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Optimization of Electronic Components Mounting Sequence for 3D MID Assembly Process

A. E. Kurnosenko and D. I. Arabov

Bauman Moscow State Technical University, ul. Baumanskaya 2-ya, 5, Moscow, 105005 Russia

Abstract

This article considers the assembly technology of three-dimensional molded interconnect devices (3D MID). The problem of performance optimization for dispensing and component placement operations is explored. Optimization is assumed on the reduction of the auxiliary time of the dispensing/placement head and manipulator have to spend traveling through all component mounting positions. The problem is defined as the traveling salesman one. The article zeroed in distance/time matrix determination for dispensing/placement head and manipulator three-dimensional movements in the case of the selected kinematics diagram of the assembly equipment. Formulas for the determination of this matrix are proposed, formal description of the optimization problem is presented, and a brief review of problem-solving methods is described.

Corresponding Author:
A. E. Kurnosenko
akurn@bmstu.ru

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1. Introduction

The ongoing tendencies toward higher functional integration, miniaturization, and manufacturability of electronic devices lead to the emergence and development of new classes of mounting and interconnecting structures designed to replace traditional electronic modules on PCBs in some applications. One of these classes includes molded interconnect mounting structures manufactured through 3D MID technologies. These three-dimensional structures are manufactured by one- or two-component molding processes from different materials including thermoplastics, with the conductive pattern and contact pads subsequently formed on their surfaces for further electronic components placement. The core advantage of 3D MID structures is the integration of many functions in one construction element: case and mounting substrate, electro-magnetic shield, antenna, carrier for power, indication and control of elements, etc. Moreover, their free 3D-form allows for flexible adaptation to layout constraints. The realization of these functions in traditional design needs many separate and dissimilar structural components. A detailed description of 3D MID devices, their applications, manufacturing technologies and equipment is given, for example, in [1, 2, 5, and 6]. One of the typical examples of 3D MID devices is shown in Figure 1.

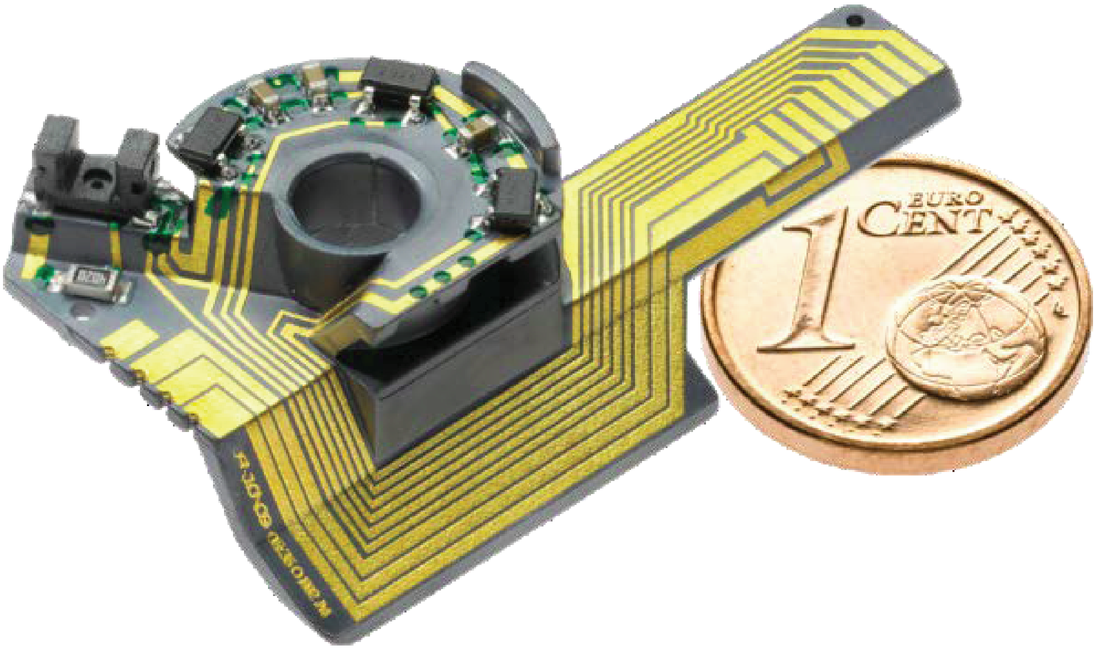

Figure 1: Position sensor for adaptive speed control (designed and manufactured by HARTING Mitronics [3]).

One of the features of 3D MID devices is the ability for surface mounting of almost any types of packaged and unpackaged electronic components – from chip components to ICs with many leads, BGA, CSP, flip chip components, wire bonding, etc. The main difference from traditional surface mount technology is the necessity for application of solder paste (by dispensing, jetting or pin transfer) and component placement on surfaces of free-form and 3D-orientation. As follows from the classification specified in [1] and [2], the traditional automated dispensing and placement equipment working with flat PCBs and other similar mounting structures can only work with 2D and (limitedly) 2½D ones, and for n x 2D and 3D structures, there is a need for mutual three-dimensional orientation of mounting base and dispensing/placement head in order to realize a scheme by which dispensing/placement operation is performed normal to the mounting plane (or to the surface tangent to it in case of curved surface). The additional restriction is the need to avoid the collisions of head and device during the mutual orientation of actuating mechanisms and assembled devices.

2. Materials and Methods

In the general case, there are many different electronic components to be mounted on 3D MID device. The performance of dispensing/placement operation will play the essential role in the case of a large quantity of mounted components and mass production of the device. This performance, in turn, depends on the auxiliary time the dispensing/placement head or coordinate table with the fixed device have to spend traveling through all component-mounting positions.

Provided constant speed of the movement of actuating mechanisms, the spent time will be linearly dependent on the total length of the route that the dispensing/placement needs to travel. Let us take this assumption for the further definition of the problem.

Thus, the problem of the mentioned operation will be considered as the optimization of the length or time of the dispensing/placement route. This problem in the linear programming usually is defined as the traveling salesman one [4]. The detailed formulation and solution of this problem for 2D surface mounting of electronic components is performed in many works, in particular [4, 7]. In this article, the traveling salesman problem is applied to the case of three-dimensional locations of components.

3. Problem Definition for Dispensing/Placement Route Optimization

In the general case, the problem is defined as follows: a traveling salesman that leaves the initial town must visit each of the other n-1 towns once and after that, return to the initial one. The distance matrix is known. It is required to find a route of sequential travel between towns wherein the salesman's total travel distance is minimal.

In terms of the dispensing/placement operation, this problem may be formalized as follows.

The travelling salesman is a set of working together dispensing/placement heads that sequentially travel through all *n* towns (placement positions) $P_i, i = \overline{1 \cdots n}$, structure on it that sequentially aligns placement position of each component $P_i, i = \overline{1 \cdots n}$ in the XY plane (e.g., a head works out a linear displacement in the XY plane, rotation around the OZ axis, and a manipulator aligns the placement of the surface by angles to attain parallelity of the XY working plane by the placement equipment), where *n* represents a quantity of components to be placed. In the 2D-case, the manipulator usually does not move, and travel in the XY-plane is carried out only by the dispensing/placement head.

Each town corresponds to the matrix that consists of footprint center coordinates for component *i* on the mounting substrate: $L_i^{\pi\pi} = \begin{bmatrix} x_i \\ y_i \end{bmatrix}$ – for towns on the plane surface, $L_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}$ – for towns in three-dimensional space. A town with index 0 corresponds to the initial location of an actuating mechanism.

4. Determination of a Distance Matrix for Three-dimensional Problems

The main difference between the 2D- and 3D-traveling salesman problems will be in the determination of a distance matrix between the towns $D = \begin{bmatrix} d_{00} & d_{01} & \cdots & d_{0n} \\ d_{10} & d_{11} & \cdots & d_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ d_{n0} & d_{n1} & \cdots & d_{nn} \end{bmatrix}$ with dimensions of *n* x *n*. Each element of this matrix defines the «quickness» of movement from one town to another, and their values depend on the kinematics diagram of selected assembly equipment.

For the 2D-problem, elements of the matrix represent the shortest distance between two center points of component placement positions on the XY plane (consider that X and Y movements are performed simultaneously):

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}.$$

Assuming that placement head is equipped with *n* pickup devices for components, and it does not need to return to component feeders during the travel between placement positions, let us switch from a distance matrix *D* to a time matrix D', the elements of which d'_{ij} represent the times spent on travelling from position P_i to position P_j with defined speed of linear movement of the dispensing/placement head: $d'_{ij} = \frac{d_{ij}}{V_{XYh}}$, where V_{XYh} – linear movement of dispensing/placement head in the XY plane (consider equal speeds of X and Y movements).

In the case of a 3D-problem, it is possible to realize several kinematics depending on the equipment used. Among typical kinematics diagrams of assembly equipment that were examined in [1, 2, 5, 7], we chose the following versatile diagram, often used for large-scale production of 3D MID devices (Figure 2): a component is picked up and transferred to the XY plane (along X and Y axes), by height (along the Z axis) and angle γ (around the Z axis) by means of placement head, the dispensing head is moving in the same way, and the missing degrees of freedom are provided by the automated manipulator or work carrier with a fixed 3D MID device that is to be assembled. The manipulator (work carrier) is able to rotate by angles α (around the X axis) and β (around the Y axis). Some manipulators have an additional capability of moving along the Z axis.

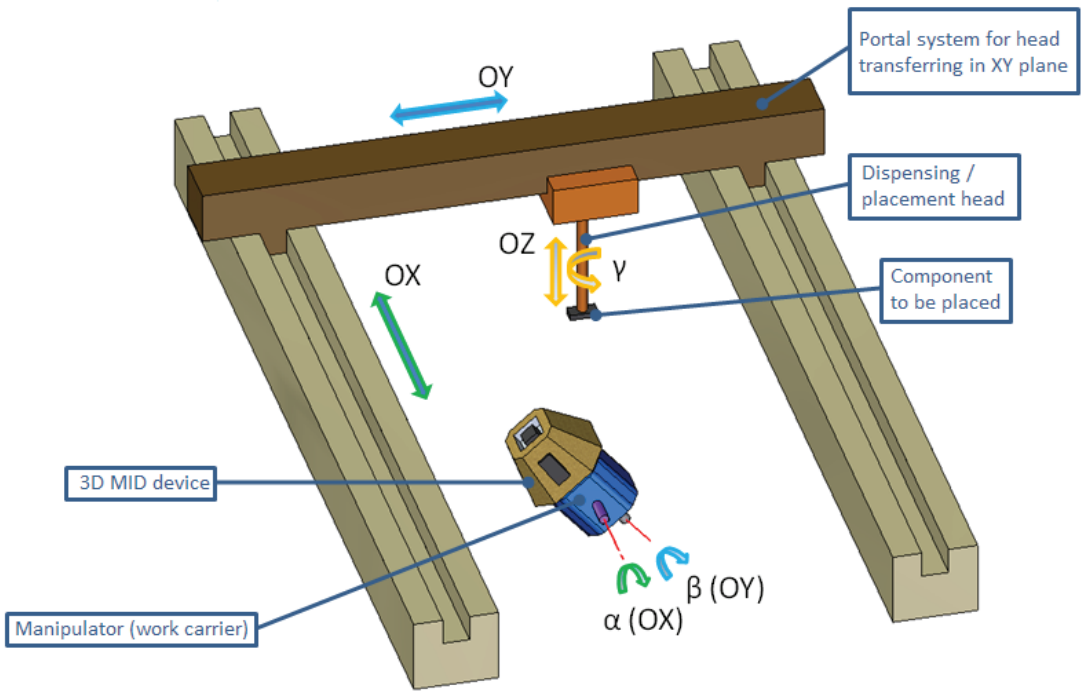

Figure 2: Kinematics diagram of automated equipment for dispensing/component placement on 3D MID devices.

Let us define matrixes that contain rotation angles of the actuator mechanism around the Cartesian axes of the assembly equipment. It is necessary to define a transfer between already aligned placement positions of two components in 3D space.

Let $\overline{OP_i}$ be a vector connecting the point of origin of the equipment and the footprint center of component P_i in an aligned position where the mounting (or tangent to it) plane for this component is parallel to the X and Y axes and an angle between the main axis of the component body and the X axis is 0° (component dispensing/placement position aligned along all axes). Then the angles α_{ij}, β_{ij}, γ_{ij} are such angles by which is necessary to rotate the projections of vector $\overline{OP_i}$ onto the corresponding planes so that the mounting (or tangent to it) plane for component P_j will also become aligned along all axes. The corresponding rotation matrixes are as follows:

$$A=\begin{bmatrix}\alpha_{00} & \alpha_{01} & \cdots & \alpha_{0n}\\ \alpha_{10} & \alpha_{11} & \cdots & \alpha_{1n}\\ \cdots & \cdots & \cdots & \cdots\\ \alpha_{n0} & \alpha_{n1} & \cdots & \alpha_{nn}\end{bmatrix}, B=\begin{bmatrix}\beta_{00} & \beta_{01} & \cdots & \beta_{0n}\\ \beta_{10} & \beta_{11} & \cdots & \beta_{1n}\\ \cdots & \cdots & \cdots & \cdots\\ \beta_{n0} & \beta_{n1} & \cdots & \beta_{nn}\end{bmatrix}, C=\begin{bmatrix}\gamma_{00} & \gamma_{01} & \cdots & \gamma_{0n}\\ \gamma_{10} & \gamma_{11} & \cdots & \gamma_{1n}\\ \cdots & \cdots & \cdots & \cdots\\ \gamma_{n0} & \gamma_{n1} & \cdots & \gamma_{nn}\end{bmatrix} \quad (1)$$

These matrixes are defined by the geometry of the 3D MID device, may be calculated based on this geometry and are included in the initial data for the problem.

The resulting coordinates x_j, y_j, z_j after rotation of the actuating mechanism from the aligned position of component P_i to component P_j in an aligned position will be determined using rotation matrixes (1) around the X, Y and Z axes:

$$M_{OX}(\alpha)=\begin{bmatrix}1 & 0 & 0\\ 0 & \cos\alpha & -\sin\alpha\\ 0 & \sin\alpha & \cos\alpha\end{bmatrix}, M_{OY}(\beta)=\begin{bmatrix}\cos\beta & 0 & \sin\beta\\ 0 & 1 & 0\\ -\sin\beta & 0 & \cos\beta\end{bmatrix},$$
$$M_{OZ}(\gamma)=\begin{bmatrix}\cos\gamma & -\sin\gamma & 0\\ \sin\gamma & \cos\gamma & 0\\ 0 & 0 & 1\end{bmatrix}. \quad (2)$$

Let us take the following sequence of rotations: OX → OY → OZ, at which we will get the coordinate values after rotations considering (2):

$$L_j^{OX}=M_{OX}(\alpha_{ij})\times L_i=\begin{bmatrix}x_j^{OX}\\ y_j^{OX}\\ z_j^{OX}\end{bmatrix}, L_j^{OY}=M_{OY}(\beta_{ij})\times L_j^{OX}=\begin{bmatrix}x_j^{OY}\\ y_j^{OY}\\ z_j^{OY}\end{bmatrix},$$
$$L_j^{OZ}=M_{OZ}(\gamma_{ij})\times L_j^{OY}=\begin{bmatrix}x_j^{OZ}\\ y_j^{OZ}\\ z_j^{OZ}\end{bmatrix}. \quad (3)$$

The element d_{ij} of the distance matrix will be summed up from the route section d_{ij}^{rot} that the center point has to travel during corresponding rotations of the actuating mechanism (a manipulator, work carrier – around X, Y axes and a head – around Z axis) and the route section d_{ij}^{lin} that this point has to travel in the XY plane and along the Z axis. The presence of this linear route section is caused by the offset of coordinates L_i and L_j^{OZ} after all rotations.

The angular route section of travel of the center point can be represented as $d_{ij}^{rot}=r\phi$, where ϕ – angle of rotation, r – radius, that is equal to a projection of rotating vector $\overline{OP_i}$ onto the plane that is normal to the rotation axis.

Then for rotation around X axis:

$$d_{ij}^{rot\ OX} = r^{OX}\alpha_{ij},\ \text{где}\ r^{OX} = \sqrt{(y_j^{OX})^2 + (z_j^{OX})^2}; \tag{4a}$$

around the Y axis:

$$d_{ij}^{rot\ OY} = r^{OY}\beta_{ij},\ \text{где}\ r^{OY} = \sqrt{(x_j^{OY})^2 + (z_j^{OY})^2}; \tag{4b}$$

around the Z axis:

$$d_{ij}^{rot\ OZ} = r^{OZ}\gamma_{ij},\ \text{где}\ r^{OZ} = \sqrt{(x_j^{OZ})^2 + (y_j^{OZ})^2}. \tag{4c}$$

The linear route section will be passed by the dispensing/placement head in the XY plane and along the Z axis, therefore the section d_{ij}^{lin} will be calculated as follows:

$$d_{ij}^{lin} = d_{ij}^{lin\ OX} + d_{ij}^{lin\ Z},$$

where

$$d_{ij}^{lin\ OX} = r^{OZ} = \sqrt{(x_j^{OZ})^2 + (y_j^{OZ})^2}; d_{ij}^{lin\ OZ} = |z_j^{OZ} - z_i| \tag{4}$$

Note that for the different radii of rotation, the routes traveled by the center point during the rotation by one angle will also be different. In terms of performance optimization, this is not correct. Therefore, let us turn from a distance matrix D to a time matrix D', of which elements d'_{ij} represent the time spent on travel from position P_i to position $P - j$ with defined linear and angular speeds of the movements of actuating mechanisms.

Then

$$d_{ij}^{rot\ OX'} = \frac{\alpha_{ij}}{\omega_{OXm}}, d_{ij}^{rot\ OY'} = \frac{\beta_{ij}}{\omega_{OYm}}, d_{ij}^{rot\ OZ'} = \frac{\gamma_{ij}}{\omega_{OZh}}, \tag{5}$$

where $\omega_{OXm}, \omega_{OYm}$ – angular speeds of manipulator (work carrier) rotation around the X and Y axes correspondingly, ω_{OZh} – angular speeds of assembly head rotation around the Z axis;

$$d_{ij}^{lin'} = d_{ij}^{lin\ OX'} + d_{ij}^{lin\ Z'}, d_{ij}^{lin\ OX'} = \frac{d_{ij}^{lin\ OX}}{V_{XYh}}; d_{ij}^{lin\ OZ'} = \frac{d_{ij}^{lin\ OZ}}{V_{Zh}} \tag{6}$$

where V_{XYh}, V_{Zh} – linear speeds of dispensing/placement head movement in the XY plane and along the Z axis correspondingly.

Thus, in the general case, the elements of a time matrix D' that represent the times spent on travel from position P_i to position P_j will be calculated considering (5), (6) and (7) as follows:

$$d'_{ij} = \frac{\alpha_{ij}}{\omega_{OXm}} + \frac{\beta_{ij}}{\omega_{OYm}} + \frac{\gamma_{ij}}{\omega_{OZh}} + \frac{\sqrt{(x_j^{OZ})^2 + (y_j^{OZ})^2}}{V_{XYh}} + \frac{|z_j^{OZ} - z_i|}{V_{Zh}}. \tag{7}$$

Let us also define a matrix $T = \begin{bmatrix} t_{00} & t_{01} & \cdots & t_{0n} \\ t_{10} & t_{11} & \cdots & t_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ t_{n0} & t_{n1} & \cdots & t_{nn} \end{bmatrix}$ with dimensions of *n* x *n*, the elements of which

$$t_{ij} = \begin{cases} 1, \text{ if the route contains a path from position } P_i \text{ to position } P_j; \\ 0 \text{ otherwise.} \end{cases}$$

At the same time, any plan of the problem unambiguously defines the *T* matrix.

5. Problem Formalization

As a result, let us formulate the mathematical model of the traveling salesman problem as follows:

$$\sum_{i=1}^{n} \sum_{j=1}^{n} d'_{ij} t_{ij} \to \min$$

provided

$$\begin{cases} \sum_{i=1}^{n} t_{ij} = 1; \\ \sum_{j=1}^{n} t_{ij} = 1; \\ j = 1, 2 \cdots n; \\ t_{ij} = 0; 1 \forall i, j, \end{cases} \tag{8}$$

time matrix D' with elements d'_{ij} calculated by formula (8) and by additional constraints imposed to the problem which relate to the requirement of simple connectedness of the route: $\nexists T^{(k)}$, that:

$$\begin{cases} \sum_{i=1}^{k} t_{ij}^{(k)} = 1; \\ \sum_{j=1}^{k} t_{ij}^{(k)} = 1, \end{cases} \tag{9}$$

where $T^{(k)}$ is any *k* x *k* – dimensional submatrix of matrix *T* that is separated from it by the selecting of corresponding rows and columns after the selection of *k* diagonal elements of matrix *T*. Without such a limitation, there is a possibility of appearance of not one but two or more routes that include only a partial amount of towns.

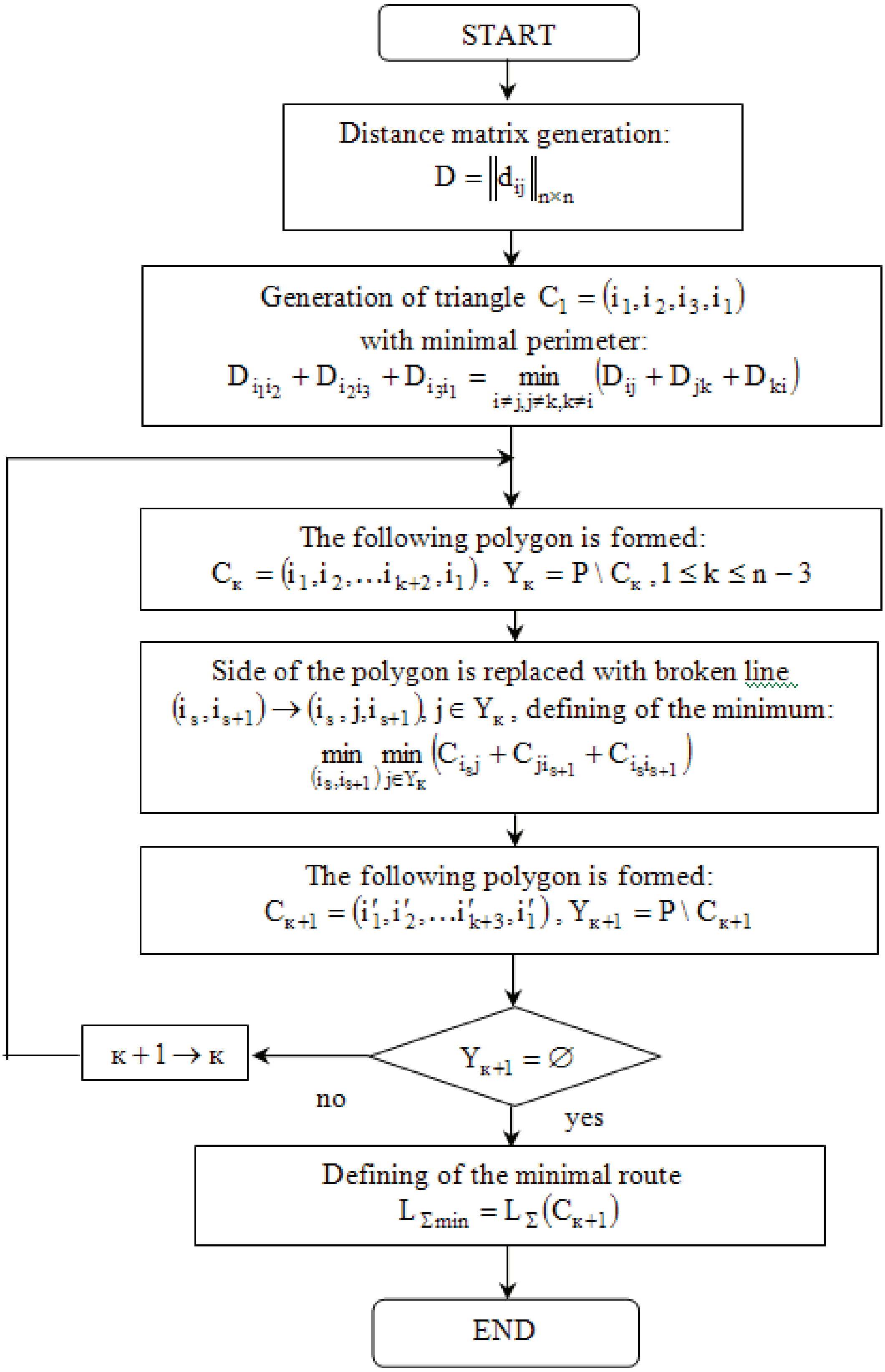

Figure 3: The algorithm of the polygon method for the optimization of the component placement sequence on PCBs.

6. Results and Discussion

There are some heuristic methods that are used to solve the traveling salesman problem. These methods require an acceptable number of operations, but they do not always give an optimal solution [4, 7, 8].

In project [7], four methods were considered:

- Hungarian method with a following stitching of the cycles;
- nearest-neighbor method;
- nearest-neighbor method with local optimization; and
- polygon method.

The algorithm of the polygon method is presented in Figure 3.

The polygon method showed the best performance among the aforementioned methods for solving a prepared set of 21 typical plane-traveling salesman problems. This method was chosen for the calculation of component placement sequence optimization problem-solving and it became the underlay of created application software [7], which is approved for developing switching 3D payments of processing of signals for pressure sensors [9].

7. Conclusions

In this article, the formalization of the traveling salesman problem for 3D MID devices assembly was carried out. The estimation of the mentioned method, among others, in application to the formalized three-dimensional problem of dispensing/component placement on 3D MID devices will be done in the subsequent articles.

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