A Study on Tool Path Optimization using Tabu Search

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Tabu Search를 이용한 공구 경로의 최적화에 관한 연구

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Introduction

It is well known that combinatorial optimization problems such as integer programming, quadratic assignment, layout optimization and etc. are computationally classified as NP-hard (Garley and Johnson, 1979). Because of their nonderministic and non-differentible feature, the conventional optimization approaches of gradient based algorithm with a monotonically decreasing value of the objective function are usually trapped in a local optima and fail to reach a global one of the NP-hard problems.

Recently, two different optimization methods for these combinatorial problems draw increasing attractions : the one is the simulated annealing (Cerny, 1985; Kirkpatric, 1983; Laarhoven Aarts, 1988) and the other is the tabu search (Bland and Dauson, 1991; Friden, 1990; Widmer, 1991). In this paper, the latter is introduced briefly, also applied to the optimization of punching tool path in sheet metal fabrication.

Tabu Search

Tabu search proves to be a powerful optimization procedure which has been successfully applied to lots of NP-hard problems mentioned above since its revival in 1986, (Glover, 1986) almost one decade after the first appearance in 1977 (Glover, 1977). Tabu search basically works iteratively with two heuristic guides-*tabu list* and *aspiration flevel*-as follows.

The tabu list is a historical record of investigated (accepted) feasible solutions. Therefore, during the search to the global solution, if a new feasible confi- guration happens to coincide with one of the

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configurations already recorded in the tabu list (thus having tabu status), a move to this new configuration can not be accepted and rejected. Thus, the tabu list eventually provides the ability of escaping local optima, while usual simple descent algorithm would be trapped in it. If a problem is suspected to have higher-order cycling nature, the list length could be increased. On the other hand, the aspiration level allows backtracking to previous solutions which have been listed in the tabu list. In other words, if a new move improves the cost function better than the recorded levels (aspiration levels) in different directions, it is accepted as a feasible solution overriding the tabu status.

Therefore, the above two features-the 'jumping out' of the valley by the tabu list and the backtracking to previous solutions by the aspiration level-ultimately lead the search to a global optima or a near-global one.

Application to Tool Path Optimization

1. Objective

In sheet metal fabrication using a numerically controlled turret punch press machine (NCT machine), the product performance is related to several factors such as the quality of products, the total processing (or punching) time and etc. Here the processing time consists of the translation time of the machine bed, the rotation time of the turret where tools are installed and the minor lead time between every hit due to machine inertia.

In this paper, the optimization goal is to minimize the total processing time for NCT operation using tabu search. Throughout the automatic tools selection (조, 1992) in order to punch out a given sheet metal part, all the punching information is obtained as follows :

-tool-id(i) : tool id for the punching location.

-(x_i, y_i) : i-th punching location.

-angle(i) : orientation of punching tool.

Note that, as summarized in Table 1., there is an analogy between tool path optimization and the path optimization of the well known travelling salesman problem (TSP).

Table 1. Analogy between tool path optimization in NCT and TSP

Tool path Optimization	TSP
nhit : no.of punching locations	ncity : no.of cities to be visited
Punching location (x ba 3; for i-th hit	i-th city location (x ba 3;
t ba 3; fh 24b; fw required for j-hit just after i-th hit	d ba 3; fh 24b; fw i-th and j-th cities.

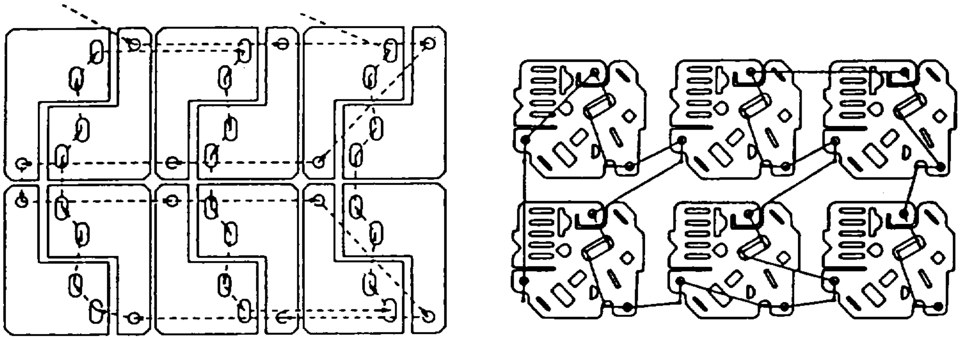
2. Conventional Tool Path Optimization

There are several software packages for sheet metal design and fabrication (Bravo 3, 1988; Cimatron '90, 1990; Euclid-IS, 1987; Unigraphics Ⅱ, 1991). Most of these softwares provide the modules of tool path optimization for NCT operation. In general, however, these modules work in conventional manners as follows :

- to minimize not the total processing time but the total path length to perform the punching operations completely.

- to minimize the tool change based on the *heuristic* that the turret rotation usually takes much longer time than the bed translation does.

Thus, since a tool has been selected for several punching locations, it will not be changed until it finishes its duty (i.e. it is foreced to visit all the locations where it is required as a punching tool). Figure 1 shows the real examples of tool path where the aformentioned heuristic prevails apparently (Bravo 3, 1988; Raggenbass and Reissner 1989, 1991).



(a) (b)

Fig. 1. Examples of tool path. (a) from (BRV 88) and (b) from (Rag 89).

In mathematical point of view, the above heuristic encourages one to relax the constraint (2) of section 3 later, and to solve the several 0-1 PIP models (the well known knapsack problems). This kind of relaxation seems to be a trade-off between the local optima and the computing efforts. However, it should be clearly notified that the path might result in a local optima instead of a global one, especially when the translation time is no longer a minor one compared with that of the turret rotation for tool change.

3. Proposed Model Formulation

To overcome the expected drawback of the conventional tool path optimization strategy, a new mathematical model is proposed hereafter. The main idea of the proposed model is that tool changes are allowed more frequently than the conventional model does.

Based on the analogy introduced before, our problem is easily modeled as pure integer programming (PIP) as below (Ledermann, 1980):

$$\text{minimize} \quad \sum_{i,j} c_{ij} z_{ij} \quad \cdots\cdots (1)$$

$$\text{subject to} \quad c_{ij} = \max\left[\frac{d_{ij}}{V}, \frac{\Delta\theta_{ij}}{\omega}\right] + \text{lead-time}_{ij} \quad \cdots\cdots (2)$$

$$\sum_{i} z_{ij} = 1 \text{ for all } j \quad \cdots\cdots (3)$$

$$\sum_{i} z_{ij} = 1 \text{ for all } i \quad \cdots\cdots (4)$$

$$u_i - u_j + \text{ncity} \bullet z_{ij} \leq \text{ncity} - 1 \quad \cdots\cdots (5)$$

$$\text{for all } i, j \neq 0 \text{ and } i \neq j$$

$z_{ij} = 1$: if j-th punching location is visited just after i-th one

0 : otherwise

u_i : the sequence number in which the i-th location is visited.

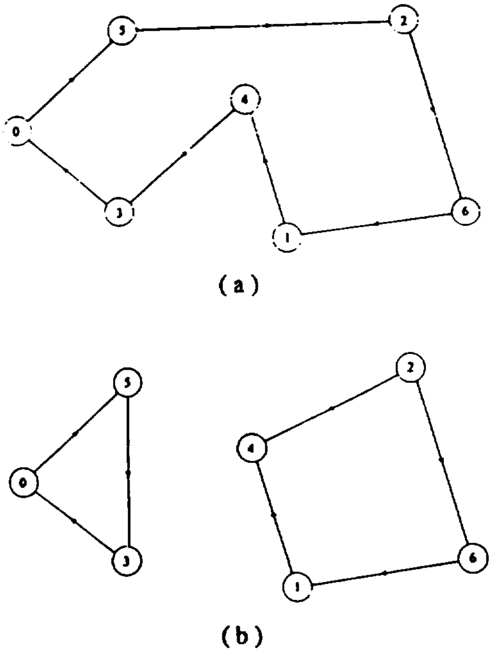
where V : translational speed of the machine bed (units/sec)

ω : rotational speed of the turret (radian/sec)

$\Delta\theta_{ij}$: turret rotation angle (radian)

d_{ij} : distance between two punching location i & j (units)

Here the final solution is u_i, i.e. the optimal order of touring all the punching locations. The constraint (2) forces the travelling cost c_{ij} to be composed of the minor lead-time for tool change and the largest one between the translation and rotation times for every hit. The constraints (3) and (4) guarantee not only each city (hit) is visited exactly once, but also each city (hit) is left in the same manner. The constraint (5) is necessary to rule out every subtour and ensures a complete tour. Figure 2 is an example of subtours among 7 cities, which are obviously not the feasible solutions for our problem.



(a)

(b)

Fig. 2. Example of subtours among 7 cities.

Simulation Results and Discussion

Figures 3 and 4 are the example punching tools to be used and the turret configuration on which the tools are installed. And following parameters are used for the simulations :

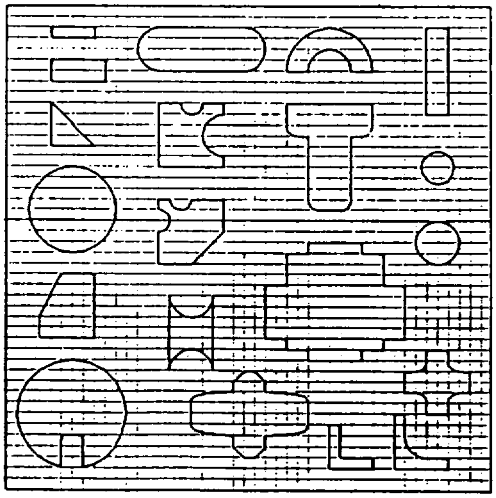
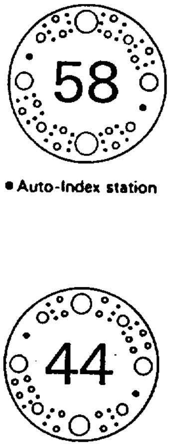


Fig. 3. Example tools.



Nominal punch size	Standard punch size	No. of stations
1/2"	1.6–12.7 mm dia. (0.063"–0.5" dia.)	36
1-1/4"	12.8–31.7 mm dia. (0.501"–1.25" dia.)	12
2"	31.8–50.8 mm dia. (1.251"–2" dia.)	4
3-1/2"	50.9–88.9 mm dia. (2.001"–3.5" dia.)	2
4-1/2"	89.0–114.3 mm dia. (3.501"–4.5" dia.)	2
Auto-Index	12.8–31.7 mm dia. (0.501"–1.25" dia.)	2

Nominal punch size	Standard punch size	No. of stations
1/2"	1.6–12.7 mm dia. (0.063"–0.5" dia.)	18
1-1/4"	12.8–31.7 mm dia. (0.501"–1.25" dia.)	16
2"	31.8–50.8 mm dia. (1.251"–2" dia.)	4
3-1/2"	50.9–88.9 mm dia. (2.001"–3.5" dia.)	2
4-1/2"	89.0–114.3 mm dia. (3.501"–4.5" dia.)	2
Auto-Index	12.8–31.7 mm dia. (0.501"–1.25" dia.)	2

Fig. 4. Turret configuration (AMA 90).

$V=133.3$ 〔unit/sec〕

$\omega=\pi$ 〔radian/sec〕

$\triangle\theta_{ij}=\pi/4$ 〔radian〕 if required, otherwise 0.

lead-time$=0.1$ 〔sec/change〕

Among these parameters, first three ones are the values specific to the hardware and here AMADA (1990). The last one, lend-time, is assumed by the auther.

To simulate the aforementioned conventional strategy, the rotational speed of the turret is set to a very small value (.e.g. 0.00001 times the real one), which is equivalent to limiting the tool change to the minimum number. Figure 5 (a) shows the path resulting from this simulation. On the other hand, figure 5 (b) is the one resulting from the proposed formulation in section 3 above. The total path lengthes are 963.8 and 612.5 in units for figure 5 (a) and (b) respectively. Eventhough tool change is more frequent in figure 5 (b), the completion of punching takes much shorter time than figure 5 (a), i.e. reduced by 8.3% approximately.

Therefore, all the pathes shown in the figure 1 (a), (b) and figure 5 (a) are not the global optimum solutions.

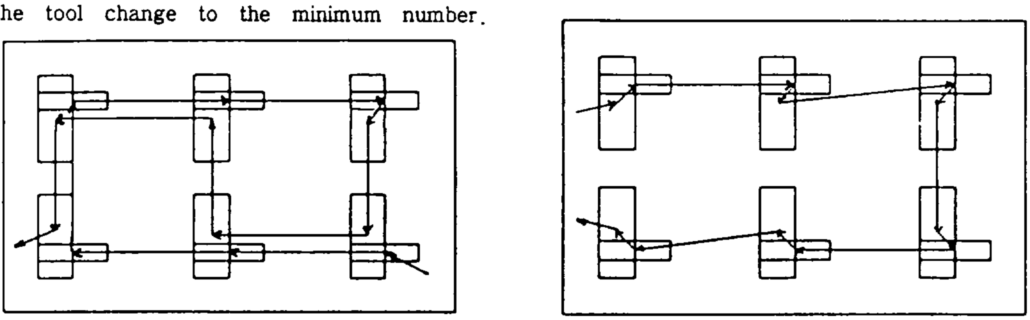
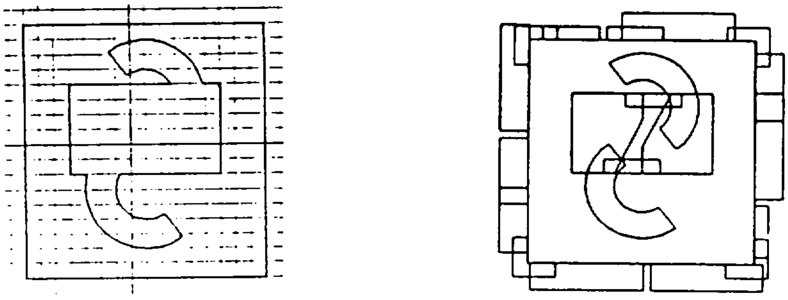
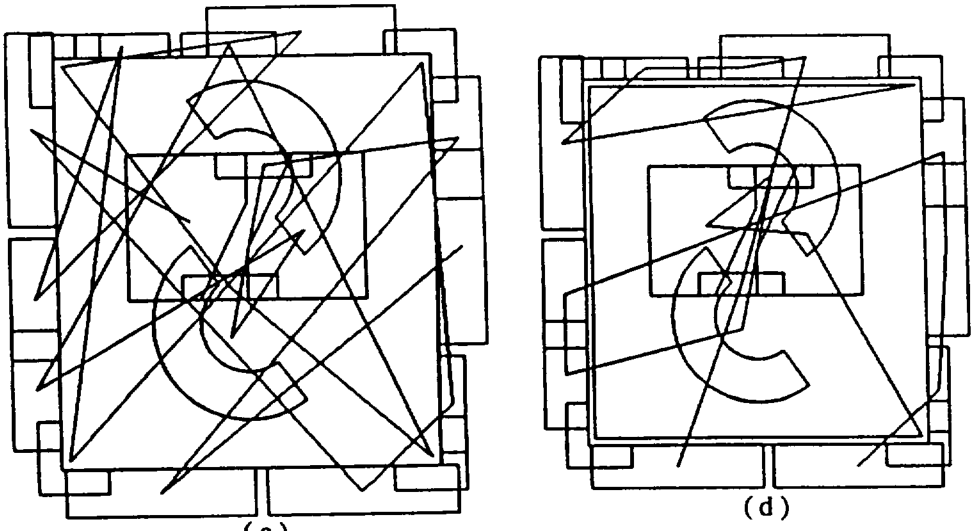

(a) (b)

Fig. 5. Tool path (a) by conventional strategy and (b) by the model proposed in this work.

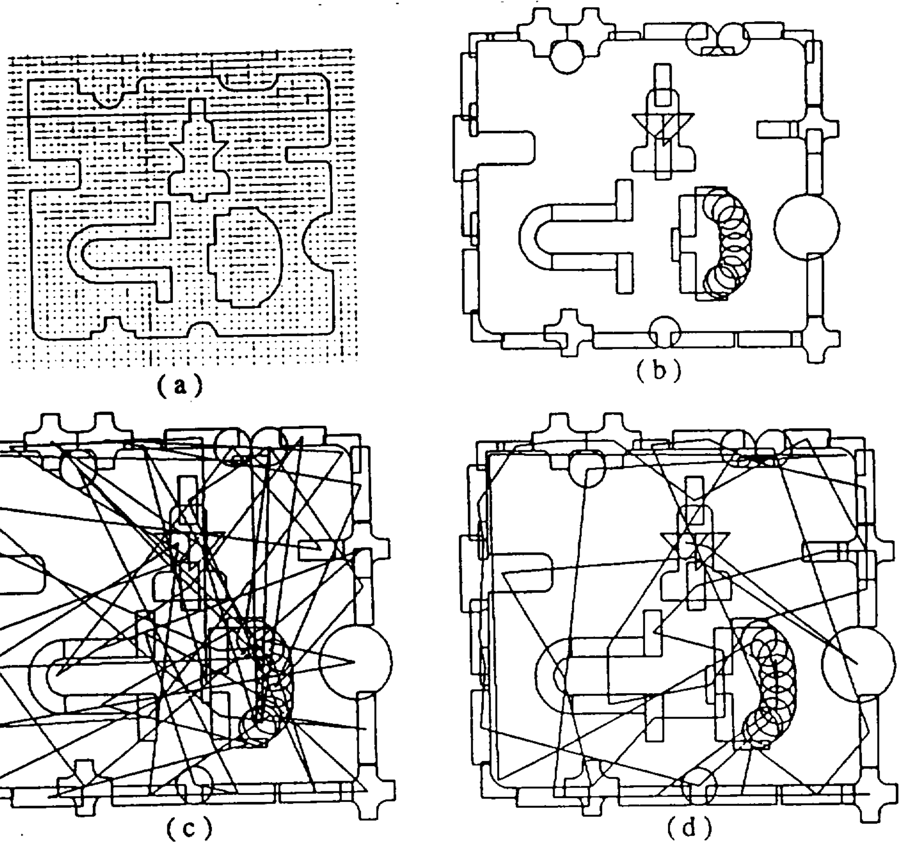
Figures 6 (a) and (b) are the example of the sheet metal part to be fabricated and the result of automatic tool selection from (조, 1992) respectively. Figure 6 (c) is the initial tool path which is generated randomly. Figure 6 (d) is the final path obtained using the tabu search. Here the tabu search is assumed to have reached a near-optima when it makes another 1000 moves to new configurations without no further improvement of the cost function. The path length and total processing time converge from 254.2 units and 9.1 sec to 182.5 units and 2.9 sec respectively.


(a) (b)


(c)

(d)

Fig. 6. Example of tool path optimization : (a) sheet metal part (b) selected punching tools and their locations (c) initial random path (d) final path.


(a)

(b)

(c)

(d)

Fig. 7. Example of tool path optimization : (a) sheet metal part (b) selected punching tools and their locations (c) initial random path (d) final path.

Fig. 8. Convergence of the cost from an initial cost of 22.5 sec to a final cost of 6.6 sec during tabu search for figure 7.

Another example is figure 7. The tool selection also comes from (조, 1992), and the initial tool path is obtained in the same way as above. Figure 7 (d) is the optimal path using the tabu search - the initial configuration of 1346.4 units and 22.5 sec converged to 749.8 units and 6.6 sec in path length and processing time respectively.

Figure 8 shows the convergence of the cost (total punching time) during the tabu search for the problem in figure 7. As can be seen from the curve, the tabu search eventually approaches the near-optima.

Tool Installation of Turret

Usually, tools of frequent usage have been installed permanently on the turret in practice. On the other hand, a few tools will be added or withdrawn depending on the shapes of the sheet metal parts. As a common practice for the permanent tool setting, a well-experienced person arranges the order of tools on the turret based on heuristics if available. Unfortunatelly, however, there is no explicit or quantitative measure whether the current turret configuration is efficient or not.

Conclusion

As a powerful optimization procedure for the combinatorial problems, tabu search is introduced to optimize the punching tool path for the numerically controlled punch press in sheet metal fabrication.

The conventional strategy of restricting the tool changes to the minimal to optimize the tool path is reviewed briefly. In this work, through a simple simulation, it is noticed that the above strategy might lead to a local minima instead of a global one. On the contrary, the proposed model, in which tool changes are allowed more frequently than in the aforementioned strategy, proves to be solved easily in a reasonable quality using the tabu search with fast computing time less than 2 minetes on 15 MIPs Unix workstation for the sample problems above.

Also some comments are made to the configuration of the turret where punching tools are installed by a well-experienced person either permanently or temporarily. Any further study would be interesting concerned with the turret configuration in regards to the efficiency or the guide for the improvement of the total processing time including the other fabrication methods such as laser cutting, flame cutting and etc.

References

AMADA, 1990, Specification of NCT (Numerically Controlled Turret Punch Press) PEGA, AMADA Company Ltd., Japan

BRAVO 3, 1988, Sheet Metal Design/ Fabrication User's Guide, U.S.A.

Bland J. A. and G. P. Dauson, 1991, Tabu search and design optimization, *Computer-Aided Design* Vol.23 No.3 April, 195~201.

Cerny, V. 1985, Thermodynamic approach to the travelling salesman problem : an efficient simulation algorithm, *J. Opt. Theory Applic* Vol.45, 41~51.

조경호, 이건우, 1992, NC 판금작업에서의 자동 공구선정, 대한기계학회 논문집(게재예정)

CIMATRON '90, 1990, CIMATRON Co., Israel.

EUCLID-IS, 1987, Sheet Metal Module-Reference Manual, Matra Datavision, France

Friden C., A. Hertz and D. Werra, 1990, TABARIS : An exact algorithm based on tabu search for finding a maximum independent set in a graph, *Comput Opns Res.* Vol.17, No.5, 437~445.

Garey, M. R. and D. S. Johnson, 1979, Computers and Intractability : A Guide to the Theory of NP-Completeness, W.H. Freeman and Co., USA

Glover, F., 1977, Heuristics for integer programming using surrogate constraints, *Desion Sci,* Vol.8, 156~166.

Glover, F., 1986, Future Paths for integer programming and links to artificial intelligence, *Comput. Operations Res.* Vol.13, 533~549.

Kirkpatrick, S., Jr. C. D. Gelatt and M. P. Vecchi, 1983, Optimization by simulated annealing, *Science* Vol.220, 671~680.

Laarhoven, P. J. M. and E. H. L. Aarts, 1988, *Simulated Annealing : Theory and Application,* Reidel Publishing Co.

Ledermann W., 1980, *Handbook of Applicable Mathematics* : Volume I ALGEBRA, Editors W. Ledermann and S. Vajda, John Wiley & Sons Ltd.

Raggenbass, A. and J. Reissner, 1989, Stamping-Laser Combination in Sheet Processing, *Annals of the CIRP,* Vol. 38/1/1989, 291~294.

Raggenbass, A. and J. Reissner, 1991, Automatic Generation of NC Production Plans in Stamping and Laser Cutting, *Annals of the CIRP,* Vol. 40/1/1989, 247~250.

UNIGRAPHICS Ⅱ, 1991, McDonnel Douglas, U.S.A.

Widmer M., 1991, Job Shop Scheduling with Tooling Constraints : a Tabu Search Approach, *J. Opl Res. Soc.* Vol. 42, No.1, 75-8210.

〈國文抄錄〉

Tabu Search를 이용한 공구 경로의 최적화에 관한 연구

'NP-hard' 문제로 분류되는 최적화 문제를 풀기위한 방법의 하나로서 최근 괄목할 만한 관심을 끌고 있는 tabu search 알고리즘을 간단히 소개하고, 이를 판재부품 가공분야에서 사용하고 있는 수치제어 펀칭기계의 공구경로의 최적화 문제에 적용시켜 만족할 만한 결과를 얻었다.