Integrated algorithm for elements placement on the printed circuit board

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Abstract. The paper discusses one of the priority design problem – the placement of elements on the printed circuit board (PCB). It relates to the NP-hard class of discrete optimization problems. The paper describes the placement problem and provides its formal statement. A complex criterion considers critical connections and total length of connections. The connection graph is selected to simulate the placement problem. To respond effectively to the challenge, there is proposed a heuristic for isolating the connected fragments of the graph model as building blocks. The developed integrated algorithm based on genetic, evolutionary and ant search strategies is organized hierarchically. This algorithm obtains quasi-optimal solutions in polynomial time, as well as parallelize the search process and partially eliminate the preliminary convergence problem. In order to conduct experiments, a software realization of the integrated algorithm has been developed. A series of tests and experiments clarify theoretical estimates of the time complexity and behavior of the developed algorithm for various structures of schemes. The time complexity has been represented by $O(n\log n)$ at the best case and $O(n^3)$ in the worst case.

1. Introduction

At present, the development of electronic technology market has become a significant step for forecasting the possible financial risk as reflected in the manufacture of a new product. The design of complex computing is characterized by high dimensionality of tasks, the large number of alternative solutions, as well as the need to accommodate various quality criteria [1–4].

The steady increase in response time and the elements’ base requires changes in a design of complex computing devices. Stricter requirements for electrical parameters of interconnects and noise immunity led to the development of more advanced mathematical models, methods and algorithms.

The most important stage in the design cycle is a topological design at which the following tasks are solved: a partitioning, a placement, a routing, a packaging and a verification [1]. These tasks are NP-complete [3]. Among them, the elements placement is the most problematic issue, because require a processing of vast amount of information. In today’s modern trends in the IT development of existing automated design algorithms cannot solve this problem or require a lot of CPU time to find effective solutions. In view of the great complexity and dimensionality of this task and emerging new trends for manufacturing of complex computing devices, there is a need to develop novel approaches, methods and algorithms to deal with this class of problems. One such approach is the development of integrated algorithms based on simulation of natural systems behaviour.
2. Problem formulation

The placing of elements on the PCB belongs to the class of NP-hard problems. For such problems it is impossible to create algorithms with polynomial computational complexity which can obtain an exact solution [6-10].

Let us formulate the placement problem in general. Input data is [2, 3]: a rectangular construction (a cell, a panel, a grid, a bar); a PCB description - a number of positions that was obtained at the previous design stage (partitioning); an element description – a form, measurements, a terminals location; a netlist defining the module interconnections.

Let us set elements and its position on the PCB. \( A = \{a_i| l = 1,2, \ldots, M\} \) is a set of elements on the PCB. Each element \( a_i \) has its contour description \( k_i \in K \) on the plane. Each \( k_i \in K \) has a base point \( O_i^\delta \) and relevant coordinates \( O_i^\delta x_i^\delta \) and \( O_i^\delta y_i^\delta \) for set a contour description of \( a_i \). A list \( C_i = \{c_{il}| l = 1,2, \ldots, M; i = 1,2, \ldots, M\} \) is of coordinates, where \( c_{il} = (x_{i1}, y_{i1}) \) are coordinates of the first output of the \( a_i \) elements. As for the PCB, the basic coordinate axes Ox, Oy and the point O (the center of the coordinate system) are specified the mounting-switching field. Each position is characterized by \( P_j = \langle x_j, y_j, w_j \rangle \), where \( x_j \) and \( y_j \) are coordinates of a point on the PCB, \( w_j \in \Omega \), \( w_j \) are possible orientations of elements relative to the coordinates on the PCB [4].

Let \( \Pi_j \) denotes position \( P_{ij} \), in which the \( a_i \) element can be placed, then \( U \cup \Pi_i = P, \Pi_i = \{p_{ij}| j = 1,2, \ldots, M\} \).

Let a restriction graph \( G(X,U) \) defines certain limits on the elements placement. The vertex \( x_{ij} \in X_i \) corresponds with the \( p_{ij} \) position to which the element \( a_i \) can be assigned. An edge between vertices exists if and only if elements \( a_{i1} \) and \( a_{i2} \) cannot be assigned to \( p_{i11} \in \Pi_i, p_{i22} \in \Pi_i \) position simultaneously due to geometrical restrictions.

Then, the placement problem is formally reduced to the determination of the optimal spatial placement of related elements (modules, fragments) with terminals (outputs) on the PCB according to the criterion G. It is necessary to minimize \( G \), i.e. so that the weight function is the smallest for all methods of identifying the vertices of the graph and the nodes of the grid.

3. Development of the integrated algorithm

Existing placement algorithms obtain results that are enough for practical purposes [4-6]. However, they do not solve the problem of modeling of the PCB. The authors propose to minimize the cost of connections between short nets. For this purpose, heuristics are proposed, which consist in representation of related fragments of the PCB graph model as building blocks formed by “short” nets. In terms of building blocks creation, the question of determining its size arises [5]. Heuristics that determine the required size of a building block do not exist. The authors propose to use the results of the previous stage of the design cycle – a partitioning. When building blocks sizes are determined, then they are placed taking into account the “long” nets and the “nested” elements placement into building blocks with regard to “short” nets.

To implement the suggested heuristic and effective solution of the placement problem, an integrated method based on modified genetic, evolutionary and ant algorithms is proposed [4-6].

The block diagram of the integrated placement algorithm (IA) is shown in the figure 1. The placement is carried out in four stages. At the first stage, the modified Ant Colony Optimization algorithm (ACO) is proposed for preliminary processing of input information. At the second stage, the coding of the initial population of alternative solutions are implemented on the basis of the PCB graph model. At the third stage, specific placement algorithms are implemented. Moreover, the calculation is carried out in two directions according to various criteria, such as the total length of connections and length of critical connection in the original scheme, as well as the complex additive criterion taking into account the length of critical connection and the total length of connections in the scheme.
At the last stage, the decoding of the placement problem solutions is performed. It implements adaptation to the external environment by decision maker (DM) in accordance with the integrated criterion.

Let us describe the structure and operation of the integrated algorithm steps in detail.

Blocks 1 – 3 describe the generation of the initial population for the placement problem, input of technological parameters and constraints: $N_{GA}$ is a number of GA iterations, $N_{max}$ is a number of IA iterations, $t$ is a current IA iteration, $N_{om}$ is a number of EA iterations, $Compl$ is the complex criterion for placement assessment.

In the Block 4 the decision maker selects a criterion for evaluating the placement effectiveness. If the criterion of the critical connection length is chosen, then the transition to Blocks 9–12 is carried out; otherwise, moving on to Blocks 5–7 is carried out.
In Blocks 5, 6 the genetic algorithm is implemented based on the criterion of the total length of the connections [7,8].

The search stop criterion (the number of iterations in the modified GA) is checked in the Block 7. If the stop criterion is reached, the ACO algorithm and a rapid evolutionary search are performed. Note, the obtained set of quasi-optimal solutions is estimated (Blocks 8, 20, 21), given only the criterion of the total length of connections. Critical connections in a switchboard graph model are defined in the Block 9. Here \( N_{Kr} \) is a number of critical connections, \( L_{Kr}(G) \) is a length of critical connections.

The modified ACO algorithm is implemented in Blocks 10-11 depending on the settings of input parameters. Note that, taking into account only the criterion of critical connections in the algorithm, it proceeds to blocks 17, 20 — the evaluation of the obtained set of quasi-optimal solutions. In the Block 12, the condition of stop criterion in the ACO algorithm is checked: whether all critical connections of the switchboard graph model have been executed. If the stop criterion is reached, a rapid evolutionary search is performed. The rapid evolutionary algorithm is executed with the mutation operators in Blocks 13-14. The condition of the stop criterion for the evolutionary search is checked in the Block 15 - whether all “completed” critical connections of the switchboard graph model have been executed. If the stop criterion is reached, the genetic algorithm is implemented or the obtained quasi-optimal solution is output (Blocks 20, 21). The criterion of the total length of connections is selected in the Block 16. The migration operator is implemented [8] and a new population is formed taking into account the solutions obtained in previous stages in Blocks 18-19.

The condition of the stop criterion for the integrated algorithm is checked in the Block 22. If the stop criterion is reached, the obtained quasi-optimal solution is output (Block 25). Otherwise, the search continues iteratively in accordance with the system settings (Blocks 23, 24).

4. Experiments
To demonstrate the effectiveness, as well as computational characteristics of the proposed algorithm, a software product was created. Let carry out series of experiments on IBM test circuits [9] by KraftWerk [10] and mPG [10] algorithms and an integrated algorithm. The dependences of the quality and time of operation of these algorithms are provided in figures 2 and 3.

![Figure 2. Dependence of operation time on IBM benchmarks](image1)

![Figure 3. Comparison of fitness function values on IBM benchmarks](image2)
5. Conclusion

The paper proposes the integrated algorithm for the placement problem, which allows to predict the placement one step ahead due to the selection of building blocks as groups of elements. This approach improves the placement accuracy and speed of the proposed algorithm. The result of the final placement depends on the graph scheme compression, the criterion for assessing the placement quality, the strategy of sequential or parallel search, as well as evolutionary and genetic operators. The implementation of such approach allows us to provide good initial solutions, reduce the search area, increase the search speed. The integrated placement algorithm analyses various model of switchboards. This approach parallelizes the optimization and obtains optimal and quasi-optimal solutions in polynomial time.

The developed integrated algorithm also partially solve the problem of premature convergence. A software environment has been developed in C++. A series of tests and experiments made it possible to clarify the theoretical estimates the time complexity of the placement algorithm and its behavior for switchboards with various structures. At best, the time complexity is represented by $O(n \log n)$, at worst - $O(n^3)$.

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