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A study on three dimensional layout design by the simulated annealing method[†]

Seung-Ho Jang[*]

College of Advanced Technology, Kyung Hee University, 1 Seocheon-Ri, Kihung-Eup, Yongin-Si, Kyunggi-Do, 449-709, Korea

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Abstract

Modern engineered products are becoming increasingly complicated and most consumers prefer compact designs. Layout design plays an important role in many engineered products. The objective of this study is to suggest a method to apply the simulated annealing method to the arbitrarily shaped three-dimensional component layout design problem. The suggested method not only optimizes the packing density but also satisfies constraint conditions among the components. The algorithm and its implementation as suggested in this paper are extendable to other research objectives.

Keywords: Layout design; Engineering product; Three-dimensional component; Algorithm; Constraint condition

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1. Introduction

Modern engineered products are becoming increasingly complicated and most consumers prefer compact designs. The layout design plays an important role in many engineered products. The simulated annealing method has been effectively applied to wafer layout and has solved packing problems [1]. In the electrical engineering field, commercial layout tools have the ability to arrange thousands of components within a small domain. However, the components in this field are limited to two dimensions [2].

A variety of non-linear programming techniques have been applied to the layout problem of three-dimensional components. Three-dimensional packing problems have been studied by using genetic algorithms [3]. Cagan developed a method to extend the simulated annealing method from two dimensions to three dimensions [4]. Kämpke reported a solution to a bin packing test problem using this technology with results superior to previous attempts [5]. The simulated annealing method has also been used on other types of three-dimensional layout design problems, such as facilities layout [6].

Hills and Smith present work in spatial engineering for made-to-order products such as offshore oil rigs [7]. Their work uses the simulated annealing method to produce initial layout configurations for later manipulation through the intervention of a layout expert to achieve the final desired layout result. Cagan, Degentesh and Yin reported a simulated annealing-based algorithm using hierarchical models [8]. However, this study cannot be applied to arbitrarily shaped three-dimensional component layout design problems.

The objective of this study is to develop a way of applying the simulated annealing method to the arbitrarily shaped three-dimensional component layout design problems. The suggested method not only optimizes the packing density but also satisfies constraint conditions between the components. The algorithm and its implementation suggested in this paper are easily extendable to other objectives.

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[*] Corresponding author. Tel.: +82 31 201 2594, Fax.: +82 31 202 9484
E-mail address: shjang@khu.ac.kr

2. Requirement of three-dimensional layout design of submersible boat

We selected a submersible boat as an example of a three-dimensional layout design. The submersible boat is used to search for suboceanic resources and making undersea maps.

Table 1. Function of parts of submersible boat.

Sensors : Water temperature sensor, distance sensor, azimuth sensor, water current sensor, PH meter, water depth sensor, vision(ccd camera) etc.

Power source : Battery for drivers, inverters, controllers, etc.

Communication apparatus : Ocean retrieval beacon and supersonic emergency communication apparatus

Driver : Control system of actuators

Inverter : Frequency transformer for AC motor

Central processing unit : Computation of the posture, stability, position, etc.

Controller : Control system of thrusters, rudder actuators, etc.

Table 2. Parts to be arranged in the submersible boat.

PART01	SUPERSONIC SENSOR
PART02	PINGER
PART03	WATER CURRENT SENSOR
PART04	WATER TEMPERATURE SENSOR
PART05	TELECOMMUNICATION APPARATUS
PART06	ANTENNA
PART07	REAR TANK
PART08	PAINT EMITTER FOR EMERGENCY
PART09	PH METER
PART10	RECEIVER
PART11	DISTANCE MEASURING SENSOR
PART12	TRANSPORTER
PART13	VERTICAL RUDDER ACTUATOR
PART14	HORIZONTAL RUDDER ACTUATOR
PART15	COMPENSATOR
PART16	AIR BOMBE FOR EMERGENCY
PART17	CAMERA
PART18	BALLAST
PART19	DEBALLASTER
PART20	STROBO
PART21	BEACON
PART22	POWER SOURCE
PART23	INVERTER
PART24	AZIMUTH SENSOR
PART25	THRUSTER(RIGHT)
PART26	THRUSTER(LEFT)
PART27	CENTRAL PROCESSING UNIT
PART28	NAVIGATOR

The functions of the main parts are summarized in Table 1. Table 2 shows a part list for the submersible boat. Table 3 gives the shape and size of each part.

The requirements of the layout design of the submersible boat are as follows:

a) Wiring: The length of wiring (for the signal and power line) between components should be short if possible. Table 4 depicts the wiring diagram of the submersible boat's components.

b) Gravitational center: The gravitational center of the submersible boat should be located at 0.4 × LENGTH (LENGTH: the length of the submersible boat) from the front side of the boat. If the gravitational center is located at the rear side of the boat, the ability to control the it will be compromised.

Table 3. Shape and size of each part.

	SHAPE	SIZE(mm)		
		a	b	c
PART01	CYLINDER	600	450	-
PART02	CONE	450	450	-
PART03	CYLINDER	300	400	-
PART04	CYLINDER	250	250	-
PART05	TETRAHEDRON	400	500	500
PART06	CYLINDER	100	700	750
PART07	CYLINDER	800	800	-
PART08	SEGMENT	600	600	750
PART09	CUBE	300	300	350
PART10	WEDGE	500	500	400
PART11	CUBE	450	450	750
PART12	CYLINDER	800	800	-
PART13	CYLINDER	700	700	-
PART14	CYLINDER	800	850	-
PART15	WEDGE	250	250	550
PART16	SPHERE	750	-	-
PART17	CYLINDER	400	400	-
PART18	CUBE	700	800	800
PART19	CUBE	700	800	380
PART20	CYLINDER	400	400	-
PART21	FILLET	700	800	900
PART22	CYLINDER	400	600	800
PART23	WEDGE	700	700	-
PART24	CONE	500	500	-
PART25	CYLINDER	500	900	-
PART26	CYLINDER	500	900	-
PART27	CUBE	400	400	700
PART28	CYLINDER	300	300	-

Table 4. Wiring diagram among parts.

PART01 --- PART14	PART08 --- PART24	PART22 --- PART23
PART03 --- PART12	PART09 --- PART23	PART24 --- PART16
PART07 --- PART17	PART27 --- PART14	PART04 --- PART17
PART05 --- PART16	PART11 --- PART18	PART18 --- PART16
PART02 --- PART24	PART19 --- PART16	PART21 --- PART11
PART08 --- PART19	PART16 --- PART13	PART05 --- PART19
PART01 --- PART14	PART27 --- PART09	PART03 --- PART13
PART05 --- PART07	PART09 --- PART24	PART05 --- PART21
PART07 --- PART24	PART16 --- PART13	PART11 --- PART13
PART08 --- PART15	PART23 --- PART17	PART21 --- PART15
PART08 --- PART22	PART15 --- PART26	PART07 --- PART14
PART07 --- PART25	PART18 --- PART23	PART09 --- PART17
PART14 --- PART28	PART19 --- PART17	PART02 --- PART13
PART08 --- PART17	PART16 --- PART04	PART07 --- PART24
PART13 --- PART08	PART13 --- PART12	PART21 --- PART28

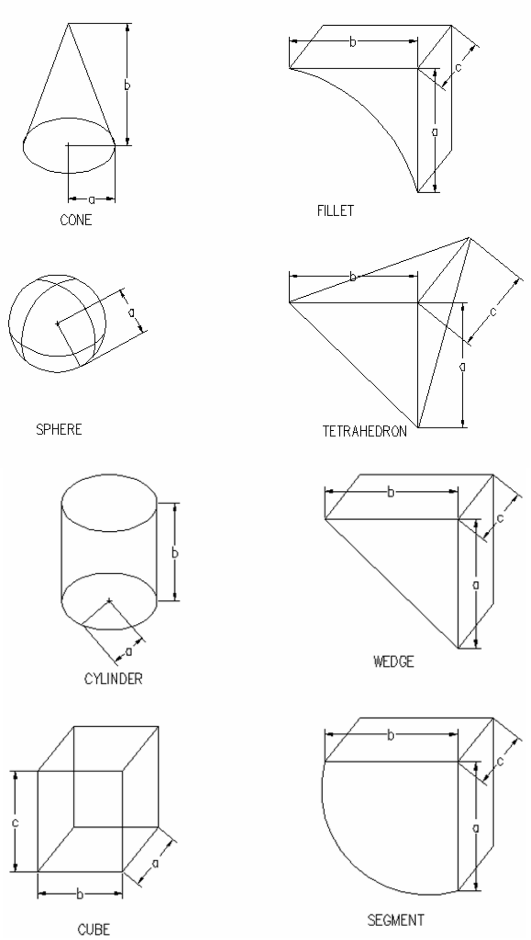


Fig. 1. Shapes of parts to be arranged by the algorithm.

Table 5. Annealing method and simulated annealing algorithm.

	Annealing method	Simulated annealing algorithm
1	material(metals)	various optimization problems
2	energy	objective function
3	crystallization	optimal solution

c) Metacenter: The position of the metacenter of the submersible boat should be located at 0.406 × LENGTH from the front side.

d) Layout space of components: The entire internal space of the body of the submersible boat is the layout space for the components. All the components should be arranged in this space. However, no components should overlap.

e) Noise countermeasure: The noise from the inverters, actuators, thrusters, power sources etc., should not affect the sensors or CPU if possible.

In addition, the components should not be placed extremely close to each other in consideration of future repairs made to the submersible boat. The Strobo should be located near the camera.

In this paper eight kinds of three-dimensional shapes (cone, fillet, sphere, tetrahedron, cylinder, wedge, cube, segment) are suggested as shown in Fig. 1.

3. Simulated annealing method

3.1 Algorithm of simulated annealing method

The annealing method of metals and the simulated annealing computer algorithm are compared in Table 5. The simulated annealing algorithm was developed by applying the annealing process of solid physics to the optimization problem. The main characteristics of this algorithm are that the optimal solution can be obtained globally, but the computing time is longer than other methods.

The simulated annealing method is based on the iterative improvement problem. An initial design state is chosen and the value of the objective function for the state is evaluated. A step is taken to a new state by applying a random move. If the step leads to an improvement by evaluating the objective function of the new state, the new design is accepted and becomes the current design state. If the step leads to an inferior state, the step may still be accepted with some probability by using the Metropolis criterion.

```
begin;
initialize(inisol, initem, iternum)
                              //inisol: initial solution,
                                initem: initial temperature,
                                iternum: iteration number
repeat
for i = 1 to   iternum do {
        Y = PERTURB(inisol)
          if E(Y) = E(inisol) or (exp(E(inisol) - E(Y))/initem) > random(0,1){
                        inisol = Y;    }      }
        UPDATE(initem, iternum)
Until(Stop-criteria)
End
```

Fig. 2. Algorithm of simulated annealing method.

$$\text{Metropolis criterion} = \exp(\frac{-\Delta}{k_B \cdot T}) \tag{1}$$

Where and are the Boltzmann constant, temperature, and change of energy, respectively. The simulated annealing algorithm is summarized in Fig. 2.

3.2 Evaluation criteria and cost function

Nine kinds of evaluation criteria were defined to evaluate the layout design results of the submersible boat, as follows:

1) Interference between noise sources: Length between noise sources (for example inverters and thrusters, etc.) (L_1).

2) Superimposition of components: Overlapped volume between components (V_1).

3) Protrusion from special domain: Protrusion volume of the components from the layout space (V_2).

4) Functional relation between components: Length between components which have a functional relation (for example camera and Strobo, etc.) (L_2).

5) Effect of noise on sensors: Length from noise sources to sensors (L_3).

6) Total packaging rate: Total empty space after layout design divided by total layout space ($V_3 = V_{tes} / V_{tls}$, where, V_{tes} is total empty space, V_{tls} is total layout space).

7) Change of position of gravitational center after deballasting: Length from the position of the gravitational center prior to dropping the ballast to the position of it after dropping the ballast (L_4).

8) Deviation of gravitational center from ideal position: Length from the ideal position of the gravitational center to the designed position of the gravitational center of the submersible boat (L_5).

9) Total wiring length between components: Total length of power lines and signal lines (L_6).

The following dimensionless cost function is suggested to estimate the three-dimensional layout design result.

$$\text{CF(Cost function)} = \sum_{t=0}^{m}\left(\frac{V_i}{V'_i}\times 100\right) + \sum_{j=0}^{n}\left(\frac{L_j}{L'_j}\times 100\right) \tag{2}$$

Where, L_j and V_i are the values of evaluation criteria for the current layout solution, L'_j and V'_i are the values of evaluation criteria for the initial layout solution.

4. Constraint conditions and method of layout state generation and transformation

The conditions of relational constraint and layout constraint were suggested for the three dimensional layout design as follows:

4.1 Conditions of layout constraint

The conditions of layout constraint consist of the constraints of layout domain, layout direction, layout position and layout direction as follows:

a) Constraint of layout domain: Parts which must be arranged in some specified domains, that is, the parts which have limitations of layout space, like distance measuring sensors (this sensor must be placed at the front domain of submersible boat), CPU, power source, etc.(Fig. 3(a)).

b) Constraint of layout direction: Parts which have limitations of layout direction, like the thruster (constraint of x direction), compensator (constraint of z direction), distance measuring sensor (constraint of x direction), etc.(Fig. 3(b)).

c) Constraint of layout domain and layout direction: Parts which have limitations of layout position and layout direction, like the ballast and deballaster (these parts must be paced under the domain of the submersible boat and have constraints in the x direction), the camera and Strobo, etc.(Fig. 3(c)).

4.2 Conditions of relational constraint

The conditions of relational constraint between parts consist of constraints of symmetrical layout and constraints of layout dependency as follows:

a) Constraint of symmetrical layout: Parts which must be arranged symmetrically on the right side and left side, front side and rear side of the submersible boat, like horizontal and vertical rudder actuators, inverters, thrusters, etc.(Fig. 4(a)).

b) Constraint of layout dependency: Parts which have dependency with other parts in the arrangement, like the ballast and deballaster (the position of ballast is dependent on that of the deballaster), right thruster and left thruster, etc.(Fig. 4(b)).

4.3 Method of layout state generation and transformation

The layout state of each component is represented as position coordinates and axis directions of parts in three-dimensional space. The layout state is generated under the constraint conditions mentioned in Chapter 4.1 and 4.2. A new subsequent layout solution is generated by the layout state generation process in Fig. 5.

```
IF    Part = Distance_Measuring_Sensor(DMS)
THEN    Position_of_DMS = Within_Cube_A(center1, a1, b1, c1)
```

(a)

```
IF    Part = Navigator
THEN    X_Direction_of_Navigator = X_axis
```

(b)

```
IF    Part = Deballaster
THEN     X_Direction_of_Deballaster = X_axis, and,
        Position_of_Deballaster = Within_Cube_B(center2, a2, b2, c2)
```

(c)

Fig. 3. Algorithm of layout constraint.

```
IF    Part = Thruster(right)
THEN    Position_of_Thruster(right) = Right_Side_of_Boat(d1, d2, d3, d4)
```

(a)

```
IF    Part = Ballaster
THEN     Position_of_Deballaster = Within_Cube_C(center3, a3, b3, c3)
```

(b)

Fig. 4. Algorithm of relational constraint.

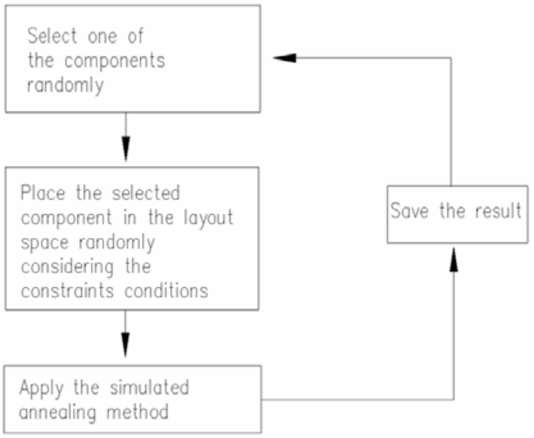


Fig. 5. Layout state generation and optimization process.

The layout state transformation selects one of the new subsequent layout solutions randomly from the surroundings of the current layout solution. That is, the layout state is transformed by interchanging the current layout solution with the new subsequent layout solution with probability by the Metropolis criterion.

$$\text{P(Probability of state transformation)} = \min\left[1, \left(\exp\left(-\Delta E / T\right)\right)\right] \tag{3}$$

$$\Delta E = CF_1 - CF_2 \tag{4}$$

Where, CF_1 is the value of the cost function of the current layout solution, CF_2 is the value of the cost function of a subsequent layout solution, $\triangle E$ is the energy, and T is the temperature. Fig. 5 is the layout state generation and optimization process.

5. Simulation

The LAYout Design Optimization Program (LAYDOP ver.2) was developed by the suggested method. As layout specifications for the submersible boat, the numbers of parts, layout constraint conditions, relational constraint conditions, and evaluation criteria were 28, 3, 2, and 9, respectively. Table 6 shows the schedule parameters and the improvement rates for the annealing method. As shown in Table 6 the initial temperature was changed from 100.0 to 300.0(step size 50.0). The layout design results by using LAYDOP ver.2 were compared with the design result by layout expert(cost value = 172.0)

Table 6(a). Simulation results.

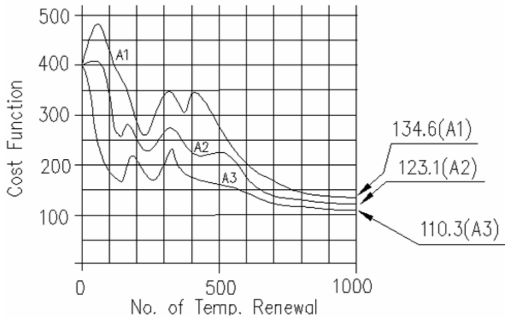
Name of schedule		Initial temp.	Initial cost value	Final cost value	Improvement rate	
Annealing	A1	100.0	400.0	134.6	+21.7%	a = 2.0
						b = 2.2
						c = 1.7
						d = 4.6
						e = 1.2
						f = 2.3
						g = 2.5
						h = 1.2
						i = 4.0
	A2	150.0	400.0	123.1	+28.4%	a = 3.5
						b = 2.5
						c = 2.1
						d = 3.2
						e = 4.5
						f = 4.3
						g = 3.2
						h = 2.0
						i = 3.1
	A3	200.0	400.0	110.3	+35.9%	a = 4.2
						b = 3.3
						c = 4.5
						d = 4.7
						e = 3.6
						f = 2.7
						g = 5.2
						h = 4.4
						i = 3.3

Table 6(b). Simulation results.

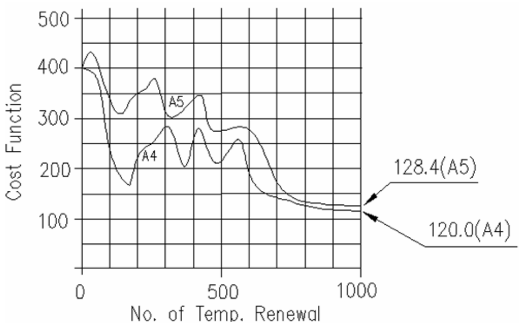
Name of schedule		Initial temp.	Initial cost value	Final cost value	Improvement rate	
Annealing	A4	250.0	400.0	120.0	+30.2%	a = 4.7
						b = 5.2
						c = -1.2
						d = 5.1
						e = 4.2
						f = 4.0
						g = 4.3
						h = -0.3
						i = 4.2
	A5	300.0	400.0	128.4	+25.3%	a = 3.4
						b = 4.4
						c = -3.5
						d = 4.5
						e = 4.8
						f = 5.0
						g = 4.3
						h = -2.1
						i = 4.5

Table 7. Evaluation criteria in improvement rate of Table 6.

a	Change of position of gravitational center after ballasting
b	Deviation of gravitational center from ideal position
c	Interference between noise sources
d	Superimposition of parts
e	Protrusion from special domain
f	Functional relation between parts
g	Effect of noise to sensors
h	Total packaging rate
i	Total wiring length between parts



(a)



(b)

Fig. 6. Simulation result. (cost value vs. number of temp. renewal)

In schedule A3 of Table 6, the value of the cost function was improved 35.9% with 1000 times of the temperature renewal. The temperature renewal was found by multiplying the initial temperature value by 0.99 at each point. The changed values for each evaluation criterion of the cost function by each schedule are summarized on the right hand side of Table 6.

Fig. 6 is the transition of the cost function by temperature renewal when the LAYDOP ver.2 was executed under the schedule of Table 6. As shown in Fig. 4, at the high temperature state (in the beginning of program execution) the values of the cost function were increased. This means that the deterioration of the value of the cost function was accepted at the high temperature state by the statistic flickering of temperature.

Comparing the annealing schedules A1, A2, A3, A4 and A5 in Fig. 4, it was found that the solution of layout design could be converged into a local minimum if the annealing schedule was not appropriate.

6. Concluding remarks

In this paper we have suggested a method to apply the annealing method to the layout design of the arbitrarily shaped three-dimensional component layout design problem. Through the suggested method, the three-dimensional LAYout Design Optimization Program (LAYDOP ver.2) was developed.

By executing the LAYDOP ver.2, the suggested method has been verified. The layout result designed by a layout expert has been improved 35.9% by using LAYDOP ver.2. The solution of layout design can converge into a local minimum if the annealing schedule is not appropriate. The suggested method not only optimized the packing density but also satisfied constraint conditions between the components. The algorithm and its implementation suggested in this paper are easily extendable to other research objectives.

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References

[1] S. Kirkpatrick, C. D. Jr. Gelatt and M. P. Vecchi, Optimization by simulated annealing, *Science* 220 (1983) 671-679.

[2] D. F. Wong, H. W. Leong and C. L. Liu, Simulated Annealing for VLSI Design, Kluwer Academic Publishers, (1988).

[3] T. Kawakami, M. Minagawa and Y. Kakazu, Auto tuning of 3-D packing rules using genetic algorithm,, *Proceedings of the IEEE/ RSJ International Workshop on Intelligent Robots and Systems IROS '91*, (1991) 1319-1324.

[4] J. Cagan, A shape annealing solution to the constrained geometric knapsack problem, *Computer-Aided Design,* 28(10) (1994) 763-769.

[5] T. Kämpke, Simulated annealing: use of a new tool in bin packing, *Annals of Operations Research* 16 (1988) 327-332.

[6] S. Jajodia, I. Minis, G. Harhalakais and J. M. Proth, CLASS: Computerizes Layout Solutions using Simulated Annealing, *International Journal of Production Research*, 30(1) (1992) 95-108.

[7] W. Hills and N. Smith, A new approach to spatial layout design in complex engineered products,, *Proceedings of the International Conference on Engineering Design(ICED 97)*, Tampere, Finland, (1997) 19-21.

[8] J. Cagan, D. Degentesh and S. Yin, A simulated annealing-based algorithm using hierarchical models for general three dimensional component layout *Computer-Aided Design*, 30(10) (1998) 781-790.

Seung-Ho Jang received his B.S. in mechanical engineering and M.S. in precision mechanical engineering from University of Han Yang in 1986 and 1988, respectively. He then went on to receive his Ph.D. in mechanical engineering from University of Tokyo in 1991. His main research areas are CAD/CAE, mechanical vibration, and optimal design.