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SCHEDULING IN A MULTI-ROBOT WELDING SYSTEM

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Abstract**:** Multi-robot systems have been introduced actively in heavy industry in order to increase the productivity. However, since the configuration of workpiece is complex and multiple robots are disposed densely in a working area, collision between adjacent robots could occur. Because the collision prevents effective production, collision occurrence should be avoided. This paper reduces the problem of minimization of total welding time subject to collision/deadlock avoidance among multi-robots to a path optimization one, and solves it through genetic algorithm (GA). Its effectiveness is shown by numerical simulations with practical workpieces.

Keywords: Robot, Scheduling algorithms, Path planning, Genetic algorithm, CAD/CAM, Industry automation

1. INTRODUCTION

Multi-robot systems have been introduced actively in heavy industry in order to increase the productivity. However, since the configuration of workpiece is complex due to multi-kind small lot production especially in shipbuilding and multiple robots are disposed as densely as possible in a working area to get high productivity, collision between adjacent robots could occur. Because the collision prevents effective production, collision occurrence should be avoided.
This paper aims to solve the issue by optimizing welding paths, that is welding orders of robots.

2. WELDING JOB AND INTERFERENCE

The multi-robot welding system studied here is an equipment which constructs various types of workpiece effectively in shipbuilding and consists of 10 welding robots (Sugitani, *et al*., 1996). These 10 welding robots perform welding in parallel with each other. Each of them is a multi-link robot with 6 axes and is hanged by the sliding equipment with 3 axes from the ceiling as shown in Figure 1. Therefore, they can move in the direction of x-axis, y-axis and z-axis by the movement mechanism with 9 axes in all. Each robot has a welding torch at the tip of the arm.

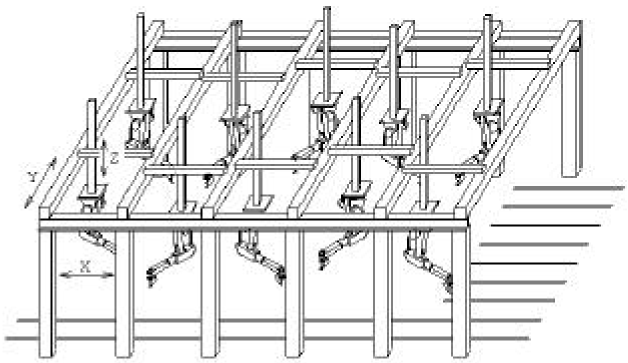

Fig.1 Configuration of multi-robot welding system

Figure 2 shows a typical example welded by the multi-robot welding system. Figure 2 also shows the cross section in the central part of a bulk carrier. Transverse panels in Figure 2 are workpieces. One of transverse panels is illustrated in Figure 3. The features are that it is large-sized and complicated-shaped with many curves and many narrow sections. Due to the feature, welding lines are large in number and placed in the various directions. Oil tankers and other types of ships have the similar features.
The welding stage is determined as a width of 8 m and a

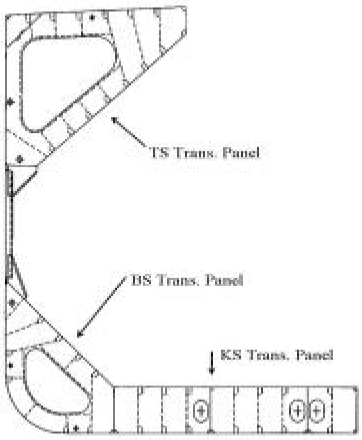

Fig.2 Structure of the central part of a bulk carrier

length of 16 m (an area of 128 m^2) based on the maximal width and maximal length of workpieces. In the case of multiple robots, it is desirable that more than one workpiece are arranged in the welding stage. Furthermore, those workpieces should be arranged, as the welding loads of each robot are as equal as possible. Then, the variance among operational times of robots becomes small and thus the production efficiency rises. Figure 4 is an example of arrangement of two nearly triangular transverse panels.

The welding stage is assigned to 10 robots. Figure 5 shows the resultant area partition. In Figure 5, solid lines in the horizontal and vertical direction are the boundary lines of partitioned areas. The area surrounded by two dotted lines sandwiching one solid line are overlapped boundary areas between adjacent robots.

As shown in Figure 4, all of the directions of welding lines are not the same. So, various attitudes are required to robots. Thus, overlapped boundary areas must be wide enough so that there is no unweldable part as illustrated in Figure 5. Figure 5 also indicates the state of collision occurrence. For example, R5 robot is about to move from the position indicated by the black circle in the left and lower direction. On the other hand, R6 robot is about to move from the position indicated by the black circle in the left and upper direction. When a robot begins an action, it creates the interference area for preventing the collision, which is illustrated as a painted circle or ellipse. In case of motions of R5 and R6 robots in Figure 5 mentioned above, these motions are interfered because their destinations are the common boundary area of R5 and R6 robot. When such an interference happens, the robot beginning its action earliest has priority over

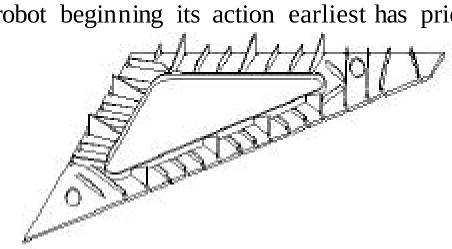

Fig.3 Example of transverse panel

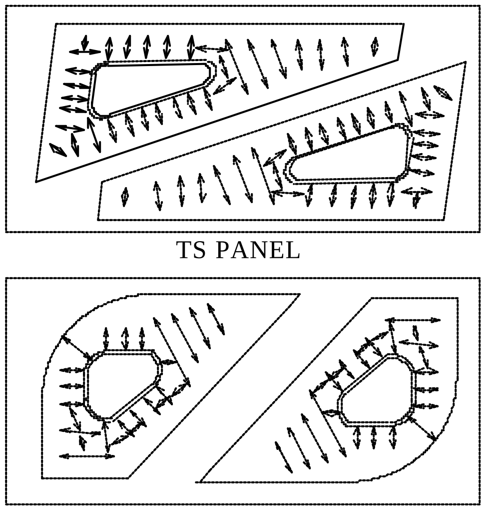

Fig.4 Example of arrangement of transverse panels

other robots and these other robots must wait until the state of interference dose not exist.

There is a special state called as a deadlock among the states of interference. For examp le, consider the state that robot A waits for the end of an action of robot B because of interference. Then, if robot B also waits for the end of the action of robot A, this state of interference cannot be removed automatically. Such an interference is a deadlock. In order to remove a deadlock, manual operations of operators are necessary.

3. JOB EFFICIENCY OPTIMIZATION PROBLEM

Programs about the actions of multi-robot are generated in CAD/CAM system, which are placed at the upper level in the hierarchical multi-robot welding system. The CAD system sets 3-dimensional shape data of workpieces and weld design data such as locations of welding line and leg length of weld. The CAM system determines assignment of welding lines to robots, welding orders of robots and attitudes to welding lines (Sugitani, *et al*.,

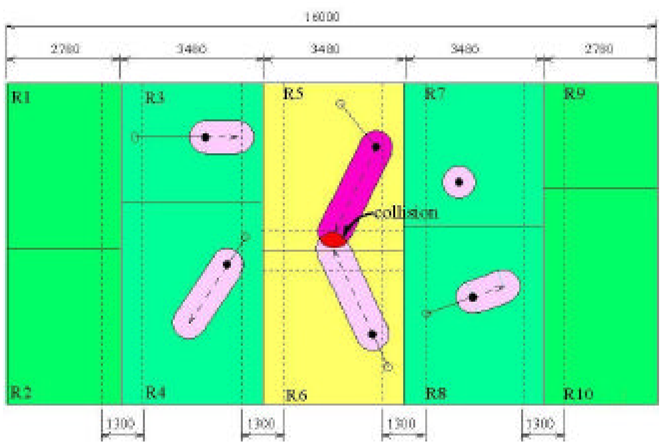

Fig.5 Partition of the welding stage and occurrence of interference welding directions

1996). Maximization of job efficiency is minimization of completion time (makespan) in a multi-robot welding system. Deadlocks lengthen the makespan and require manual operations, so deadlocks do not want to be occurred as frequently as possible.

Change of welding orders of robots enables to raise the efficiency of movement between welding lines and to shift the timing of occurrence of interference. Consequently, this issue is defined as the optimization problem which determines welding orders to minimize the following objective function F:

$$F = \max_i C_i + p \quad \text{-->} \quad \text{minimize},$$

where C_i is a completion time of welding job of robot i and p is a deadlock penalty, which is given by the following formula:

$$p = \text{penalty time} * \text{number of deadlocks}.$$

The welding jobs of robots consist of the following seven basic actions:

1) wirecut, nozzle cleaning/exchange and turn
2) aircut 2
3) going down
4) sensing
5) welding
6) going up
7) aircut 1

These seven actions are repeated in this order. Action 1) is a preliminary job for welding. The position varies dependently on whether the job is a nozzle cleaning or exchange. The position of nozzle cleaning is determined by the end position of the preceeding welding line and the starting position of the present welding line. The position of nozzle exchange is specified to each robot. Nozzle exchanges are executed when the welding elapsed time after beginning the use of the present nozzle exceeds the time limit.

Action 2) is a motion to the starting position of each welding in the x-y plane and is called aircut.

Action 3) is an approach to the appropriate position for beginning welding in the direction of z-axis.

Action 4) is to detect the starting point of welding.

Action 5) is the main action and just represents welding. There are two kinds of welding: horizontal welding and vertical welding.

Action 6) is to retract and to rising after welding.

Action 7) is a motion to the position of next action 1) and is also called aircut.

At the beginning of the job, that is time 0, each robot is placed at the specified initial position. Each robot starts from the initial position and repeats seven actions and then returns to the initial position after completing all jobs. The time of each action is expressed as follows if interferences do not occur.

$$t_1 = \begin{cases} T_W + T_C + T_T & ; \text{ nozzle cleaning} \\ T_W + T_A + T_T & ; \text{ nozzle exchange} \end{cases}$$

$$t_2 = d(x^W(k_j), x^S(k_j)) / v_H$$
$$t_3 = h / v_V$$
$$t_4 = T_S$$
$$t_5 = \begin{cases} d(x^S(k_j), x^E(k_j)) / w_H & ; \text{ horizontal welding} \\ d(x^S(k_j), x^E(k_j)) / w_V & ; \text{ vertical welding} \end{cases}$$
$$t_6 = h / v_V$$
$$t_7 = d(x^E(k_{j-1}), x^W(k_j)) / v_H$$

The notations used by above formulae are as follows.

k_j : number of j-th welding line
h : distance of going up/down
v_H , v_V : horizontal, vertical aircut velocity
w_H , w_V : horizontal, vertical welding velocity
T_W : wire cut time
T_C : nozzle cleaning time
T_T : turn time
T_A : nozzle exchange time
T_S : sensing time
$x^S(k_j)$: starting position of j-th welding
$x^E(k_j)$: ending position of j-th welding
$x^W(k_j)$: position of action 1) in j-th welding
d(a,b) : distance between a and b
t_i : time required for action i) ; i=1,…,7

4. APPLICATION OF GENETIC ALGORITHMS

In this optimization problem, there are following complex factors.

1)Interferences or deadlocks occur.
2)The necessity of nozzle cleaning and exchange depends on the past history.

Due to them, it is not easy to develop an exact algorithm. Then approximate algorithms are required. The search space of this optimization problem is huge. On the other hand, we want to find good solutions within the practical time limit. From these reasons, we have adopted genetic algorithm (GA) (Goldberg,1989).

As for the size of search space, for example, the permutation of the case study considered in the next section is as follows.

$$15! * 11! * 19! * 19! * 42! * 32! * 18! * 18! * 15! * 17!$$
$$= 5.44433 * 10^{198}$$

It is an extraordinary size. In case of huge search space, methods in which several regions scattered appropriately are searched parallel are very powerful. GA is one of such methods.

4.1 Chromosome Representation

The decision variables of the problem are welding orders, so the chromosome of an individual in GA is represented as shown in Figure 6. The number of welding jobs assigned to each robot is not necessary the same. The set

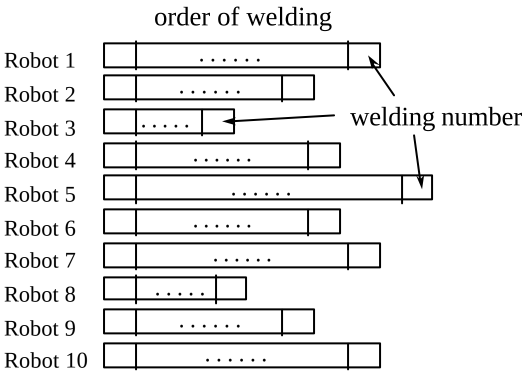

Fig.6 Chromosome representation

of welding orders of 10 robots forms one individual.

4.2 Crossover and Mutation

For robot k, k=1,...,10, pairs are chosen randomly. From each pair, two new individuals are generated by replacing the welding orders of robot k with the new ones created by order crossover (Davis,1985)(Figure 7). Then for each individual, the new individual is generated by replacing the welding orders of robot k with the new ones created by mutation. Mutation is defined as transferring subsequence of welding orders of robot k (Figure 8).
In mutation, robot k and the subsequence are chosen randomly. In crossover and mutation operations, original individuals remain among the population, so the population becomes larger temporarily

4.3 Fitness

This optimization problem is to minimize the objective function F, so the fitness is defined as -F. In order to evaluate the function F, the completion time of welding job of each robot and the number of deadlocks are necessary. However, these values cannot be known in advance. All behaviors of all robots are required to know these values. Therefore, we have developed the simulator of multi-robot welding system. Given welding orders of all robots, this simulator outputs all behaviors of all robots including the completion time of welding job of each robot and the number of deadlocks.

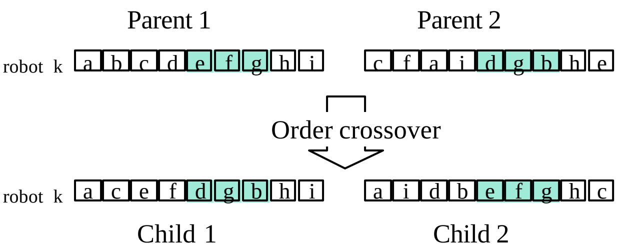

Fig.7 Crossover

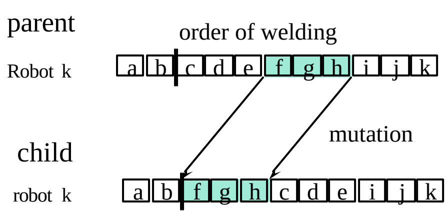

Fig.8 Mutation

4.4 Selection

The population of next generation is selected by ranking strategy. If the population is formed by only individuals of higher rank, the divergence in the population is lost and thus escape from local optima is often difficult. On the other hand, though the probability is low, it is expected that individuals with high fitness be generated from individuals with low fitness. This is why we adopted ranking strategy.

4.5 Two-step optimization method

In the method mentioned so far, each robot is dealt with equally. On the other hand, there is another method focusing on a particular robot. In some cases of workpieces, the load of a certain robot is much larger than those of other robots. Roughly speaking, in such cases, so long as the welding order of the maximal loaded robot is optimized, those of the other robots need not be optimized. Based on this consideration, we have proposed the following two-step optimization method:
<u>step 1:</u>
Assuming that only the maximal loaded robot is in operation, we solve the path optimization problem for the robot by GA.
<u>step 2:</u>
In step 2, the welding order of the maximal loaded robot is fixed to the order obtained in step 1. Then we solve the path optimization problem for the other robots by GA.
In this two-step optimization method, the optimal value of the objective function in step 1 gives the lower bound to the value of the objective function in step 2. Therefore, in step 2, the computation can be terminated when the best value of the objective function is equal to the lower bound.
The maximality of load can be estimated by comparison among the total times of action 5) of robots. The total time of action 5) is the sum of the time for only welding and is computated in advance. Because this time monopolies 40-50 % of the total work time, if the time of a certain robot is much larger than those of other robots, we can think the robot as the maximal loaded robot.

5. CASE STUDIES

Our GA is applied to TS transverse panel. TS transverse panel is one of typical workpieces in a bulk carrier. Two TS transverse panels are placed in the specified welding stage as shown in Figure 4. The number of welding lines assigned to each robot is as follows.

15,11,19,19,42,32,18,18,15,17

The penalty parameter of deadlock is 120 second.

Before showing results by GA, we show results by random search in Figure 9. In Figure 9, histograms of 10,000 cases and 100,000 cases are drawn. (a) indicates values of objective function and (b) numbers of deadlock. Figure 9 shows that random search cannot find a solution with no deadlock even in 100,000 searches. Comparing the histogram of 10,000 cases with that of 100,000 cases, both are close to the normal distribution with nearly equal mean and variance. Considering the probability based on the normal distribution, we guess that it is very difficult for random search to find a solution with no deadlock.

Next, we show results by GA. Table 1 shows the results to different pairs of population size and maximal generation. Pairs are chosen on the condition that the

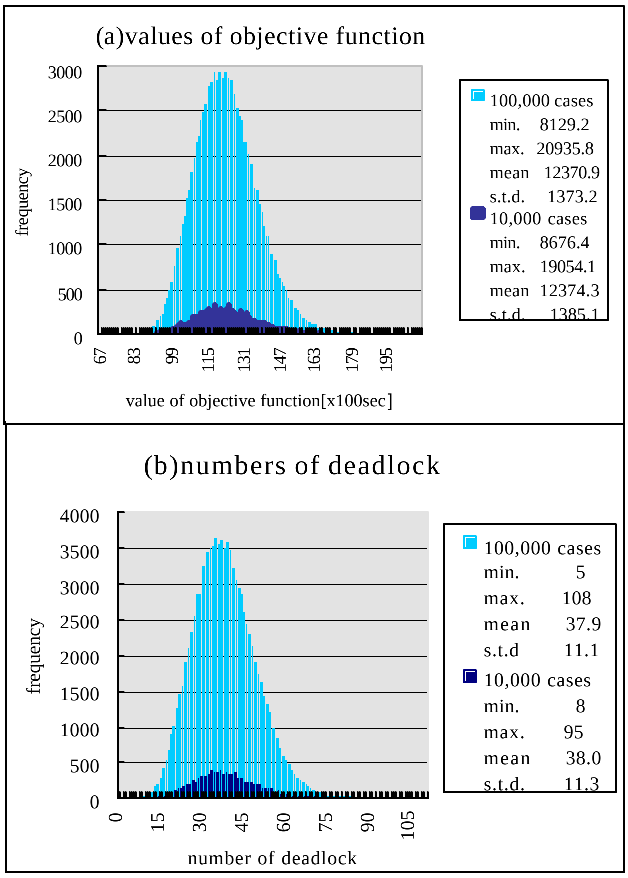

Fig.9 Histograms of objectives in case that welding orders are set randomly

Table 1 Comparison of results with respect to parameters

parameters		values of objective functions [sec]			
population size	generation	min.	max.	mean	s.t.d.
10	1600	6831	6990	6896	49.5
20	800	6841	6970	6888	43.1
40	400	6844	6918	6878	24.4
80	200	6828	6915	6875	27.7
100	160	6847	6945	6893	33.9
120	133	6854	6929	6882	21.6
160	100	6853	6926	6891	21.1

computing time is nearly one hour by a personal computer with Pentium III 450 MHz CPU. 10 cases of different random number are computed to each pair. Results are varied dependently on random numbers, so in Table 1 (also in Figure 10, Figure 11 and Table 2), maximal, minimal and mean values of objective function among 10 cases are shown. Solutions with no deadlock are obtained in all cases. From these results, we adopted the pair: (population size, maximal generation) = (40,400). Figure 10 shows the result in case that maximal generation is 1000 instead of 400. Even if maximal generation is lengthened to 1000, the improvement rate is only about 0.5%. Therefore, it is sufficient that computing is terminated at 400 generation.

Figure 11 indicates the dependence on initial individuals. The initial individual in all results in Table 1 and Figure 9 is an output by CAM system. In CAM system, the working area of each robot is divided into 4 zones and welding orders are generated so that the movements by the zone of all robots become as synchronous as possible. This is a good idea, but this solution is not satisfactory. In this solution, deadlocks occur several times and the value of objective function is 9418. However, as compared with results by initial individuals set randomly, the former

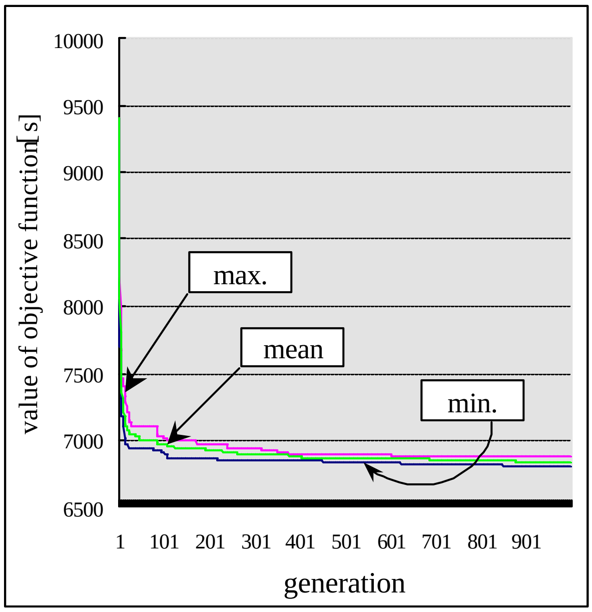

Fig.10 Transitions of objective function in case of population size = 40

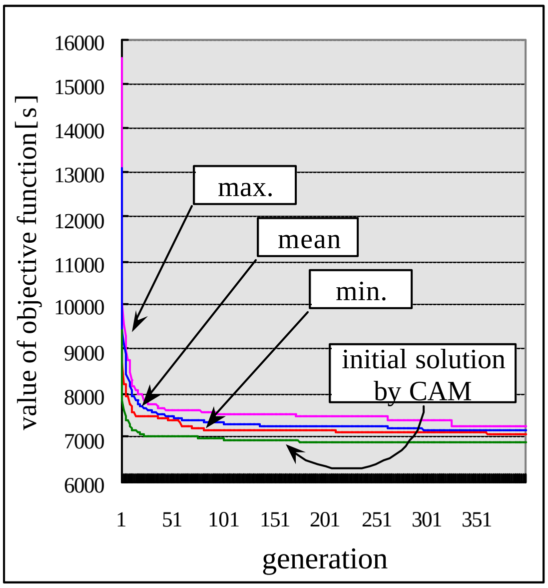

Fig.11 Dependence on initial individuals

result is better. Figure 11 shows these results. This suggests the necessity of synchronous movement among robots.

Table 2 shows the result of two-step optimization method. The maximal loaded robot is robot 5. As compared with the result in Table 1, the result in Table 2 is better.

In two-step optimization method, however, we must find the maximal robot in advance. If this is not easy ordinary GA is better.

Table 2 Results of two-step optimization method

value of objective function [sec]								convergence rate
first step				second step				
min.	max.	mean	s.t.d.	min.	max.	mean	s.t.d.	
6751	6778	6763	9.8	6751	6864	6784	38.6	0.7

6. CONCLUSION

In the multi-robot welding process of shipbuilding, the minimization system of job completion time has developed by GA. As compared with the welding orders used currently (output of CAM system), the solution by GA has no deadlock and has higher efficiency. Two-step optimization method has higher performance. Since there are cases in which this method is difficult to be applied, one of these two methods should be selected according to situations.

Besides the minimization of job completion time, robustness of obtained schedules is also important. Because of modeling errors and some machine troubles, the deviation between the real operation and the schedule could occur. In such a case, if the deviation is not so large, it is desired that the schedule is not necessary to be changed. In path optimization, the arrangement of workpieces is specified. The optimization of the workpiece arrangement is expected to get higher productivity. These are future works.

REFERENCES

Davis ,L.(1985).
Applying Adaptive Algorithms to Epistatic Domains. Proc. of 9-th Int. Joint Conf. on Artificial Intelligence, pp.162-164

Goldberg,D.E.(1989).
Genetic Algorithms in Search, Optimization and Machine Learning, Addison-Wesley

Sugitani,Y. *et al*.(1996).
Multi-Robot Welding System for Shipbuilding Subassembly Fabrication. NKK TECHNICAL REVIEW, No.75,pp.58-67