fig. 2. The light track is line $BDFG$. Hypothesis: the air medium refractive index is n_1; the dual-spherical convex lens refractive index is n_2; the incident light angle is θ ($\angle DBC$); the lens convex radii are r_1 (left), r_2 (right); the incident angle between laser light BD and normal line NI is α_1 ($\angle BDN$); the angle between refraction light DF and normal line NI is β_1 ($\angle FDI$); the angle between laser light DF and normal line CP is β_2 ($\angle DFC$); the incident angle between refraction light FG and normal line CP is α_2 ($\angle GFP$); the distance between points B and O is $BO = m = b + a\tan 2\omega_x\cot\theta$; the convex lens focal length $f = OH$; the point of intersection is between convex lens central line and main optical axis; and $\angle DIK = \phi_1$, $\angle FCK = \phi_2$, $DE = h = \left[(a\tan 2\omega_x)^2 + (b\tan 2\omega_y)^2\right]^{1/2}$.

The result was gained and as

$$R = r_1 \sin\phi_2 - \left[f - \frac{t}{2} + r_1(1 - \cos\phi_2)\right]\tan(\alpha_2 - \phi_2), \qquad (5)$$

where $\phi_2 = \beta_1 - \phi_1 + \beta_2$, $\phi_1 = \sin^{-1}(h/r_2)$, $\beta_1 = \sin^{-1}[\frac{n_1}{n_2}\sin(\theta + \phi_1)]$, $\beta_2 = \sin^{-1}\left\{\frac{h \times \cot(\beta_1 - \phi_1) - h \times \cot\theta}{r_1} + \frac{m + t/2 - r_1}{r_1}\sin(\beta_1 - \phi_1)\right\}$.

The focal point coordinates could be obtained. The geometry control model could be founded based on the OEF algorithm. And any point coordinates can be obtained in the scanning manufacturing plane,

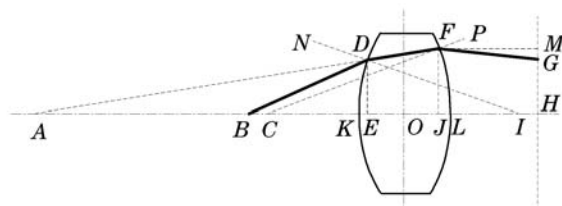$$X = R\cos\Phi, \qquad (6)$$

$$Y = R\sin\Phi. \qquad (7)$$

Fig. 2. Principle of dual-spherical convex lens optical focusing.

The analyzing process was verified in the dual-galvanometer scanning laser manufacturing[3]. Supposed 1) the lens convex radii are $r_1 = 50$ mm, $r_2 = 20$ mm; 2) the focal length of convex lens is $f = 30$ mm; 3) the convex lens central height is $d = 4.5$ mm; 4) the refractive indexes are $n_1 = 1$, $n_2 = 1.5$; 5) the turning angles of swaying mirror are $w_x = w_y = 2.5°$.

Based on these hypotheses the result was $R = 3.6028$ mm through the formula $R = HG$. Moreover the result was $R = 3.7000$ mm through the formula $f\theta$. And the two results were unequal evidently. The control system based on $f\theta$ made the manufacturing track to be geometrically distorted, and the distorted geometry was like 'pillow' figure. And the control system based on OEF algorithm was satisfied with manufacturing requirement. In Ref. [6], we gave the experimental simulating effect and the control program. The manufacturing error increases with the scanning scale, but it is not direct ratio. The deduced algorithm was right by executing experiment. The error of the system using $f\theta$ algorithm can reach 0.3 mm theoretically under remedy programmer with 100×60 mm^2 scanning scale, however the error of the system using OEF algorithm is only 0.001 mm theoretically. As the same situation the system error is 0.1 mm including mechanism errors, control hardware system errors, installation errors, thermal drift caused errors, and the errors of motor velocity non-linearity, the bearing wobbling, and the dither (shift from the defined position) caused by electronic noise in DEA control model based on OEF algorithm.

The foundation of DEA control model based on OEF algorithm was introduced as follows. According to the principle of scanning mirror, rotating angle of optical scanning mirror, and control voltage are direct ratio,

$$\begin{cases} w_x = k_x v_x \\ w_y = k_y v_y \end{cases}. \qquad (8)$$

The parameters v_x and v_y were obtained through D/A board when the scanning mirrors were controlled. The bipolar was adopted in using D/A board. And it was convenient for scanning mirrors rotating. Through analyzing $f\theta$ algorithm and OEF algorithm, the manufacturing track based $f\theta$ algorithm was smaller than based OEF algorithm. That is to say that $f\theta$ algorithm shortened the designing graphics. The foundation of control model based $f\theta$ algorithm was not true enough. Thus the $f\theta$ algorithm made the manufacturing track to be distorted. The DEA control model was founded based on OEF graphics control algorithm. The processing of DEM control model was divided two segments. The first, named calculating-end approach, was that the ω_x,

ω_y calculated through the formulas $x = f\omega_x$, $y = f\omega_y$. And the rotating angle of scanning mirrors was gotten by controlling the D/A board. The rotating angle was made to approach the calculating angles ω_x and ω_y. The second, named design-end approach, was that along the direction of calculating-end approach, add the $\delta\omega_x$ and $\delta\omega_y$ to make the manufacturing track to approach the design-end. The flow chart of DEA control model was shown in Fig. 3. Where the point (x', y') was obtained through E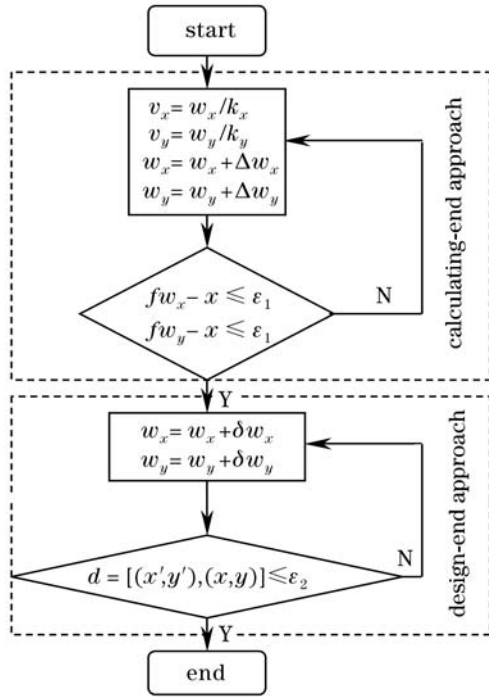qs. (6) and (7), and it also was coordinates of current manufacturing point. And the point (x, y) was design coordinates.

Five conclusions were obtained from the analyzing of OEF algorithm. 1) It can be known from the deduced algorithm that the dual-galvanometer scanning manufacturing OEF geometry control algorithm was related not only with the distance of the two swaying mirrors, the distance between the swaying mirror and convex lens, the mirror swaying angle, and the lens focal length, but also with the lens central height, the lens convex radius, and the medium refractive index. 2) The laser scanning manufacturing OEF geometry control algorithm was based on refraction law of light. And the precision formula was obtained by strictly deducing. 3) The laser scanning manufacturing OEF geometry control algorithm deduced offered the theoretical material for establishing mathematic control model. 4) DEA control model was founded based on OEF geometry control algorithm. 5) The manufacturing system can manufacture satisfied geometry with the creative DEA control model in the experiments of manufacturing and simulation.

Fig. 3. The flow chart of DEA.

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