

## **An Integrated Approach to Optimal Three Dimensional Layout and Routing**

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### **Introduction**

This paper describes the combination of previously-developed component placement and routing algorithms into an integrated computational approach to product layout optimization. Previous work introduced simulated annealing-based algorithms for optimal component packing (Szykman and Cagan, 1995), constrained layout (Szykman and Cagan, 1997), and routing (Szykman and Cagan, 1996). These problems exhibit ill-behaved (multi-modal and discontinuous) objective function spaces, which were optimized with a simulated annealing-based algorithm (Kirkpatrick et al., 1983).

The utility of these algorithms has been demonstrated on a variety of problems, including the layout of electronic switching systems (Szykman, 1995), a cordless power drill (Szykman and Cagan, 1997) and components for a wearable computer (Campbell et al., 1995), as well as routing of a chemical production plant (Szykman and Cagan, 1996). The broad spectrum of product layout tasks in engineering includes other applications such as layout of HVAC equipment, automobile engine compartments, mechanical and electromechanical assemblies, and aerospace applications.

Cagan et al. (1996) showed how the algorithms were used to optimize the component placement and routing of a heat pump product for an industrial partner. That work illustrated how these design tools yield improvements over the standard approach of manual placement and routing by improving design objectives and significantly reducing the design time. The application of the layout and routing optimization tools in that problem was done sequentially, just as manual layout and routing are traditionally done.

In practice, routing is highly influential in determining the cost of the heat pump (as well as other products in general). We hypothesize that taking routing objectives into consideration during the component placement phase will significantly improve the quality and cost of the overall layout. This research was initiated with the goal of combining the layout and routing optimization algorithms into a single integrated approach to product layout, whereby the tasks of component placement and routing are performed concurrently rather than sequentially.

The integrated approach to product layout is described and applied to the design of a heat pump to compare the integrated method to the sequential layout-then-route approach. The results demonstrate the power of the concurrent approach in terms of simplicity, elegance, and cost of the routes and component placement over the more restrictive sequential approach. The results also demonstrate the adaptability of the simulated annealing approach to product layout in terms of the ease of integrating the individual algorithms into a single method.

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### **Integrated Layout and Routing**

Both the component layout and routing algorithms developed previously perform optimization using simulated annealing, a stochastic optimization technique that was introduced by Kirkpatrick et al. (1983). At the start of an optimization using simulated annealing, the algorithm begins at an initial design state. The algorithm then takes a step to a new design state by randomly perturbing the current design using a move selected from an available move set. The objective function value of the new state is compared to that of the previous state. If the new state is better than the previous one, it is accepted; if it is worse, it is accepted or rejected with some probability. The probability of accepting an inferior state (i.e., a step in a direction away from an optimum) is a function of a parameter called temperature. The control of the temperature parameter as the algorithm runs is done using an *annealing schedule*. The individual placement and routing algorithms utilize the annealing schedule developed by Huang et al. (1986), as does the integrated algorithm.

An important benefit of the simulated annealing approaches to component placement and routing is that they both use the same optimization algorithm and differ only in the objective function terms and the move sets used to modify a design in stance during the optimization. To create the integrated product layout algorithm, all the objectives need to be combined into a single objective function and the move sets for placement and routing must be merged into a single set. The result is an integrated algorithm which modifies the placement and routing for a current design, and which evaluates a design based on both placement and routing objectives.

The individual objective functions are combined into one function that consists of three design objectives as well as several penalty terms that penalize infeasible designs. Spatial constraints between components and the container are specified and included in the objective function as one such penalty term. Other penalties are formed for intersections between objects (components, the container, and routes). The overall objective function consists of a weighted sum of the objective function, where each term is normalized to fall between zero and one before being multiplied by its weight. The first design objective is a measure of the inverse of volumetric packing density (which, when minimized, maximizes packing density). The objective is given by:

$$f_1 = \frac{V_{bb}}{n \sum_{i=1} V_i}, \quad (1)$$

where  $V_{bb}$  is the volume of the bounding box of the design (a box that completely encloses the design),  $n$  is the number of components, and  $V_i$  is the volume of the  $i$ th component. The other two design objectives are the total routing length, and the number of bends required for the routing.

The move set for the placement algorithm consists of three different moves that are used to perturb a given placement: *translate*, which changes the location of a component, *rotate*, which changes a component's orientation, and *swap*, which switches the locations of two components. The move set for the routing algorithm consists of four different moves: *add*, which selects a route at random and inserts a new bend at a random location in the route, *remove*, which deletes a random bend in a randomly-selected route, and *relocate* and *vector-relocate*, which change the location of a bend in a route, either in a random direction or

**Table 1. Comparison of integrated layout and routing approaches (averages)**

	Inverse-density	Total route length	Number of bends
Sequential layout and routing	2.53	1214.7	15.0
Concurrent layout and routing	2.70	681.1	12.7
Percent difference	6.72 %	-43.9 %	-15.3 %

along the vector created by one of the route segments that meet at the bend, respectively. These moves sets are combined into a single set for the integrated algorithm.

In simple simulated annealing algorithms, the probability of selecting a given move remains fixed as the algorithm runs. Moves that are useful (and therefore are accepted often) early in the optimization may be less effective at latter stages; the reverse may be true for other moves. Using fixed move probabilities can adversely impact both quality of results as well as algorithm run time. This problem becomes more substantial as the size of the move set increases, as occurs when combining move sets for the integrated algorithm.

To address this issue, the integrated algorithm utilizes a technique for dynamically allocating move selection probabilities based on past performance as the algorithm runs, as described in (Hustin and Sangiovanni-Vincentelli, 1987). With this technique, a *quality factor* is assigned to each move in the move set by calculating an average change in objective function attributed to that move over a number of iterations. A high quality factor indicates that a move is likely to have a large effect on the objective function, while a low value indicates that a move is less likely to affect the objective function significantly. The move selection probabilities are then periodically updated so that the probability of selecting a given move is proportional to the most recent quality factor.

### Example: Heat Pump

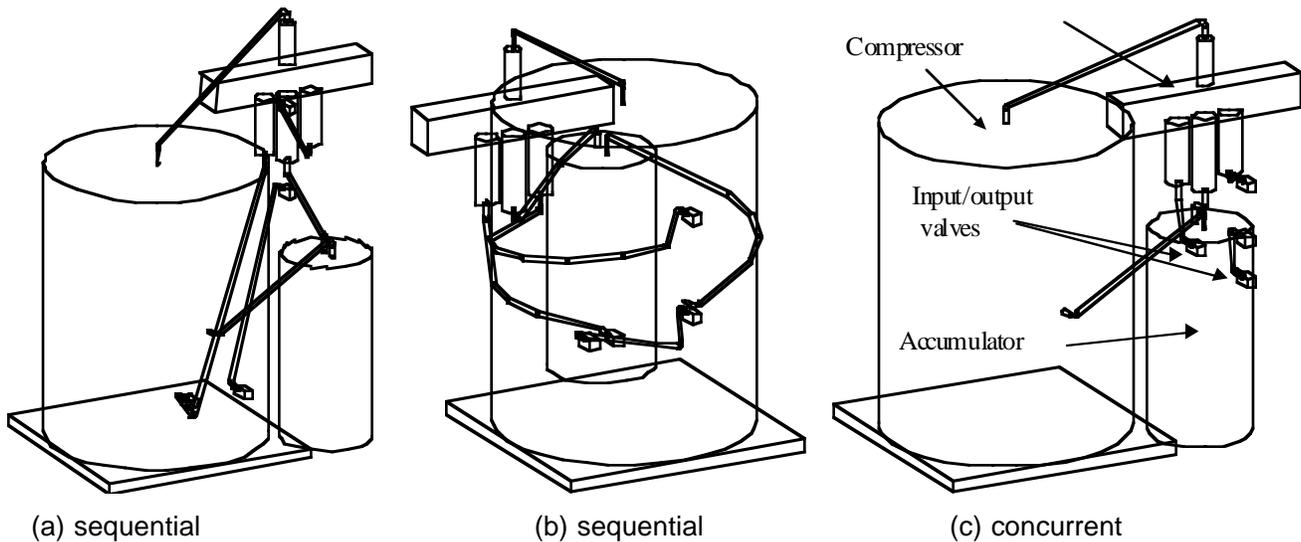
In this section, both the sequential layout-then-route and the proposed integrated layout-and-routing algorithms are applied to an industrial design problem: the design of a heat pump. The problem consists of laying out the main components of the heat pump: the compressor and its base, the accumulator, the reversing valve, the input and output valves to the coil (*i.e.*, heat exchanger), and the input and output service

valves to the overall unit. A number of constraints are used to define the problem. (See Appendix for details.)

Each algorithm was run ten times and the final values for each of the design objectives (inverse-density which when minimized maximizes packing density, route length and number of bends) were averaged (Table 1). As the results illustrate, there is a marked difference in performance between the two algorithms. For the inverse-density objective alone, the sequential algorithm performs slightly better on average. This is not surprising; because the routing objectives are ignored during the component layout phase, we expect the layout to be highly optimized. However, this difference in inverse-density is small and clearly comes at the expense of the heat pump routing.

Examining the remainder of the table, the contrast between the two algorithms is considerably more substantial for the routing objectives. The greatest difference is in the total route length, where the concurrent algorithm results in an average reduction of length over the sequential algorithm of nearly 44%. The average reduction in number of bends is smaller, but still a significant 15%. As described previously, the substantial decrease in routing costs with the concurrent algorithm occurs because the layout and routing are both being modified simultaneously, taking into account the routing objectives when components are being moved. Because these objectives are ignored in the sequential algorithm, component placement makes the subsequent routing problem more difficult.

Figures 1(a) and (b) show example results of the sequential approach with cramped placements and complex routings. Note, however, that even when given the poor relative placement of the accumulator and valves in Figure 1(b), the routing algorithm was still able to find a near-optimal (minimum length) routing by closely following the curve of the compressor. Figure 1(c) shows a typical concurrent solution with simpler routes giving a cleaner overall layout with much lower routing costs.



**Figure 1. Layout and routing for the sequential (a) & (b) and concurrent (c) algorithms<sup>4</sup>**

<sup>4</sup> Note that the appearance of intersections is due to a lack of hidden line removal in the figures; the designs shown are free of interference between multiple objects or objects and routes.

## Conclusions

The simulated annealing algorithm described in this paper provides an integrated framework to concurrently lay out and route products, as demonstrated through the heat pump example. The concurrent approach is superior to the sequential approach for problems where both layout and routing significantly impact the cost of a design. Although this work includes only problem-independent objectives and uses a simplified geometric representation, the approach readily lends itself to extensions to the basic algorithm. Work in progress addresses other problem-specific objectives, such as thermal objectives (Campbell et al., 1996) and alternative geometric representation and intersection analyses (e.g., Kolli et al., 1996).

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## References

- Cagan, J., R. Clark, P. Dastidar, S. Szykman and P. Weisser (1996), "HVAC CAD Tools: A Case Study of University/Industry Collaboration," in: *Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference: Design Theory and Methodology Conference, paper no. 96-DETC/DTM-1505*, Irvine, CA, August 18-22.
- Campbell, M. I., C. H. Amon and J. Cagan (1996), "Optimal Three-Dimensional Placement of Heat Generating Electronic Components," *ASME Journal of Electronic Packaging* (accepted for publication).
- Huang, M. D., F. Romeo and A. Sangiovanni-Vincentelli (1986), "An Efficient General Cooling Schedule for Simulated Annealing," *ICCAD-86: IEEE International Conference on Computer-Aided Design—Digest of Technical Papers*, Santa Clara, CA, November 11-13, pp 381-384.
- Hustin, S. and A. Sangiovanni-Vincentelli (1987), "TIM, a New Standard Cell Placement Program Based on the Simulated Annealing Algorithm," presented at IEEE Physical Design Workshop on Placement and Floorplanning, Hilton Head, SC, April.
- Kirkpatrick, S., C. D. Gelatt, Jr., and M. P. Vecchi (1983), "Optimization by Simulated Annealing," *Science*, **220**(4598):671-679.
- Kolli, A., J. Cagan and R. A. Rutenbar (1996), "Packing of Generic, Three Dimensional Components Based on Multi-Resolution Modeling," in: *Proceedings of the 1996 ASME Design Engineering Technical Conferences and Computers in Engineering Conference: Design Automation Conference, paper no. 96-DETC/DAC-1479*, Irvine, CA, August 18-22.
- Szykman, S. (1995), *Optimal Product Layout Using Simulated Annealing*, Ph.D. dissertation, Carnegie Mellon University, Pittsburgh, PA.
- Szykman, S. and J. Cagan (1995), "A Simulated Annealing-Based Approach to Three Dimensional Component Packing," *ASME Journal of Mechanical Design*, **117**(2(A)):308-314.
- Szykman, S. and J. Cagan (1996), "Synthesis of Optimal Non-Orthogonal Routes", *ASME Journal of Mechanical Design*, **118**(3):419-424.
- Szykman, S. and J. Cagan (1997), "Constrained Three Dimensional Component Layout Using Simulated Annealing," *ASME Journal of Mechanical Design*, **119** (1):28-35.

## Appendix

This appendix provides details regarding the optimization problem presented, for researchers interested in using it as a benchmark problem for comparison of optimization techniques.

**Components:** The compressor (the larger cylinder in the figures) is modeled as a cylinder of 255 mm diameter and 320 mm height with a 255 mm square by 10 mm thick block for the base. The accumulator (the smaller cylinder in the figures) is a 105 mm diameter by 215 mm height cylinder. The reversing valve (the long block with four cylinders protruding from it) consists of a 200 mm X 35 mm X 35 mm block with a 15 mm diameter by 50 mm long cylinder centered on the top and three 24 mm diameter cylinders on the bottom; the end cylinders are 65 mm long while the middle one is 78 mm long. Four valves (two service valves and two coil ports, appearing as small blocks at the end of several of the routes in the figures) have dimensions of 10 mm X 20 mm X 10 mm.

**Tube Routes:** Six tube routes are also defined with end points as follows: (1) from the top of the compressor to the top tube of the reversing valve, (2) from the side of the compressor to the top of the accumulator, (3) from the top of the accumulator to the bottom tube 2 of the reversing valve, (4) from the bottom tube 1 of the reversing valve to the side of coil port 1, (5) from the bottom tube 3 of the reversing valve to the side of service valve 1 (6) from the side of coil port 2 to the side of service valve 2.

**Constraints:** To provide a point of reference the reversing valve is fixed at the origin. None of the components are permitted to rotate outside of the plane; the orientation of the compressor, accumulator and reversing valve are fixed to preserve their vertical orientations, and, in order to fix the direction from which tubes enter the valves, rotations of the coil and service valves are forbidden. Several additional location constraints that are characteristic of heat pump layout problems are also applied to the components:

- the coil ports and service valves may not rotate and are required to be to the right of the compressor, the accumulator and the reversing valve;
- the service valves are required to be on the same side of the heat pump container;
- the coil ports are constrained to have the same horizontal coordinates, with one valve being 100 mm above the other;
- the compressor is constrained to be directly on top of the compressor base, centered about the same point in the horizontal plane;
- the bottoms of the compressor base and the accumulator rest on the same horizontal plane, representing the base of the heat pump container;
- the bottoms of the reversing valve, coil ports and service valves are constrained to be above the bottom of the compressor base, *i.e.*, above the base of the container.