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## Minimization of passive motion time in laser microvia drilling of ABF dielectrics

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### Abstract

Printed Circuit Board manufacturing is a key sector of modern electronics industry where improving the throughput of microvia drilling operations is of paramount importance. One effective solution is maskless laser technology which provides high accuracy and processing flexibility. However, its bottleneck remains the beam positioning speed, limited by the inertia of galvanometer-based scanners. This work proposes a hybrid control method for microvia laser drilling that combines a galvanometer-based scanner and an acousto-optic deflector. The set of vias is pre-partitioned into clusters so that all vias within each cluster can be processed by the acousto-optic deflector inside its deflection field without involving the galvanometer. Cluster centers are then connected by a minimal trajectory computed using a combination of a greedy algorithm and the pairwise exchange method (2-opt) which minimizes the total travel length of the galvanometer and the overall drilling cycle time. This approach enables coordinated use of the high-speed acousto-optic deflector for local processing and the long-range galvanometer for movements between clusters. Implementation of the proposed method reduced the galvanometer travel length from 3,097.05 mm to 1,674.19 mm and decreased the total processing time by more than a factor of 3.3 compared with traditional approaches. The effect is achieved by minimizing the number of large inertial moves and shifting a portion of the motion tasks to the high-speed acousto-optic deflector. Unlike known approaches that optimize a single traveling salesman problem route over all vias, the proposed method realizes a hierarchical routing scheme. Classical methods minimize route length but do not account for the dynamic limitations of the galvanometer which leads to excessive inertial moves. Pure acousto-optic deflector based systems provide very high speed but are limited by a small deflection field. The hybrid approach combines advantages of both technologies: the acousto-optic deflector delivers high-speed processing within clusters, while the galvanometer performs efficient transitions between them. The method requires no substantial hardware modifications, can be integrated into existing control systems, and is adaptable to microprocessing of glass substrates (for through glass vias) for 2.5D and 3D packaging architectures.

### Keywords

deflector, greedy algorithm, laser drilling, clusterization, path optimization

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## Минимизация времени пассивных векторов при лазерном сверлении микроотверстий в ABF-диэлектриках

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**Аннотация**

**Введение.** Производство печатных плат является ключевым направлением современной электронной промышленности, где особое значение имеет повышение производительности операций сверления микроотверстий. Одним из эффективных решений является применение безмасочной лазерной технологии, обеспечивающей высокую точность и гибкость обработки. Вместе с тем основной проблемой остается скорость позиционирования лазерного луча, ограниченная инерционностью гальванометрических систем.

**Метод.** Предлагается гибридный метод управления процессом сверления микроотверстий, сочетающий гальванометрическую систему и акустооптический дефлектор. Множество отверстий предварительно разделяется на кластеры так, чтобы все отверстия внутри каждого кластера могли быть обработаны акустооптическим дефлектором в пределах его поля отклонения без участия гальванометра. Центры кластеров соединяются минимальной траекторией, рассчитанной с помощью комбинации жадного алгоритма и метода парного обмена, что минимизирует суммарную длину перемещений гальванометра и общее время цикла сверления. Такой подход обеспечивает координированное использование быстродействующего акустооптического дефлектора для локальной обработки и дальнедействующего гальванометра для перемещений между кластерами.

**Основные результаты.** Реализация предложенного метода позволила сократить длину траектории движения гальванометра с 3097,05 до 1674,19 мм, а суммарное время обработки — более чем в 3,3 раза по сравнению с традиционными методами. Эффект достигается за счет минимизации числа крупных перемещений и переноса части операций на быстродействующий акустооптический дефлектор. **Обсуждение.** В отличие от известных подходов, основанных исключительно на решении задачи коммивояжера для всех отверстий, предложенный метод реализует иерархическую схему маршрутизации. Традиционные методы минимизируют длину траектории, но не учитывают ограничения динамических характеристик гальванометра, что ведет к избыточным инерционным перемещениям. Альтернативные системы, использующие только акустооптический дефлектор, обеспечивают высокую скорость, но имеют ограниченное поле отклонения. Гибридный подход сочетает преимущества обеих технологий: акустооптический дефлектор обеспечивает высокоскоростную обработку внутри кластеров, а гальванометр — эффективное перемещение между ними. Методика не требует значительных аппаратных модификаций и может быть внедрена в существующие системы управления, а также адаптирована к микрообработке стеклянных подложек для 2,5D- и 3D-архитектур.

**Ключевые слова**

дефлектор, жадный алгоритм, лазерное сверление, кластеризация, оптимизация пути

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**Introduction**

Printed Circuit Board (PCB) manufacturing, particularly for high-density multilayer modules, represents a cornerstone of the modern electronics industry. It underpins such critically important sectors as telecommunications, high-performance computing, artificial intelligence systems, and consumer electronics. Increasing requirements for precision, mounting density, and processing speed are driving the development of laser micromachining methods among which maskless laser drilling occupies a leading position due to its flexibility, accuracy, and elimination of chemical reagents [1].

This technology is especially relevant in the production of processor boards, where Ajinomoto Build-up Film (ABF), a multilayer polymer film for PCB assembly, is used as the primary dielectric material. This material possesses low dielectric permittivity, high stability, and compatibility with thin-film metallization, making it the standard for processor boards from Intel, Advanced Micro Devices as well as for server, graphics, and telecommunications devices. Typical characteristics, such as layer thickness (20–40  $\mu\text{m}$ ), mechanical strength, and thermal resistance, can be found, for example, in the Ajinomoto GX92R/GX92<sup>1</sup> specifications.

<sup>1</sup>Ajinomoto Build-up Film product data sheet. Available at: [https://www.aft-website.com/en/products/insulating\\_film-abf/](https://www.aft-website.com/en/products/insulating_film-abf/) (accessed: 15.09.2025).

For drilling microvias in ABF layers, nanosecond lasers with wavelengths of 343 nm or 355 nm are traditionally used, since at these wavelengths the material demonstrates high absorption coefficient, allowing radiation to be focused into a spot on the order of 10  $\mu\text{m}$ . Typical via dimensions range from 2  $\mu\text{m}$  to 60  $\mu\text{m}$  [2–4]. Although CO<sub>2</sub> laser radiation (10.6  $\mu\text{m}$ ) is also well absorbed, its focusing to micron sizes is technically difficult.

Current trends in microelectronics, particularly in High-Density Interconnect packaging, impose increasingly stringent requirements on laser processing resolution. In this regard, considerable attention is paid to picosecond laser ablation technologies which enable the formation of microvias with diameters less than 7  $\mu\text{m}$  even in non-polymer dielectrics without photosensitive additives. For instance, study [5] presents results of applying a picosecond ultraviolet laser with a wavelength of 355 nm and pulse duration of 5 ps which produced vias with diameters less than 7  $\mu\text{m}$  in 5–7  $\mu\text{m}$  layers of ABF and PLS-S connectors. This became possible due to high repetition rate (80 MHz) and minimal thermal impact on the polymer, making this approach promising for mass production of next-generation microvias meeting the requirements of 2.5D interposers and fan-out boards.

Modern quality requirements for vias assume their conical shape, ensuring reliable subsequent copper deposition without defects. For this purpose, strict control of the via profile during drilling is necessary. Typically, 10 to 150 laser pulses are consumed per via, which at repetition

rates from 0.5 to 4 MHz<sup>1</sup> corresponds to processing time of one via from 2 to 300  $\mu\text{s}$ . Moreover, the use of lasers with burst mode (nanosecond pulse bursts) allows drilling vias in 2–10 pulse bursts, further reducing total processing time [6]. However, at high via density, the main factor limiting productivity becomes not the active laser processing time, but the passive time — the beam positioning time between vias. It is determined not only by the movement time but also by the stabilization time of the mechanical subsystem.

The objective of this work is to develop a method aimed at substantially reducing passive movement time (inertial vectors) while maintaining high precision of formed vias.

### Object of the study

For forming vias with high precision, three-level scanning systems are used: motorized platform for macro-level movements up to  $2000 \times 2000$  mm; galvanometer scanner, for example, ScanLab Intelliscan 14, which is an industry standard, for movements within  $200 \times 200$  mm with acceleration up to 5000 g and speed up to 10 m/s<sup>2</sup>; Acousto-Optic Deflector (AOD), for example, Isomet D1384-XY-aQ170-7, providing inertia-free submicrosecond positioning over a field up to  $300 \mu\text{m}^3$  (Fig. 1).

It should be emphasized that for galvanometer scanners, the positioning time for small distances is determined by the Small Step Response Time parameter and ranges from 0.45 to 3 ms, which is tens and hundreds of times greater than the actual drilling time of one via. This makes the task

of optimizing movements critically important for dense via structures.

Before formulating our optimization problem for laser beam movement during microvia drilling, it is appropriate to review existing approaches to minimizing processing time. One common direction is minimizing the travel distance between vias which corresponds to the Traveling Salesman Problem (TSP). This problem is widely studied in the context of automated drilling of holes in PCBs, where routing of the drilling tool is performed by a Computer Numerical Control system. The literature describes numerous approaches to solving this problem. For example, work [7] proposes a heuristic hybrid algorithm for reducing the total drilling tool path length. A mathematical model for estimating total processing time is also presented, accounting for both the length of movements between vias and the effect of stacking multiple boards. The authors show that effective solution of the routing problem can significantly increase productivity; however, increasing the number of simultaneously processed boards does not always lead to improved performance: there exists an optimal number of boards in the stack, exceeding which reduces efficiency.

A broader review shows that both classical heuristics and modern metaheuristic methods are applied to minimize the path length between vias. In particular, such algorithms as Simulated Annealing, Genetic Algorithms, Particle Swarm Optimization, Ant Colony Optimization (ACO), Harmony Search, Cuckoo Search, as well as their hybrid combinations have been used [8]. Application of these methods allows not only to minimize tool movement time but also to integrate constraints related to thermal deformations, technological features of microvia drilling, and precision requirements.

Furthermore, in modern Computer-Aided Process Planning and Computer-Aided Manufacturing platforms, the application of Artificial Intelligence algorithms and open control architectures based on G-codes is actively investigated [9, 10], which opens additional possibilities for adaptive real-time optimization of the drilling route.

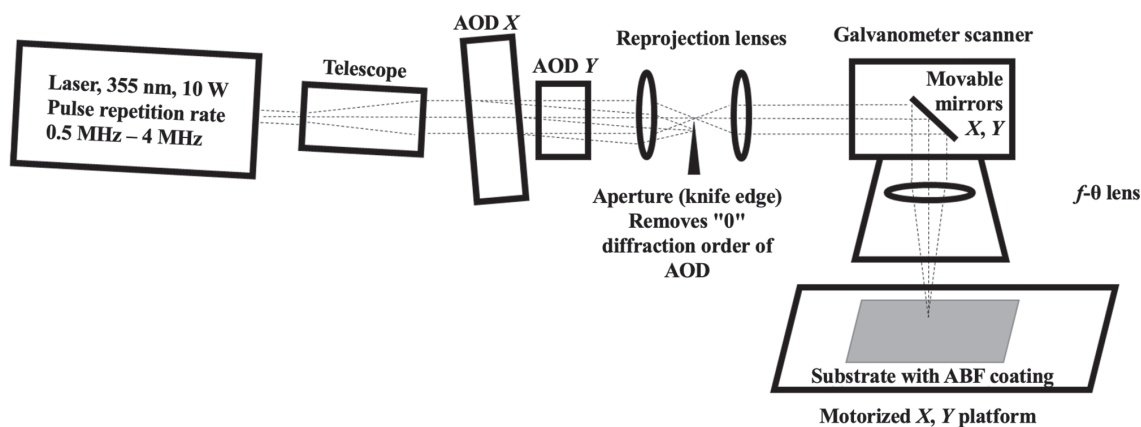


Fig. 1. Schematic of the laser via drilling process in a hybrid positioning system, including a motorized platform along X and Y axes, galvanometer scanner, AOD, and reprojection optical system. During reprojection, an aperture is used that cuts off the zero diffraction order arising on AOD gratings. Beam focusing onto the PCB with ABF coating is performed using an  $f$ - $\theta$  ( $f$ -theta) lens (a scan lens that provides an approximately linear mapping between the scan angle  $\theta$  and the focused spot position in the working plane, with proportionality close to the effective focal length,  $f$ )

Although the aforementioned works do not directly address microvia drilling in ABF polymer dielectric, they emphasize the key role of tool movement strategy in achieving high productivity.

The objective of this work is to develop and verify a hybrid methodology for controlling the laser microvia drilling process in ABF structures, aimed at substantially reducing passive movement time (inertial vectors) while maintaining high precision of the formed vias. Within this objective, the following tasks are set: to formalize and implement a via clustering algorithm considering the AOD field of view; to develop a method for global planning of cluster center traversal (minimizing the total galvanometer path length) based on a combination of greedy algorithm and pairwise exchange (2-opt); to evaluate the influence of system parameters (AOD field size, galvanometer characteristics, via density) on productivity; and to confirm the effectiveness of the proposed approach through simulation and experiment using the example of drilling transition vias in ABF. As a practical benchmark, achieving significant reduction in cycle time and ensuring compatibility of the methodology with existing control systems and prospects for application in TGV 2.5D/3D technologies is set.

### Optimization of Laser Drilling Algorithm

Based on the critical literature review and the stated objective — reducing passive movement time during microvia drilling in ABF structures — this work develops a hybrid methodology [11] utilizing coordinated operation of an AOD and galvanometer.

In the optical part, the system is represented by a standard sequence: telescope matching beam size with AOD aperture; two-axis AOD providing inertia-free submicrosecond deflection [12, 13]; projection optics forming the AOD aperture image on the galvanometer mirror and eliminating the zero diffraction order; and  $f$ - $\theta$  lens for final focusing on the surface (Fig. 1).

Considering the limited AOD field of view and significant inertia of the galvanometer subsystem, the methodology formalizes the task as two-stage: first, the set of via coordinates is partitioned into clusters considering the AOD deflection field size and via radii (the condition for cluster membership is formalized through a connectivity matrix); then the centers of obtained clusters are used as nodes for global galvanometer routing (Fig. 2). Algorithmically, this is implemented through construction of a binary adjacency matrix for point pairs, extraction of subgraphs around vertices with maximum degree, exact search for maximum cliques in small subgraphs (to form relevant clusters), and subsequent route optimization along cluster centers by a combined method (modified greedy algorithm followed by 2-opt).

This scheme allows transferring a significant share of short, high-speed movements to the AOD, leaving the galvanometer only relatively rare long transitions, which substantially reduces total positioning time without changing hardware configuration. For quantitative evaluation of the proposed method effectiveness, a formula

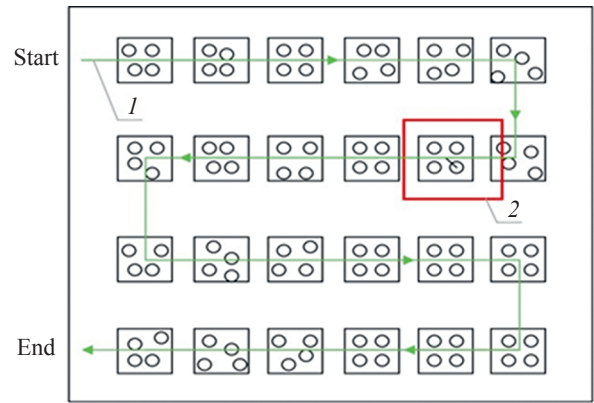


Fig. 2. The laser beam trajectory  $l$  passes through the centers of via clusters. Beam movement in region 2 is performed by the AOD, while transition from cluster to cluster is controlled by the galvanometer

is used for calculating total processing time during laser drilling:

$$T = \frac{l}{v} + n\Delta t, \quad (1)$$

where  $l$  is the distance that the laser beam travels when moving from one cluster to another using the galvanometer;  $v$  is the beam movement speed;  $n$  is the number of points;  $\Delta t$  is the time required for acceleration and deceleration of the electromechanical device (galvanometer) when passing from one point to another. For most galvanometers used in industry,  $\Delta t$  is on the order of 1 ms.

The formula assumes that the time required for drilling one via is significantly less than the transition time of the laser beam from one cluster to another. We deliberately do not account for time spent directly on the drilling process, since this parameter depends on the properties of ABF dielectric, via geometry, and laser parameters, and cannot be optimized by movement routing methods. As shown earlier, for ABF coatings, the drilling time for one via constitutes only fractions of a millisecond, which is an order of magnitude less than the positioning time between vias. Therefore, when solving the movement optimization problem, this term is excluded as a constant that does not affect relative comparison of different trajectory efficiencies. Thus, by minimizing the number of points (number of via clusters) and reducing route length, we can significantly decrease processing time.

Based on formula (1), the problem being solved can be divided into several subproblems: the task of clustering the set of vias with their partition into the minimum number of clusters and the task of minimizing path length.

For vias to belong to one cluster  $K$ , the following condition must be satisfied:

$$\forall_{j \in K} (|x_i - x_j| < [F_{AOD_x} - R_i - R_j]) \times (|y_i - y_j| < [F_{AOD_y} - R_i - R_j]), \quad (2)$$

where  $K$  is the set of vias belonging to one cluster;  $x_i$  and  $y_i$  are the coordinates of the center of the via with index  $i$ ;  $F_{AOD_x}$  and  $F_{AOD_y}$  are the sizes of the region within which

the laser beam can move using the AOD; and  $R_i, R_j$  are the radii of drilled vias.

We compose an elementary matrix  $\mathbf{M}$  of pairs  $(i, j)$ , in which values equal one if condition (2) for pair  $(i, j)$  is satisfied, otherwise equal zero.

$$\mathbf{M}_{i,j} = (|x_i - x_j| < [F_{AOD_x} - R_i - R_j]) \times \\ \times (|y_i - y_j| < [F_{AOD_y} - R_i - R_j]).$$

We consider  $\mathbf{M}$  as a graph, where unit elements of the matrix are vertices with edges  $(i, j)$ . Thus, our task can be reduced to the problem of partitioning the graph into the minimum number of clusters or cliques. A graph represents a network of interconnections between points that can be connected to each other. To solve the clique problem, an algorithm is used that begins with forming an adjacency matrix for the graph. This matrix is filled with zeros and ones, where each element indicates the presence or absence of an edge between corresponding graph vertices. The clique problem is a computationally complex task, especially when working with large graphs. In programming, working with graphs includes application of algorithms for data processing<sup>1</sup>, such as Breadth-First Search (BFS), Depth-First Search (DFS), topological sorting, Minimum Spanning Tree, Dijkstra's<sup>2</sup> algorithm, and others. Graph connectivity checking is performed by DFS or BFS algorithms, traversing all graph vertices and checking their accessibility. Algorithm execution time can significantly increase with a large number of vertices, on the order of 100 or more, making them inefficient. Therefore, a hybrid method was proposed: sequential search for the vertex with the maximum number of edges, extraction of the graph connected to this vertex, and finally, finding the maximum clique in this graph. The vertex with the maximum number of edges can be found as the element having the maximum column sum:

$$\max_i \sum_j \mathbf{M}_{i,j}.$$

Next, we extract submatrix  $\mathbf{G}$  (subgraph) from the graph associated with vertex  $i$ . Let  $\mathbf{M}$  be the graph adjacency matrix and  $\mathbf{V}$  be the set of vertices. Then the submatrix  $\mathbf{G}_i$  connected to vertex  $i$  can be expressed as follows:

$$\mathbf{G}_i = \{\mathbf{M}_{p,q} | p, q \in \mathbf{V}_i\},$$

where  $\mathbf{V}_i$  is the set of vertices connected to vertex  $i$ , and  $\mathbf{M}_{p,q}$  is the adjacency matrix element indicating the presence or absence of an edge between vertices  $p$  and  $q$ .

At the next stage, the vertices included in this graph form a new subgraph. Considering that the number of vertices in this subgraph is usually small, in practice it does not exceed 12, which allows using exact methods to find the maximum clique in this subgraph. To solve this task,

we apply the Bron-Kerbosch algorithm [14] which is one of the effective methods for searching all maximal cliques (clusters) in a graph. The algorithm begins by selecting a graph vertex, after which for each selected vertex, a recursive search for maximal cliques including this vertex is performed. Recursion continues as long as there exist vertices that can be added to the current clique. When this is no longer possible, the current clique is declared maximal.

After the maximum clique in the graph is determined, elements are removed from matrix  $\mathbf{M}$  (the main graph) that belong to this clique. The process is repeated until the graph consists of disconnected elements, that is, until the graph includes only single vertices.

The found cliques and single vertices are via clusters that can be processed by the AOD without galvanometer involvement. The region in which laser beam movement by the AOD occurs is bounded by a rectangle with vertices:  $(W_1, W_3), (W_2, W_3), (W_2, W_4), (W_1, W_4)$ , where:

$$W_1 = X_i - R_{x_i} \text{ и } W_3 = Y_i - R_{y_i}, \\ W_2 = X_i + R_{x_i} \text{ и } W_4 = Y_i + R_{y_i}.$$

Note that this region is deliberately smaller than  $F_{AOD_x}$  and  $F_{AOD_y}$ .

The cluster center  $(X_{t_k}, Y_{t_k})$  can be determined as:

$$X_{t_k} = \frac{\max(W_2) + \min(W_1)}{2}, \\ Y_{t_k} = \frac{\max(W_4) + \min(W_3)}{2}.$$

Cluster centers are points to which movement is performed using the galvanometer. At the next optimization stage, we connect these centers in such a way that the trajectory length is minimal (optimization of  $l$ ). This optimization stage was solved by a combination of methods: greedy algorithm [15] and 2-opt algorithm [16]. A modified greedy algorithm adapted to the asymmetry of the problem with predetermined start and end points and to board geometry is applied in the work. Unlike the classical "nearest neighbor" strategy, the criterion for selecting the next point considers not only distance but also direction of movement relative to the "start-end" line and a simple single-step estimate of remaining cost. The start and end points are preliminarily selected from candidate centers (cluster centroids) by a fast route quality heuristic considering directed movement of the motorized platform. This approach preserves the computational lightness of the greedy algorithm, forms a more oriented starting solution, and increases the effectiveness of subsequent local optimization by the 2-opt method.

2-opt method involves iteratively removing two edges from the route and replacing them with two other edges connecting the fragments created by edge removal into a new and shorter route. This method is effective for approximate solution of the Traveling Salesman Problem [17] and is often used in combination with other methods, such as the greedy algorithm, to obtain more accurate solutions.

<sup>1</sup> Available at: <https://www.hackerearth.com/practice/algorithms/graphs> (accessed: 15.09.2025).

<sup>2</sup> Available at: Dijkstra's Shortest Path Algorithm — A Detailed and Visual Introduction URL: <https://www.freecodecamp.org/news/dijkstras-shortest-path-algorithm-visual-introduction/> (accessed: 15.09.2025).

### Experimental Investigation of the Proposed Method

A numerical study of the effectiveness of the proposed hybrid methodology was conducted on a real processor PCB topology, in which the number of microvias  $N$  equals 12,200. The following equipment parameters were used in calculations: ScanLab Intelliscan 14 galvanometer (positioning time 0.2 ms for short movements up to a millimeter, used input beam aperture 8 mm), Isomet D1384-XY-aQ170-7 AOD (scanning angle 4.4 mrad, used input beam aperture 5 mm), 355 nm wavelength laser, and  $f$ - $\theta$  lens with focal length 250 mm. Comparative calculations were performed for four routing schemes: basic greedy algorithm; greedy algorithm with local 2-opt optimization; combined scheme with preliminary clustering and subsequent greedy planning; combined scheme with additional 2-opt application. Results are presented in Tables 1–4 and Fig. 3.

Analysis shows that the main reduction in total time is achieved through clustering, i.e., transferring short fast movements to the AOD and reducing the number of inertial galvanometer transitions. At  $F_{AOD_x}, F_{AOD_y}$  equal to 0.8 mm, total processing time was reduced by approximately 3.6 times compared to the basic greedy

algorithm; application of 2-opt additionally decreased time by about 10–15 % (Table 1). The optimized trajectory length decreased from 3,097 mm to 1,120 mm with the combined method with 2-opt. Tables 3 and 4 demonstrate strong dependence of processing time on two factors: AOD field size and galvanometer positioning time. Increasing the AOD field from 0.1 mm to 1.6 mm leads to about 15-fold reduction in the number of clusters (Table 2) and to multiple reduction in time  $T$  at fixed positioning time (up to 8 times at positioning time 0.8 ms), which indicates the importance of using broadband AODs [12]. The best numerical indicators are observed with AOD field size more than 0.3 mm and  $t$  less than 0.4 ms; in this regime, cycle time reduction of more than 3 times relative to the original variant is achieved, and at optimal parameters — up to 40 times compared to the baseline scenario.

### Discussion

The proposed method fundamentally differs from classical approaches operating with global TSP optimization over all vias. The key difference lies in physically justified task decomposition: the AOD field of view is introduced as a constraint when forming clusters, and routing is reduced to a two-level problem — local processing within

Table 1. Results of comparative analysis of laser drilling trajectory optimization algorithms

Algorithm	AOD field, mm	Positioning time, ms	Number of clusters	Number of microvias	Laser drilling time, s	Length, mm	Increased productivity
Greedy algorithm	0.8	0.2	—	12,200	5.537	3,097.05	1.0 (baseline)
Greedy algorithm + 2-opt	0.8	0.2	—	12,200	5.185	2,744.80	1.07
Clustering + greedy algorithm	0.8	0.2	1,356	12,200	1.535	1,263.45	3.60
Clustering + greedy algorithm + 2-opt	0.8	0.2	1,356	12,200	1.392	1,120.49	3.98

Table 2. Dependence of the number of clusters on AOD field size

AOD field, mm	Number of clusters	Movement Reduction, %
0.1	12,128	0.6
0.2	10,579	13.3
0.3	3,685	69.8
0.8	1,356	88.9
1.6	793	93.5

Table 3. Dependence of drilling time  $T$  (s) for the “Clustering + greedy algorithm + pairwise exchange” algorithm on AOD field and galvanometer positioning time

AOD field, mm	Positioning time, ms				
	0.2	0.4	0.8	1.6	3.2
0.1	5.178	7.603	12.454	22.157	41.562
0.2	4.730	6.846	11.077	19.540	36.467
0.3	2.411	3.148	4.622	7.570	13.466
0.8	1.392	1.663	2.205	3.290	5.460
1.6	1.053	1.211	1.528	2.163	3.432

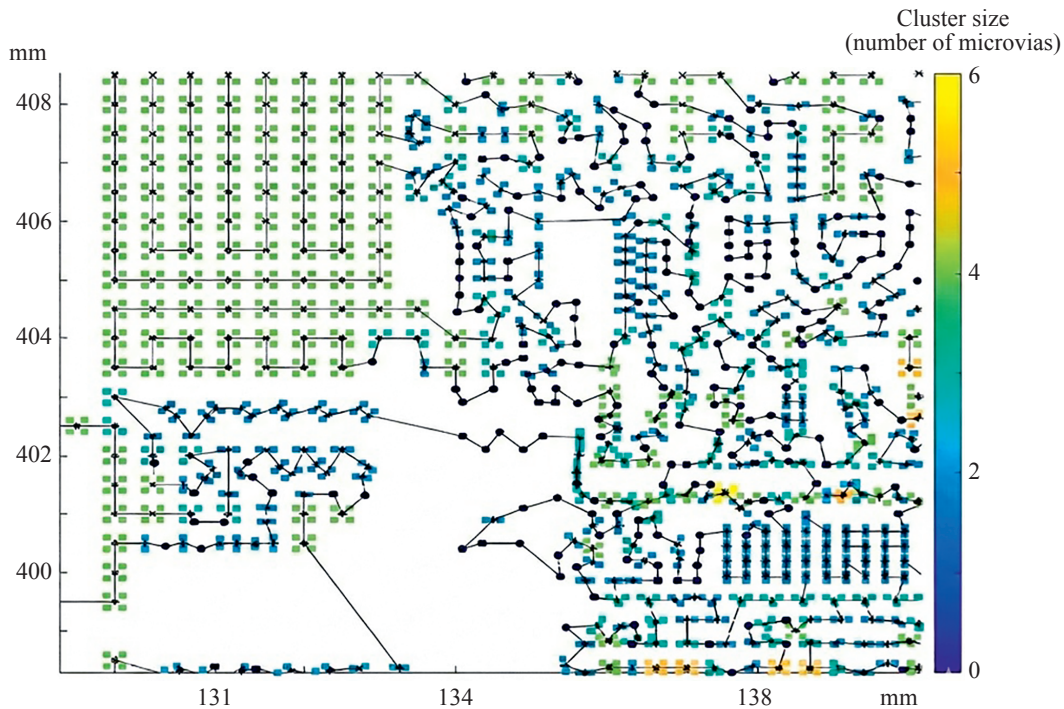


Fig. 3. Fragment of via arrangement on a processor PCB. Colors (color corresponds to the cluster size) denote via clusters processed within the AOD field; lines connect cluster centers and show the optimized (by 2-opt) galvanometer movement trajectory

Table 4. Dependence of galvanometer trajectory length on AOD field size, mm

AOD field	Trajectory length
0.1	2,752.16
0.2	2,614.14
0.3	1,674.19
0.8	1,120.49
1.6	894.02

clusters + global routing between cluster centers. Such hierarchy allows combining the advantages of high-speed inertia-free systems (AOD) and long-range galvanometers, unlike “pure” galvanometer schemes (limited by inertia) and “pure” AOD schemes (limited by deflection field).

Compared to common metaheuristic methods — such as simulated annealing, genetic algorithms, and ant colony optimization — that are often applied to non-clustered instances of the traveling salesman problem, the proposed methodology provides a better “solution time — route quality” ratio for industrial conditions where dynamic drive characteristics are critical. The combination of physical clustering with modified greedy start and subsequent 2-opt local optimization yields high-quality routes with substantially lower computational costs than global metaheuristics applied to the full set of points.

Experimental data confirms the practical value of the approach: with typical equipment parameters (AOD field size more than 0.3 mm, galvanometer positioning time less than 0.4 ms), a three-fold or greater reduction in cycle time compared to the traditional scheme is achieved. This makes the method attractive for integration into industrial CAD/

CAM systems without substantial hardware modernization. Prospects for further optimization are associated with adaptive adjustment of clustering parameters to local via densities and combined use of more advanced local optimizers with limited computational resources.

The developed methodology can be scaled and adapted to more modern micromachining tasks, such as forming Through-Glass Vias for IC packaging in 2.5D and 3D architectures [18–20]. High positioning precision and drilling time reduction are critically important when creating glass interposers with high connection density, especially in the areas of high-frequency electronics, optoelectronics, and System-on-Chip.

## Conclusion

The proposed methodology for optimizing laser beam trajectory during via drilling in printed circuit boards, based on via clustering and coordinated operation of galvanometer and acousto-optic deflector, has demonstrated high effectiveness. Conducted experiments showed reduction in beam travel length and processing time by more than 3.3 times, which contributes to significant productivity growth and production cost reduction. The hybrid approach, combining acousto-optic deflector precision in processing within clusters and high speed of galvanometer movement between clusters, ensures optimal coverage of large working areas.

Further development of clustering and routing algorithms, as well as expansion of the acousto-optic deflector field of view, will effectively adapt the proposed solution to Through-Glass Vias technology tasks, contributing to progress in manufacturing highly integrated electronic modules.

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