

Laser Scanner-Stage Synchronization Method for High-Speed And Wide-Area Fabrication

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This paper presents an on-the-fly method to synchronize a laser galvanometer scanner and linear stage for fast and wide-area fabrication. The location and velocity information of the linear stage is transferred to the galvanometer scanner control board by an encoder signal. The scanner control board calculates the amount of laser beam movement by subtracting from original CAD data to linear stage movement. The on-the-fly method is different from the existing step and scanning method in that it ensures continuous stage movement and real-time signal transfer between the linear stage and galvanometer scanner.

Keywords: Laser, Galvanometer scanner, Linear stage, On-the-fly, Synchronization
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1. Introduction

Short-pulsed laser technology allows for material fabrication processes using ultra-precision lasers, such as via-hole drilling [1], FPCB (Flexible PCB) cutting [2], and surface texturing [3]. This trend of laser fabrication requires a high-speed, wide-area, and dry process due to concerns over environmental problems. The galvanometer scanner is being widely used as a marking tool [4]. Recently, it has been applied to many laser material fabrication fields [5]. However, the working field size of this scanner is limited by the focal length of the f-theta objective lens, which is measured from the scanner head to the sample. When the focal length is increased, the working field size of the scanner becomes wider, but the resolution of the scanning field decreases, which can be a drawback for precise fabrication. A hybrid method that involves the use of both a linear stage and a scanner is being considered for wide-area fabrication. The initial approach that has been adopted is known as the step and scanning method. The stage repeatedly moves and stops in steps, and the scanner operates when the stage stops. Therefore, this method causes discontinuous quality and increases the fabrication time, because stage motion stops when the scanner is operating. To overcome this problem, a hybrid method that involves the use of both a linear stage and a scanner has recently been developed. Manufacturers of the scanner-stage synchronization processing equipment include ESI, LPKF, and AEROTECH. Electro Scientific Industries (ESI) applied on-the-fly equipment to micro via-hole drilling and FPCB cutting. The ESI UV laser drilling system HDI 5330 is capable of on-the-fly processing with a 533 mm × 635 mm working area; this system can guarantee 20μm accuracy with a 500mm/s fabrication speed. LPKF of Germany recently released the MicroLine 6000 model for cover layer cutting of PCB or FPCB. The company provides software

known as LPKFCAM, which profiles the stage path and scanner working path and reduces the fabrication time by 20%. In recent years, AEROTECH of the United States has developed similar on-the-fly equipment with the preprocessing path optimization software Automation 3200. Some examples of on-the-fly equipment are shown in Fig. 1.



Fig. 1 Photos of on-the-fly equipment of several companies: ESI, LPKF, and AEROTECH.

Some commercial scanner control boards provide on-the-fly applications with options, such as the RTC 5 board of SCANLAB and the marking on-the-fly (MOTF) add-on board of RAYLASE. However, the main application of the MOTF board is limited to marking of the serial number, time, and so on, of large-area electronic parts in the conveyor feed stage. In this study, we mainly focused on ap-

plication to FPCP cover layer cutting; the work can be summarized as follows:

- (1) Stage path and velocity profiling software development for preprocessing
- (2) On-the-fly control board development for laser fabrication purposes
- (3) On-the-fly system buildup with a linear stage
- (4) On-the-fly system validation by experiments

2. On-the-fly system configuration

2.1 Stage path/velocity profiling

The on-the-fly control system is composed of stage path/velocity profiling software, a scanner control board, and a stage control board. First, the tool path for laser fabrication needs to be determined by the stage path profiling algorithm. In the CAD data, the stage allocates a rough path because its velocity and acceleration are small compared to the scanner's velocity and acceleration. For the detail region, which is commonly called the high-frequency region in CAD data, the scanner works because the galvanometer mirror system in the scanner enables delivery of the laser beam with almost zero inertia. As shown in Fig. 2, the stage path is smoothed into a parabolic shape to minimize the stage acceleration and deceleration when fabricating a 90° corner line. The radius of curvature of the stage path is determined by the stage acceleration time (Ta). If the value of the stage acceleration time is large, the stage path becomes smoother. An example of stage path profiling is shown in Fig. 3. To fabricate targeting CAD data, the stage path can be determined by the variations in Ta. If Ta changes from 60 ms to 80 ms, the stage path becomes smooth, and the stage movement decreases.

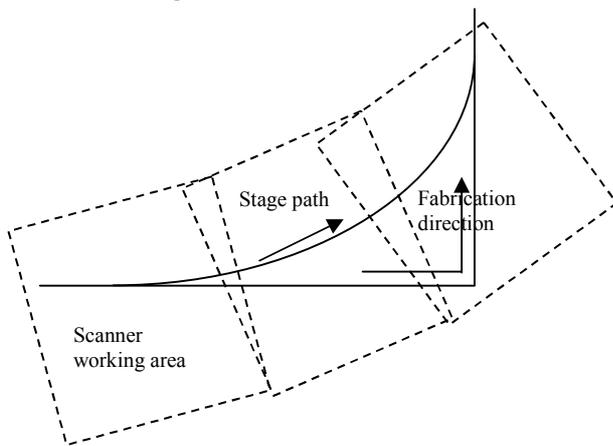


Fig. 2 Example of stage path profiling

Once the stage path is determined, the scanner working path can be calculated from the vector relationship, as shown in Fig. 4. The fabrication movement vector ($\vec{P}_{fa,i}$) is the summation of the stage movement vector ($\vec{P}_{st,i}$) and scanner movement vector ($\vec{P}_{sc,i}$) for a certain period and is defined by Eq. (1) as follows:

$$\vec{P}_{st,i} + \vec{P}_{sc,i} = \vec{P}_{fa,i} \quad (1)$$

To synchronize the scanner stage, the duration of each movement vector should be

$$\frac{|\vec{P}_{st,i}|}{v_{st,i}} = \frac{|\vec{P}_{sc,i}|}{v_{sc,i}} = \frac{|\vec{P}_{fa,i}|}{v_{fa,i}} \quad (2)$$

where the stage velocity ($v_{st,i}$) and scanner velocity ($v_{sc,i}$) can be calculated by Eq. (3) as follows:

$$v_{st,i} = \frac{|\vec{P}_{st,i}|}{|\vec{P}_{fa,i}|} \times v_{fa,i} \quad (3-a)$$

$$v_{sc,i} = \frac{|\vec{P}_{sc,i}|}{|\vec{P}_{fa,i}|} \times v_{fa,i} \quad (3-b)$$

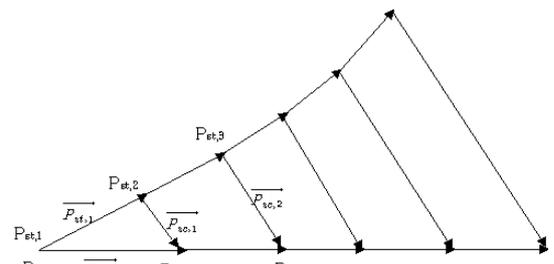
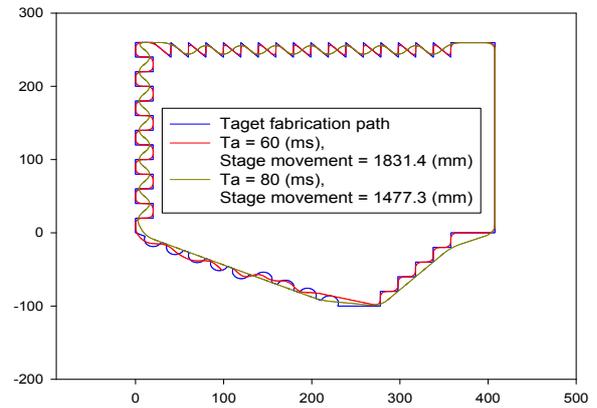


Fig. 4 Vector decomposition of each component path

2.2 On-the-fly control board development

The stage path and velocity are determined by the PC level using position profiling and preprocessing. The information obtained from the stage position and velocity is then transferred to the stage control board. The stage motion and speed are controlled by the stage driver command. The information obtained from the stage location and velocity is also transferred to the scanner control board with an encoder signal, as shown in Fig. 5. In the scanner control board, the scanner movement and velocity are calculated using the CAD data and the stage path and velocity. The stage movements may not follow the command, and the stage tracking error is also added or subtracted in the scanner control board.

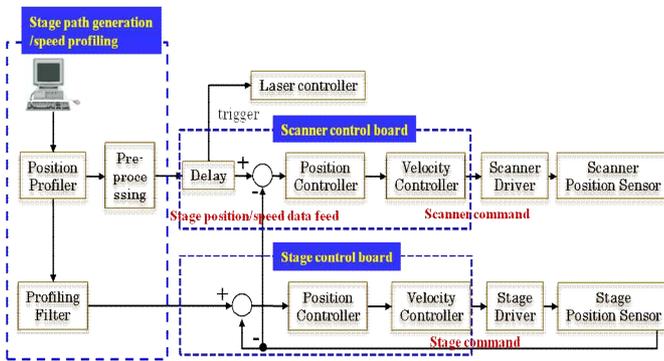


Fig. 5 On-the-fly control system layout

2.3 Comparison of on-the-fly method with step and scanning method

Initially, a one-axis stage–two-axis scanner on-the-fly system was developed and tested, as shown in Fig. 6. An IPG fiber laser with a 30 ns pulse width, 12 W power, and 1064 nm wavelength was used for the on-the-fly marking experiment. A CTI scanner head with an aperture of 10 mm and focal length of 100 mm was used. The stage of DASAROBOT has a 400-mm stroke with a maximum speed of 500 mm/s and a precision of approximately 5 μm.



Fig. 6 Photo of one-axis stage–two-axis scanner on-the-fly system

The marking precisions of the step and scanning method and on-the-fly method were compared at a low pulse repetition rate of 1 kHz. The marking speed was 300 mm/s, and the scanner working area was 50 mm × 50 mm. In the step and scanning method, the stage stops when the scanner is operating. After the scanner operates within the working area, the stage shifts 50 mm to the right to begin with the next process. The scanning and step movement process is repeated to mark the entire area. However, in the on-the-fly system, the stage and scanner move and work together. Various marking directions from 0° to 90° were tested, as shown in Fig. 7. Three areas were selected to compare the marking qualities between the two methods.

Figure 8 compares the two methods at the marked spots. In the scanner working area of both methods, the distances

between the marking spots were almost constant in all directions. In the step and scanning method, irregular spots were observed at the boundary of the scanner working area. This is because the exact marking positions could not be controlled owing to the irregular start and stop movements of the stage. However, the on-the-fly method showed an almost constant marking distance between spots in the boundary region and working area. This is a critical advantage of the on-the-fly system over the step and scanning method.

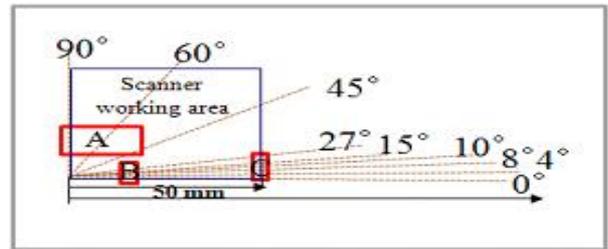


Fig. 7 Experimental scenario of laser marking test for comparison between step and scanning and on-the-fly methods

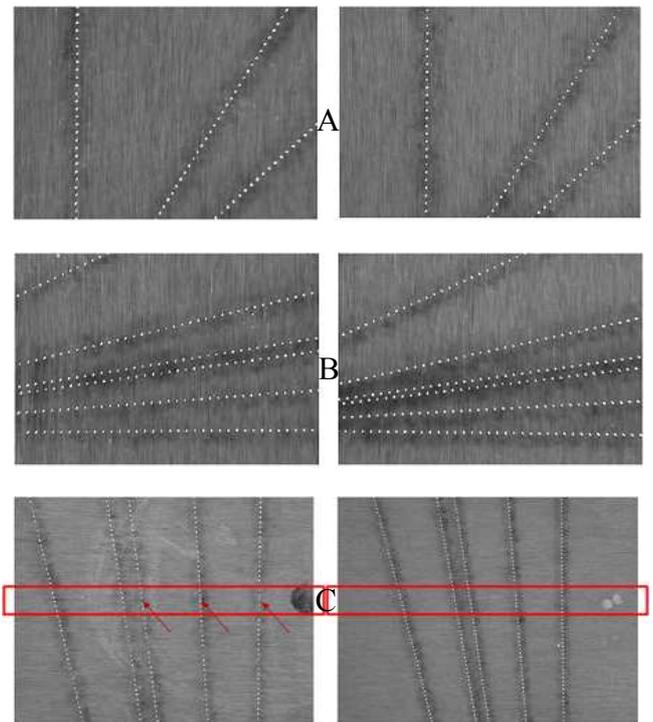


Fig.8 Results of laser marking pattern of two methods: step and scanning method (left) and on-the-fly method (right)

2.4 Accuracy measurement of on-the-fly system

Recently, we expanded the one-axis linear stage in the on-the-fly system to a two-axis linear stage. The scanner control board can input encoder signals to both the x and y axes of the stage motion board. The hardware was built up with a two-axis gantry linear stage having a z-axis linear stage, as shown in Fig. 9.

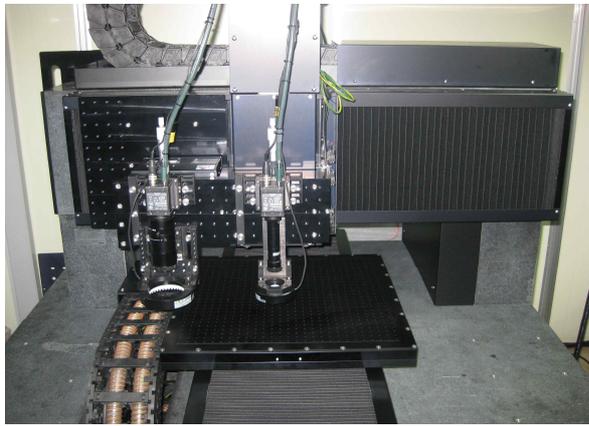


Fig. 9 Photo of two-axis stage and two-axis scanner on-the-fly system.

Each axis of the linear stage was tested and measured for accuracy by a laser interferometer made by RENISHAW. The repeatability was measured to be $0.4 \mu\text{m}$ for the x axis and $0.29 \mu\text{m}$ for the y axis over the entire work area of $500 \text{ mm} \times 500 \text{ mm}$. The accuracy of the linear stage was measured to be $3.03 \mu\text{m}$ along the x axis and $1.29 \mu\text{m}$ along the y axis.

Initially, the accuracy of the system was measured without synchronization of the galvanometer and two-axis linear stage. To measure the accuracy of the scanner system itself, a square shape with a length of 40 mm on one side was marked when the linear stage stopped. The error of the scanner system is summarized in Table 1. The maximum error of the side length was less than $8 \mu\text{m}$, and the average error of the four side lengths was $2.5 \mu\text{m}$.

Table 1. Error of galvanometer scanner when marking a square with a side length of 40 mm .

	Position (mm)		Side length (mm)		Error (μm)
	x	y			
1	0	0	S1	40.000	0
2	0	40	S2	39.997	-3
3	39.997	40.005	S3	40.008	8
4	40.005	-0.003	S4	40.005	5
Average				40.0025	2.5

The galvanometer scanner and linear stage were then synchronized, and the wide area was marked by a square shape with a side length of 350 mm . The test results are summarized in Table 2. The maximum deviation of the side length was $8 \mu\text{m}$, which is similar to the summation of the linear stage and scanner errors. However, the error for the average side length of the large rectangle was still less than $5 \mu\text{m}$. The maximum angular error occurred between M3 and M4 and was measured to be 0.0025° , which is a quite trivial value. For this marking test with the on-the-fly system, the error included both of the stage and scanner errors. Again, information of the position and velocity of the linear stage was transferred to the scanner control board through the encoder signal. At the scanner control board, the stage position was corrected by a comparison with reference CAD data. Even though the corrected information was commanded by the scanner control board, the galvanometer system can have error sources: for example, optical distortions and mechanical error.

The test results for the accuracy of the scanner system and on-the-fly system are shown in the Fig. 10.

Table 2. Error of the on-the-fly system when marking a square with a side length of 350 mm .

	Position (mm)		Side length (mm)		Error (μm)
	x	y			
1	0	0	M1	350.000	0
2	-0.005	350	M2	350.008	8
3	350.003	349.993	M3	350.003	3
4	350.007	-0.010	M4	350.007	7
Average				350.0045	4.5

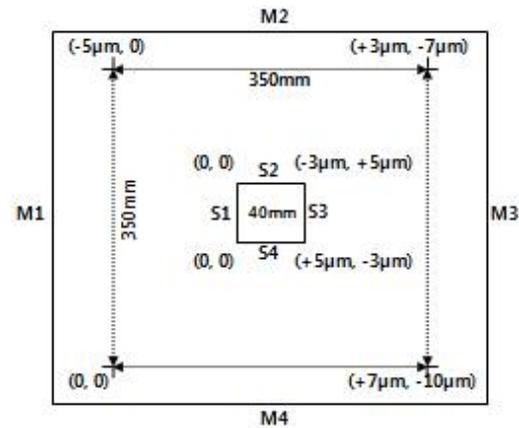


Fig. 10 Results for the position accuracy of the scanner and the on-the-fly system: the small square in the center represents the scanner system error, and the outside square represents the on-the-fly system position error.

The on-the-fly system accuracy was then tested by synchronization of the two systems. Three equilateral triangles with side lengths of $100, 200, \text{ and } 300 \text{ mm}$ were marked at a 350 mm/s marking speed, and the three sides and angles of each triangle were measured. The error of the side length was measured to be about $5 \mu\text{m}$ and was quite similar for all three triangles.

However, the side lengths of L1 and L2 show deviated results from nominal value all three cases. One side length may have been overestimated, and the other side may have underestimated the measuring interception point between L1 and L3. Another possibility may be that the stage control by the UMAC company was not finely tuned enough to make the cross line L2. The largest angular error was at a1. All angular errors were measured and found to be less than 0.05° in the three triangle cases. The test results are summarized in Table 3.

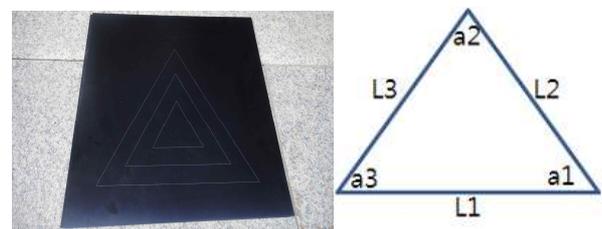


Fig. 11 Marking results of three triangles (left) and measurement points (Right)

Table 3. Error of on-the-fly system when marking three different triangles.

	100-mm Triangle	200-mm Triangle	300-mm Triangle
L1 (mm)	100.06704	200.1119	300.16525
L2 (mm)	99.94538	199.89254	299.84076
L3 (mm)	100.00391	200.01105	300.01027
Average (mm)	100.00544	200.00516	300.00543
Error(μm)	5.44	5.16	5.42
a1($^\circ$)	59.9972	59.9965	59.9944
a2($^\circ$)	60.0624	60.0593	60.0600
a3($^\circ$)	60.0639	60.0564	60.0584
Average($^\circ$)	60.0412	60.0374	60.0376
Error($^\circ$)	0.041	0.037	0.038

3. Conclusion

An on-the-fly method was developed to synchronize the galvanometer scanner and linear stage. The stage path and velocity were determined at the PC level by position profiling preprocessing. The stage path was determined from the stage acceleration value. When T_a was increased, the stage path became smoother and shorter. The information obtained from the stage path and velocity was transferred to both the stage control driver and the scanner. On the scanner control board, the amount of scanner movement was calculated from the difference between the CAD data and the stage movement information. In the one-axis stage–two-axis scanner on-the-fly system, the marking distances between certain spots were measured. Almost constant distances were observed at both the scanner working area and the boundary region. However, in the step and scanning method, irregular marking points were observed at the boundary of the scanning area, which may affect the quality of fabrication.

The on-the-fly system was expanded to the two-axis linear stage and two-axis scanner system. First, the two-axis linear stage was evaluated for its repeatability and accuracy through the use of a laser interferometer. The accuracy of the linear stage was measured to be about 3 μm . The galvanometer scanner error was about 2.5 μm . The maximum error of the on-the-fly system was then measured to be less than 10 μm when marking a wide-area square shape. The precision test was expanded to mark triangles with different sizes. The length error of the side was measured to be about 5 μm , and the angular error was measured to be less than 0.05 $^\circ$; these results were almost independent of the triangle size. The precision of the developed on-the-fly system was well-validated by various marking tests. The maximum error of the developed on-the-fly system almost corresponded to the current state-of-art on-the-fly system, which has an accuracy of 20 μm with a 500 mm/s fabrication speed. In the future, we will develop a high-speed on-the-fly system with high accuracy.

Acknowledgments and Appendixes

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