A method of profile control applied in laser technology

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ABSTRACT

The proposed model allows the generation of any two-dimensional profile, which can be applied, for example, in laser welding and cutting techniques. In the paper, a system model for generating two-dimensional profiles using two galvanometer mirrors placed on two perpendicular axes is studied and designed. The forward and inverse kinematic equations establishing the relationship between the mirror motion and the laser profile are proposed and thoroughly solved by the author, and the author also presents the control problem to generate the desired profile. Simulations on Matlab are performed for circular and figure-8 profiles. The simulation results obtained profiles similar to the desired profile, both in shape and scanning frequency.

Keywords: Laser technology; Laser scanner; Laser profile; Galvanometer mirror.

1. INTRODUCTION

Laser technology uses high-energy laser beams for cutting, welding, engraving, and surface treatment. Laser applications can be found in surgery, cosmetic surgery, surface treatment, surface scanning, cutting, and welding [1, 2]. Laser cutting and welding techniques, although more expensive, are increasingly being applied due to their advantages over traditional methods, including the ability to heat non-contact, control precise contours, concentrate heat on a local area, and minimize heat loss. In welding techniques, laser welding allows welding small parts without damaging or breaking the structure [3].

With laser applications, profile control plays a very important role. In [4], the authors propose a solution to move the laser head on a translational axis mechanism to create contours. In [5], a two-axis contour scanning mechanism is used to create micro-grids used in laser cosmetic treatments. In [6], Chen Wei and his colleagues proposed a solution to create two-dimensional profiles using piezo actuators. In this mechanism, the change in relative length between the actuators controls the reflected laser beam to scan according to the desired profile.

In industry, laser welding and cutting machines commonly use fiber laser sources. To create profiles, the nozzle often has a single-axis structure. This method has the advantage of being easy to manufacture and simple to control. However, it can only create simple profiles, circles, and lines. In many other applications we need to create different profiles to increase the quality of the weld. Some studies have shown that the quality of the weld can be increased when the laser profile is suitable for the surface properties, geometry, as well as the materials used [7-9]. Based on studies on the two-axis laser beam control mechanism, the author proposed a method to create two-dimensional profiles used in laser applications. This method allows to the creation of any two-dimensional profile, with a preset scanning frequency and a constant laser projection speed over the entire profile. In this paper, the author presents a model of a two-axis profile control system, studies the solution of the forward and inverse kinematics problems, proposes a control algorithm, and conducts experimental simulations.

2. A MODEL OF PROFILE-GENERATION CONTROL SYSTEMS

2.1. Profile-generation system design

For laser devices, the main components usually include a laser source, fiber optic cable, two-axis profiling control system, lens and nozzle. In the profiling system model, two galvanometer mirrors G1, G2 are arranged on the mounting frame in the direction of two perpendicular axes. Laser source S is arranged on the OY axis. Mirror G1 rotates around the OX axis, reflecting the beam from laser source S. Mirror G2 rotates around an axis parallel to OY, reflecting the laser beam from the secondary source (located at point O). The two galvanometer mirrors are arranged so that the distance between the two mirror centers is h. The distance from these centers to the profiling screen is d. The model parameters are shown in table 1.

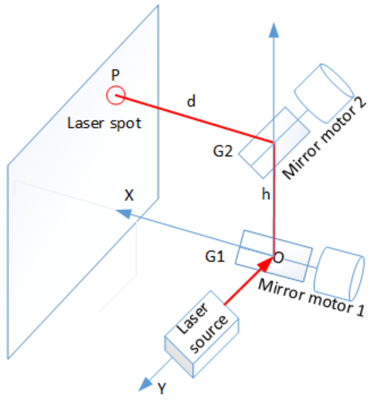


Figure 1. *Two-axis profile generation system.*

Table 1. *Parameters used in the model.*

Parameter	Unit	Description	Parameter	Unit	Description
W_{G1}	mm	edge perpendicular to axis G_1	W_{G2}	mm	edge perpendicular to axis G_2
L_{G1}	mm	edge parallel to axis G_1	L_{G2}	mm	edge parallel to axis G_2
α	^{o}	angle of incidence to mirror G_1	β	^{o}	Angle of incidence to mirror G_2
ω_1	^{o}/s	angular rate of G_1	ω_1	^{o}/s	angular rate of G_2
h	mm	center distance from G_1 to G_2	d	mm	distance from center G1, G2 to profile plane
R_Y	mm	width of profile along the Y axis	F_{scan}	Hz	profile scanning frequency
R_Z	mm	width of profile along the Z axis	T_{scan}	s	profile scanning period

The rotation angle limit of mirror G_1 must ensure that the laser beam after reflection on G_1 can enter the reflecting surface of the mirror G_2, this angle is determined by (1):

$$\Delta_\alpha = |\alpha_1 - \alpha_2| = K_1OK_2/2 = KOK_1 = \arctan(KK_1/OK) = \arctan(L_{G2}/2h) \qquad (1)$$

Where: Δ_α - Rotation range of the mirror G_1; points O, K, K1, K2 – Described in figure 2. If L_{G2} = 20 mm, h = 30 mm, then $\Delta_\alpha = 18.5^o$.

To determine the rotation range of the mirror G_2, we rotate mirror G_1 to the position where the reflected ray on G_1 coincides with OK. When mirror G_2 is at position $\beta = \beta_1$, the reflected ray on G_2 coincides with KP_4 (figure 2). Let rotate G_2 to position $\beta = \beta_2$, the reflected ray coincides with

KP_5. Rotation angle range of G_2 is:

$$\Delta_\beta = |\beta_1 - \beta_2| = \frac{1}{2} P_4OP_5 = P_4OP = \arctan(PP_4 / KP) = \arctan(R_Z / 2d) \quad (2)$$

Where: Δ_β - Rotation range of the mirror G_2. If R_Z = 30 mm, d = 200 mm, then $\Delta_\beta = 4.5^o$.

2.2. Forward kinematic equation

To simplify the calculation, we consider the laser beam as a single ray. In the initial state, the angles α = 45°, β = 45°. Then, the reflected ray from mirror G_1 will coincide with the OK ray, and the reflected ray from mirror G_2 will coincide with the KP ray (figure 2). Let the mirror G_1 oscillate around the 45° position, the mirror G_2 is fixed at the angle β = 45°. Let $\alpha = 45^o - \Delta_\alpha / 2$, the angle Δ_α is limited by condition $\Delta_\alpha \le \arctan(L_{G2} / 2h)$. Laser spot slides on the edge PP_1 parallel to the axis of G_2.

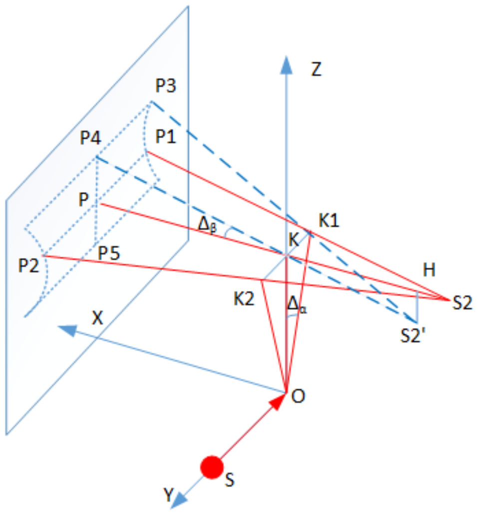


Figure 2. *Laser beam through the system of mirrors.*

Let S_2 be the image of the secondary laser source (point O) via the mirror G_2. Let the mirror G_1 be fixed at position α = 45°, the mirror G_2 oscillates around position 45°. S_2 then oscillates around the axis G_2. Suppose S_2 moves to a new position $S_2^'$ when $\beta = 45^o - \Delta_\beta / 2$. According to the properties of mirror reflection: $S_2^'KS_2 = PKP_4 = \Delta_\beta$. Reflected ray KP_4 passes through $S_2^'$ and $KS_2^' = KS_2 = KO = h$. Let H be the projection of $S_2^'$ on KP: $S_2^'H / PP_4 = KH / KP$.

Therefore: $PP_4 = S_2^'H.KP / KH = d\tan(\Delta_\beta)$ (3)

It can be seen that the profile expansion in the OZ direction depends only on the distance d and the rotation angle of the mirror G_2. Next, let the mirrors G_1 and G_2 oscillate around the position $\alpha_0 = 45^o$, $\beta_0 = 45^o$:

$$\alpha = \alpha_0 - \Delta_\alpha / 2; \ \beta = \beta_0 - \Delta_\beta / 2 \quad (4)$$

OK_1 is the reflected ray on the mirror G_1, K_1P_3 is the reflected ray on the mirror G_2. K_1P_3 extends through the image $S_2^'$. Applying geometric properties:

$$KK_1 / P_3P_4 = S_2^'K / S_2^'P_4 = HK / HP = h\cos(\Delta_\beta) / (h\cos(\Delta_\beta) + d) \quad (5)$$

$$\Rightarrow P_3P_4 = KK_1(h\cos(\Delta_\beta) + d) / h\cos(\Delta_\beta) = (h + d / \cos(\Delta_\beta))\tan(\Delta_\alpha) \quad (6)$$

The expansion of profile according to OY direction depends on $d, h, \Delta_\alpha, \Delta_\beta$. Thus, solving the forward kinematics problem, we can determine the position of the laser spot (point P_3), its coordinates are determined by (6) and (3).

2.3. Inverse kinematic equation

In the inverse kinematics problem, we propose a control method to obtain a given desired profile. Any profile can be approximated by a spline (for example cubic spline interpolation). Given a profile $\widehat{P}$ approximated by segments $\widehat{P}_i$, $\widehat{P} = \left\{\widehat{P}_1, \widehat{P}_2, ..., \widehat{P}_n\right\}$. Here:

$$\widehat{P}_i(\gamma) = \left[Y_i(\gamma) \quad Z_i(\gamma)\right]^T, \ \gamma \subset [\gamma_i, \gamma_{i+1}] \tag{7}$$

The length of the profile is determined by the expression: $L = \sum_{i=1}^{n} L_i = \sum_{i=1}^{n} \int_{\gamma_{1i}}^{\gamma_{2i}} \sqrt{\dot{Y}_i^2(\gamma) + \dot{Z}_i^2(t)} \gamma d\gamma$.

Let v be the velocity of the laser spot when running on the profile. When scanning, the velocity of the laser spot is determined by:

$$v = dL_i / dt = (dL_i / d\gamma)(d\gamma / dt) = \sqrt{Y_i'^2(\gamma) + Z_i'^2(\gamma)}\, \dot{\gamma} \tag{8}$$

Where t – Real time, γ - Path parameter. For major laser applications, we want this speed to be constant. The velocity v then:

$$v = \sqrt{Y_i'^2(\gamma) + Z_i'^2(\gamma)}\, \dot{\gamma} = L / T_{scan} \Rightarrow \dot{\gamma} = L / T_{scan} \sqrt{Y_i'^2(\gamma) + Z_i'^2(\gamma)} \tag{9}$$

According to (6) and (3), the coordinates of the laser spot on the profile:

$$Y = \overline{P_4 P_3} = (h + d / \cos(\Delta_\beta)) \tan(\Delta_\alpha) \ (*), \ Z = \overline{PP_4} = d \tan(\Delta_\beta) \ (**) \tag{10}$$

Take the derivative of both sides (10**) versus time and combine (9), we have:

$$\frac{dZ_i}{dt} = \frac{dZ_i}{d\gamma}\frac{d\gamma}{dt} = \frac{L\dot{Z}_i}{T_{scan}\sqrt{Y_i'^2(\gamma) + Z_i'^2(\gamma)}} = \frac{d\dot{\Delta}_\beta}{\cos^2(\Delta_\beta)} \Rightarrow \omega_2 = \dot{\Delta}_\beta = \frac{L\dot{Z}_i \cos^2(\Delta_\beta)}{dT_{scan}\sqrt{Y_i'^2(\gamma) + Z_i'^2(\gamma)}} \tag{11}$$

Here: ω_2 - Angular velocity of G_2. Similarly, take the derivative of both sides (10*) versus time:

$$\frac{dY_i}{dt} = \frac{dY_i}{d\gamma}\frac{d\gamma}{dt} = \frac{L\dot{Y}_i}{T_{scan}\sqrt{Y_i'^2(\gamma) + Z_i'^2(\gamma)}} = (h + \frac{d}{\cos(\Delta_\beta)})\frac{d(\tan(\Delta_\alpha))}{dt} + \tan(\Delta_\alpha)\frac{d}{dt}(h + \frac{d}{\cos(\Delta_\beta)}) \tag{12}$$

Or:

$$\frac{h\cos\Delta_\beta + d}{\cos\Delta_\beta}\frac{\omega_1}{\cos^2\Delta_\alpha} + d\tan(\Delta_\alpha)\frac{\sin\Delta_\beta}{\cos^2\Delta_\beta}\omega_2 = \frac{L\dot{Y}_i}{T_{scan}\sqrt{Y_i'^2(\gamma) + Z_i'^2(\gamma)}} \tag{13}$$

Where: $\omega_1 = \dot{\Delta}_\alpha$ - Angular velocity of the mirror G_1. Expression (13) describes the motion relationship between two mirrors G_1 and G_2. From (11) and (13) it is possible to determine the rotational velocities of the two mirrors.

2.4. Profile generation control

In the proposed model, two galvanometer mirrors are used. It has the advantages of compactness and high response frequency compared to using step motors for control. The control problem of profile generation includes planning the displacement angle of the mirrors and constructing controllers for the galvanometer mirrors.

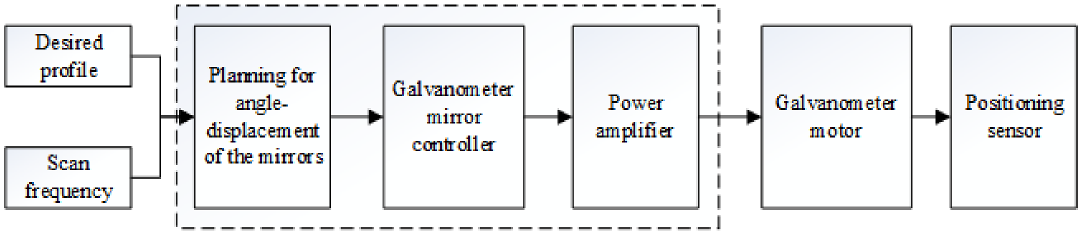


Figure 3. *Block diagram of profile control.*

2.4.1. Plan the displacement angle

The initial position of the mirror is determined when t = 0. At this time, the initial angle of the mirror is determined as:

$$\Delta_{\beta|t=0} = \arctan(Z_{|\gamma=0} / d)\,;\ \Delta_{\alpha|t=0} = \arctan(Y_{|\gamma=0} / (h + d / \cos(\Delta_{\beta|t=0}))) \qquad (14)$$

Let N be the number of samples, set $dt = T_{scan}/N$ – Sampling time. At moment $t_k = kdt$, the rotation angle of mirrors G_1, G_2 is determined as: $\Delta_{\alpha|k+1} = \Delta_{\alpha|k} + \omega_{1|k} dt$, $\Delta_{\beta|k+1} = \Delta_{\beta|k} + \omega_{2|k} dt$. The angular velocities are derived from (11) and (13). The values $\Delta_{\alpha|k}$, $\Delta_{\beta|k}$ will be pushed to the galvanometer mirror controller with an update cycle of T_{scan}/N.

2.4.2. Controller for galvanometer mirrors

The kinematic equation for the galvanometer mirror can be found in [10]:

$$E = K_b(d\theta / dt) + L(di / dt) + Ri(t);\ J(d^2\theta / dt^2) = K_t i(t) - B_v(d\theta / dt) \qquad (15)$$

Where E, i are the voltage and current passing through the motor stator coil, respectively; R, L are the resistance and inductance, respectively; θ - Rotation angle, J – Moment of inertia of the rotor and mirror; K_t, B_v – Respectively torque-constant and damping coefficient. From [11] and (15), the transfer function describing the galvanometer mirror object:

$$\theta / E = K_t / (LJs^3 + (LB_v + RJ)s^2 + (RB_v + K_b K_t)s) \qquad (16)$$

From (16), some control techniques such as PID, sliding control, etc. can be used to build a controller for the galvanometer mirrors. In this paper, the authors does not go deep into the design of the galvanometer mirror controller. For this, we can refer to [12] for more detail on controller design.

3. SIMULATION AND COMMENTARY

Table 2. *Input parameters for circular profiles.*

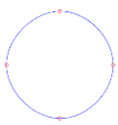
Parameters	Description
T_{scan} = 100 ms	Profile scanning cycle
N = 100	Number of samplings
dt_{real} = 1 ms	Sampling time
h = 30 mm	Distance between mirrors G_1 and G_2
d = 200 mm	Distance from mirror center to profile plane
Parametric equations describing circles: 	$\begin{cases} Y = \cos(t) \\ Z = \sin(t) \end{cases},\ t \in [0, 2\pi]$

Table 3. *Simulation results for circular profiles.*

t_{real} (s)	t	ω_1 (độ/s)	ω_2 (độ/s)	Δ_α (độ)	Δ_β (độ)
0	0	0	18.0092	0.24924	0
1e-03	0.062832	-0.9833	17.9736	0.24924	0.01801
2e-03	0.12566	-1.9627	17.867	0.24825	0.03598
……	……	……	……	……	……
0.1	6.2832	-5E-11	18.0092	0.24924	4.4E-08

Consider the case of a circular profile. The input parameters are described in table 2. Table 3 shows the calculation results when running the algorithm. Figure 4 shows the change in the rotation angle of mirrors G1 and G2 over time in the scanning process. Figure 5 compares the obtained circular profile with the desired profile. The simulation results show that both obtained and desired profiles are similar. Despite that, there is a shift between these profiles. In the case of circular profiles, the displacement is 0.05 mm.

Table 4. *Input parameters for 8-figured profiles.*

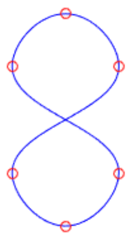
Parameters	Description
T_{scan} = 100 ms	Profile scanning cycle
N = 100	Number of samplings
dt_{real} = 1 ms	Sampling time
h = 30 mm	Distance between mirrors G_1 and G_2
d = 200 mm	Distance from mirror center to profile plane
8-figured profile can be described by a cubic spline interpolation: 	Breaks points: [0 1.5708 4.7124 6.2832 7.8540 10.9956 12.5664]. pieces: 6, order: 4, dim: 2, coefs: [12×4 double]: -0.1170 -0.0475 1.0000 0 0.1843 -0.6948 0 2.0000 0.1277 -0.5990 -0.0155 1.0000 --- -0.1170 0.5990 -0.0155 -1.0000 -0.1843 0.1737 0.8185 1.0000

Table 5. *Simulation results for 8-figured profiles.*

t_{real} (s)	t	ω_1 (độ/s)	ω_2 (độ/s)	Δ_α (độ)	Δ_β (độ)
0	0	30.052	0	0	0.5732
5E-04	0.0602	29.951	-2.83608	0.015026	0.5732
1E-03	0.1208	29.663	-5.54273	0.030002	0.5718
……	……	……	……	……	……
0.0995	12.506	29.951	2.83654	-0.01493	0.5715

Consider the case of any profile described by a spline. For example, the 8-figured profile. The input parameters and simulation results are shown in table 4, table 5. Figure 6 describes the change in the rotation angle of G1 and G2 versus time. Figure 7 compares the obtained profile with the 8-figured given profile. The displacement of profiles in this case is 0.04 mm. Figure 8 compares the obtained profiles corresponding to different number of sampling N. With a larger N, the obtained profile is more similar to the desired profile, and its displacement to the desired one also decreases.

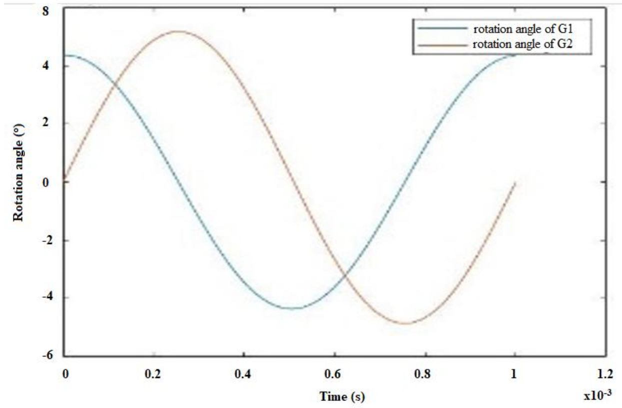


Figure 4. *Changing in rotation angle of mirrors G1, G2 versus time for the circular profile.*

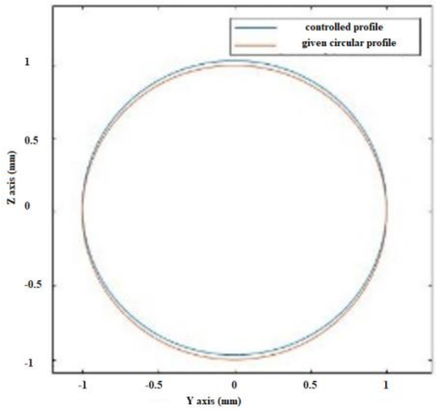


Figure 5. *Comparing the obtained and desired circular profiles.*

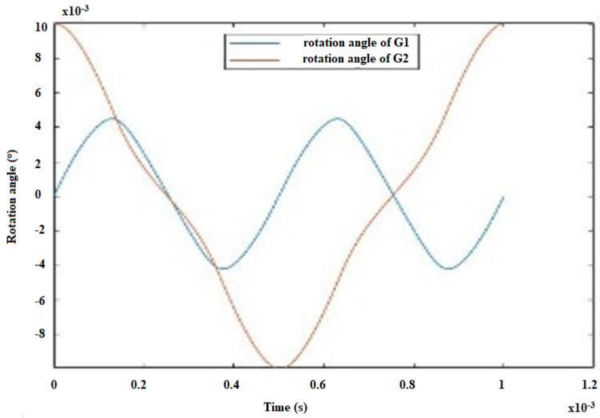


Figure 6. *Changing in rotation angle of mirrors G1, G2 versus time for the 8-figured profile.*

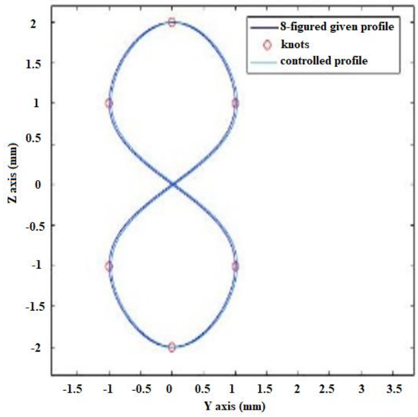


Figure 7. *Comparing the obtained and desired 8-figured profiles.*

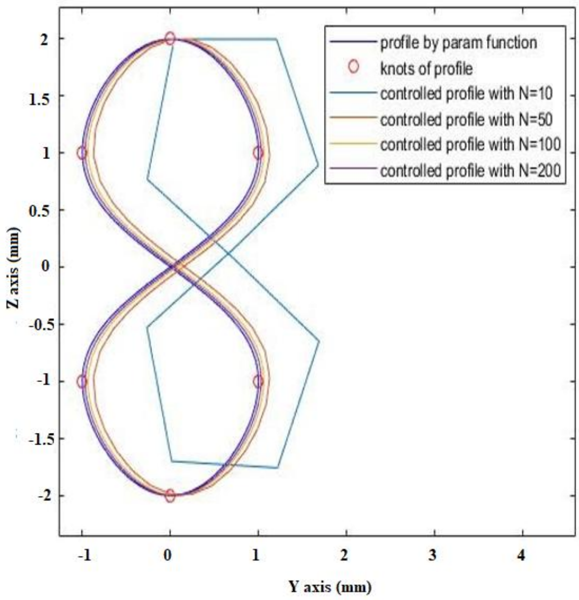


Figure 8. *Profiles obtained with different number of sampling.*

Thus, with the proposed method, the simulation results demonstrate that the proposed model allows the creation of any profiles similar to the desired ones (in frequency and shape, scanning speed).

Compared to the mechanical systems in [4, 13] with the laser head moving on the axis system, the proposed method has a more compact structure. The laser head is stationary compared to the system frame, so errors due to vibration of the mechanism can be avoided. In [4], the deviation of the running profile is 0.12 mm, larger than the deviation obtained by the proposed method (0.04 mm). This result can be compared with some machines such as the Fiber Laser PL130 of Raycus (error of 0.012 mm), Swiitol Laser (error of 0.06 mm), or DW-6040B of CWG (error of 0.01 mm).

4. CONCLUSIONS

The paper successfully introduces a model of a two-axis profile scanning control system applied in laser technology. The proposed solution is tested through simulation on Matlab. With the proposed method, the simulation results are similar to the desired profile, both in terms of scanning frequency and shape; the displacement of the obtained profiles to the desired ones does not exceed 0.05 mm. The results from the simulations demonstrate the feasibility of implementing the proposed model to build a profile scanning control system in practice, which could be applied to laser welding and cutting applications. Further research can develop in the direction of delving into the design of a galvanometer mirror controller. Another direction is developing a profile-generating system in practice with the proposed solution.

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TÓM TẮT

Về một phương pháp điều khiển biên dạng trong công nghệ laser

Bài báo trình bày nghiên cứu thiết kế hệ thống điều khiển tạo biên dạng hai chiều ứng dụng trong công nghệ laser. Mô hình đề xuất cho phép thể tạo ra biên dạng hai chiều bất kỳ có thể dụng cho kỹ thuật hàn, cắt laser. Trong bài báo, mô hình hệ thống tạo ra biên dạng hai chiều sử dụng hai gương điện kế đặt trên hai trục vuông góc được đề xuất. Các phương trình động học thuận và nghịch thiết lập mối quan hệ giữa chuyển động của gương và biên dạng laser được tác giả đưa ra và giải quyết triệt để, đồng thời tác giả cũng trình bày vấn đề điều khiển để tạo biên dạng mong muốn. Mô phỏng trên Matlab được thực hiện cho biên dạng hình tròn và hình số 8. Kết quả mô phỏng thu được biên dạng giống với biên dạng mong muốn, cả về hình dạng và tần số quét.

Từ khóa: Công nghệ laser; Quét laser; Biên dạng laser; Gương điện kế.