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A genetic algorithm approach to piping route path planning

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A genetic algorithm (GA) approach to support interactive planning of a piping route path in plant layout design is presented. To present this approach, the paper mainly describes the basic ideas used in the methodology, which include the definition of genes to deal with pipe routes, the concept of spatial potential energy, the method of generating initial individuals for GA optimization, the zone concept in route generation using GAs, the evaluation of crossover methods, and definition and application of fitness functions. The prototype system that has been developed based on the methodology gives designers an environment to design a piping route path in an interactive and collaborative manner with a very simple operation. The GA optimization technique generates a route path through evolution of genes that represent the pipe route. A designer evaluates the route path, modifies it, conducts another GA optimization and/or repeats the procedure until the appropriate route is designed. The paper also presents some simulation results using the prototype system to show the validity of this approach.

Keywords: Pipe route planning, genetic algorithm, optimization, conceptual design, computer-aided design

1. Introduction

To be competitive in markets, companies are required to create timely innovative products to satisfy their customers' requirements, which are becoming increasingly individualized and diverse. Among several approaches that have been proposed to comply with those requirements, the study focuses on the importance of interaction and concurrency in design issues and pursues a methodology to support conceptual design.

Given the initial specifications for a product, a designer must create the description of a physical device that meets those requirements. The final design must simultaneously meet cost and quality requirements, as well as meet the constraints imposed by activities such as manufacturing, assembly and maintenance. In addition to this basic approach to product design, the competitiveness of companies is closely related to their capability to create timely innovative products to satisfy their customers' requirements, which are becoming increasingly individualized and diverse. Concurrent engineering (CE) (Fukuda, 1993) is one of the key concepts meeting those challenges. In addition to the key idea to develop high quality products and offer them at a lower price and in significantly shorter time to the competitive global market, concurrent design (CD) (Finger *et al.*, 1992) is concerned with more sophisticated designs using considerations of various design phases simultaneously and co-operatively. Several methodologies of CD, including multi-agent architecture, engineering data management, virtual manufacturing, etc., have already been applied to design support systems, and their availability and effectiveness have been reported.

In the meantime, the radical notion that interactive systems are more powerful problem-solving engines than algorithms is making a new paradigm for computing technology built around the unifying concept of interaction (Wegner, 1997). As for designers who use design support systems as a tool to work on design tasks, thoughts of designers are effectively activated by nice system interactions (Hancock and Chignell, 1989). The interactions may stimulate designers to produce some innovative ideas. Using the basic categories of interaction style, including key-modal, direct manipulation and linguistic (van Dam, 1997), various approaches have been studied to build interactive systems (Newman and Lamming, 1995).

The study focuses on these two paradigms, i.e. concurrency and interaction in design issues, and proposes a genetic algorithm (GA) approach to pipe route planning

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(Takakuwa, 1978) in layout designs. Layout design is critical in engineering designs of various production systems, chemical plants, power plants, factories, etc. (Hatamura, 1993). Its main aim is to utilize the functionality of component equipments effectively and to satisfy the spatial constraints appropriately. Pipe route planning is one of the key issues in these layout designs. The author's goal is to create a computer-based design system with a powerful problem-solving engine that will enable a designer to make concurrent rather than sequential consideration of requirements regarding pipe route planning in a collaborative and interactive manner, and to evaluate the impact of design alternatives in terms of various perspectives.

In the following, first the piping around us and its route planning is reviewed. Then a detailed description of the methodology based on GA is provided, which includes a definition of a gene, the concept of spatial potential energy, a method to generate initial individuals, the zone concept in route generation, evaluation of the crossover method, and a definition and application of fitness functions. Lastly, some results of simulation based on the methodology are presented.

2. The piping around us and its route planning

Simply speaking, the aim of piping is to transfer a certain volume of liquids from a starting point to a destination point within a certain time interval through an appropriate route. Piping is very popular in our daily lives and we can see it in many places, for example, in electric power plants, chemical plants, factories, buildings, sewage, automobiles, etc. Figure 1 shows an example of plant piping.

As for the design of piping, the design should be considered from various view points. First of all, it is very important to determine the appropriate flow speed from an economic point of view. The inner diameter of a pipe can be calculated, based on the flow speed, to minimize overall pressure losses. In plant piping designs, pipes are categorized into several classes: process lines for the insides of equipment, yard lines for the outsides of equipment and utility lines for water, steam and fuels. Pipes of the same category in plant pipings, should be arranged so that they are placed together. From the view point of mechanical design, on the other hand, pipes are categorized differently, namely, in terms of the place of installation: on the ground, in the air and under the ground. Maintenance is also another important factor to be considered in designing a pipe route. Although piping should be accessed easily for maintenance, it should not be placed on the walk way. Equipment should be placed in such a way that pipes are placed in parallel or rectangular, basically avoiding a diagonal path. Each structure should possess the durability to support the piping. For example, the supporting materials should have good heat resistance so that they can minimize shape deformation.

As far as piping design is concerned, there are so many things to consider from various perspectives, as mentioned above, and the development of piping designs, therefore, is a

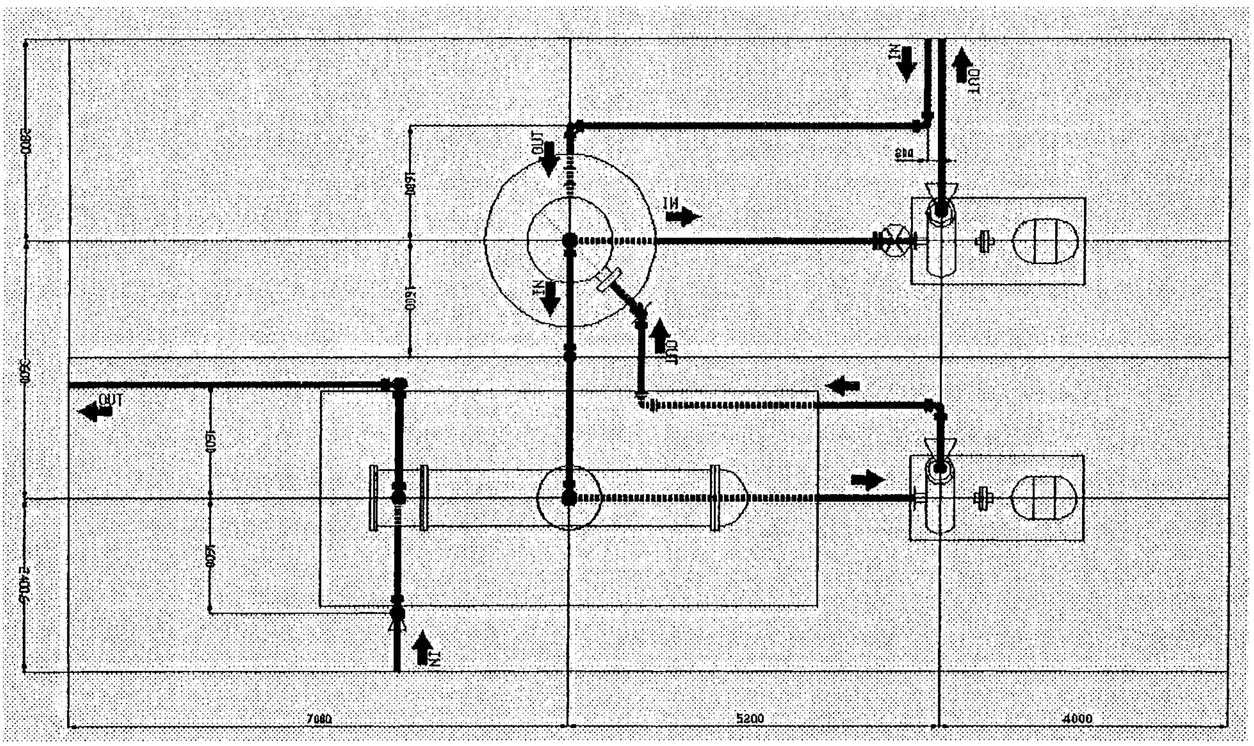

Fig. 1. An example of piping route path planning.

difficult and time consuming task. One of the most difficult aspects of piping design is to conduct pipe route planning, which is to design the appropriate route for piping connecting the starting and goal points. If the optimal pipe route is designed, it could be said that the most difficult part of piping design is completed. But it is very difficult even for a skilled designer to design the optimal pipe route especially under very complicated spatial constraints, which is just like going through a labyrinth, while keeping an appropriate space between the pipe and the surrounding walls or the equipment metaphorized as obstacles.

As a general approach to piping design, a designer initially creates an appropriate design model, and interactively and iteratively modifies the model in a trial-and-error manner until an appropriate design specification is completed. The approach presented in this paper focuses on this interactive, iterative and concurrent session of designing. During the designing session using the methodology, various pipe route candidates are generated based on the starting and goal points, and/or several subgoals if necessary, all of which are specified by the designer using a simple pointing device operation, or mouse, which cannot interrupt the designer's thoughts about piping design. The research uses the GA optimization method in the approach here, however, the goal of the approach is not just to find the best pipe route, but rather to present the designer with several appropriate routes that could assist the designer in finding the *best* pipe route. A designer could collaboratively develop pipe route planning, referring to the proposed pipe route. The GA approach used here will be described in more detail in the remaining sections.

3. Piping route generation by GA

3.1. *Outline of GA for design optimization*

As an optimal search method for multiple peak functions, GA, stemming from the evolution of living things, is applied to various optimization problems and its validity has been verified so far (Fujita *et al.*, 1993; Yamamura and Kobayashi, 1994; Matsumura and Usui, 1996). GA is a kind of programming technique using a mechanism of biological evolution. Because living things have been evolving through natural selection or mutation, and changing themselves so as to match the environment, GA evolves the solution to obtain a better answer to a given problem (Goldberg, 1989, 1994; Agui and Nagao, 1993).

The general formula to solve design parameters in an objective function under some constraint conditions is shown below:

Find $x = \{x_1, x_2, \ldots, x_n\}$ (design parameters)
to minimize $f(x)$ (objective function):
Subject to $g_j(x) < g_j; (j = 1, 2, \ldots, M)$
(constraint conditions)

To apply GA to solve optimization problems in design, design parameters versus character gene sets, and the objective function versus the fitness value must be considered and constraint conditions may be included in the objective function under a penalty function. In this way, after repeating GA manipulations, a new character set that represents a new generation can reveal the appropriate design parameters.

3.2. *Definition of chromosome in route planning*

In order to use GA in pipe route planning as one of the optimization problems, a route from a starting point to a destination point is represented by a character string and is regarded as a design parameter.

In the approach given here, the working space for pipe route planning is represented by a model, and the space is divided into cells of $M \times N$. A route is represented using a combination of cells connecting a starting cell and a destination cell. To represent the direction of a route path, a unit vector set, $\boldsymbol{v} = \{\boldsymbol{r}, \boldsymbol{u}, \boldsymbol{l}, \boldsymbol{d}, \boldsymbol{0}\}$, is defined; each vector represents right, up, left, down and stop, respectively; and a character string of $\{1, 2, 3, 4, 0\}$ corresponds to each vector. Using information on the cells that compose the route, each individual is coded. For example, the gene type for a route is expressed using symbols including $\{1, 2, 3, 4, 0\}$, where zero means that the current point has already reached the destination cell. In Fig. 2, the route C_1 is represented by $C_1 = \{1, 1, 1, \ldots, 2, 1, 0, 0, 0, 0\}$.

To summarize the above, the definition of a chromosome is as follows:

(1) each gene contains one character set $\{1, 2, 3, 4, 0\}$;
(2) the chromosome genotype is given by $C_1 = \{1, 1, 1, \ldots, 2, 1, 0, 0, 0, 0\}$; and
(3) a genotype represents a route path.

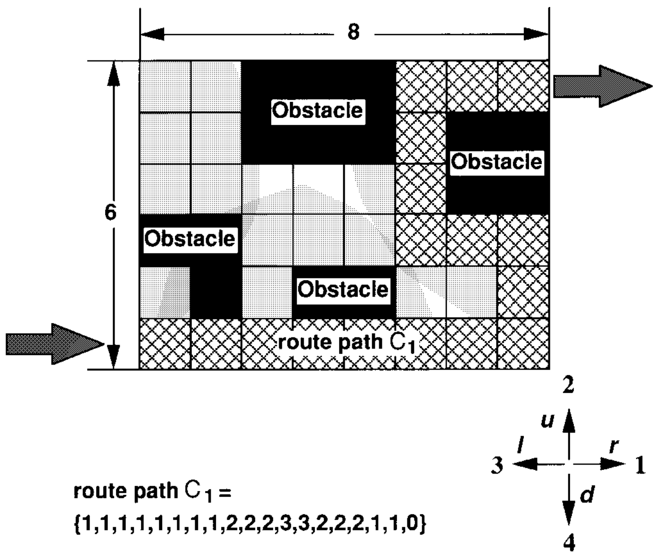

Fig. 2. Piping route path and its chromosome.

3.3. *Spatial potential energy in pipe route generation*

In pipe route planning, high priority is given to the shorter route path. In addition to this, a route must go along the wall and obstacles as closely as possible, avoiding a diagonal path, then the most appropriate route is designed. Using the concept of spatial potential, the degree of access to the wall or the obstacles is quantitatively calculated, and used as part of the objective function for generation of a pipe route using GAs.

To determine the distribution of spatial potential, the working space is divided into $M \times N$ ($M = 1, 2, \ldots; N = 1, 2, \ldots$), those cells that contain any portion of an obstacle are given the potential value P_n, each cell is given a potential value of $P_1, P_2, \ldots, P_{n-1}$ according to the distance from the obstacle cell. Those cells that are located next to the wall are given the potential value P_0, which means that the route path is more favourable if it goes along the wall. Only the positive values are used as a potential energy. The higher value means that the cell is far from the wall or the obstacle. Figure 3 shows some examples of potential energy settings. The current cell in Fig. 3a is located on an obstacle, thus a route path cannot take this cell, so its potential energy is high. The current cell in Fig. 3b is located next to an obstacle, thus the cell is favourable, just like in Fig. 3d, which is close to the surrounding wall. The current cell in Fig. 3c is not surrounded by anything so that it can be located but it is not stable. In this way, the potential energies of each cell are determined. Figure 4 shows an example of potential energy distribution.

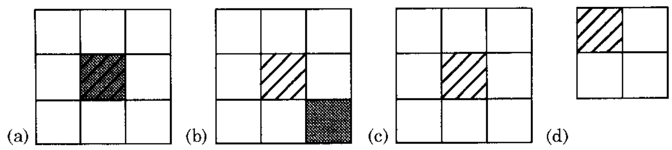

Fig. 3. Current cell (▨) and potential energy around the cell. (■) Cell on obstacles.

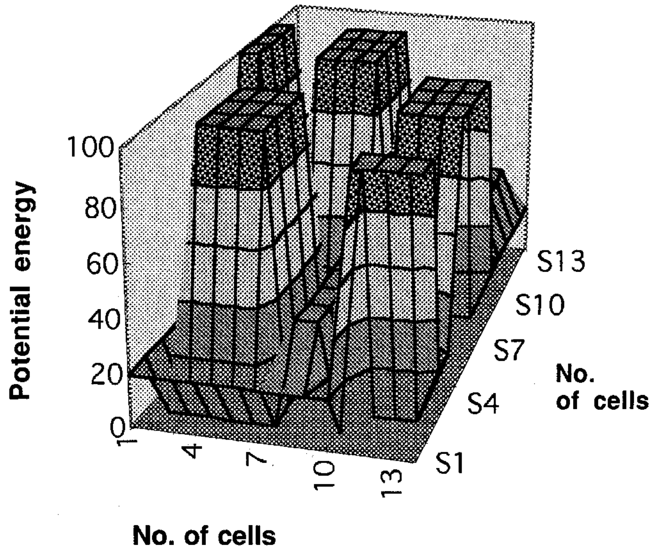

Fig. 4. Distribution of potential energy.

4. The crossover method

4.1. *Characteristics of genes*

Determination of crossover methods depends upon the application. For example, uni-crossover is suitable for the case where each gene has individual information, blend crossover is suitable for the case where the genotype has a continuous value. In the case of a piping route path, the genotype shows a continuous value. A route must connect a starting and a goal point. In addition to that, considering the layout of the equipment, the physical temperature conditions, maintenance and so on, the most appropriate route among various candidate routes is designed. In other words, how the goal point is to be reached is the important thing to consider.

Figure 5 shows a route and its genotype. The portion A in the route corresponds to the portion A of the genotype. A unit vector combination gives the characteristics of a portion of a route. These characteristics can be inherited by offspring through crossover operations.

4.2. *Applied crossover operations*

A route must connect two points, namely, the starting and goal points. The length of the genotype is variable and not fixed, which means that a genotype is elastic like a rubber band. Figure 6 illustrates a chromosome image indicating a piping route path. A route path is like a rubber band that is

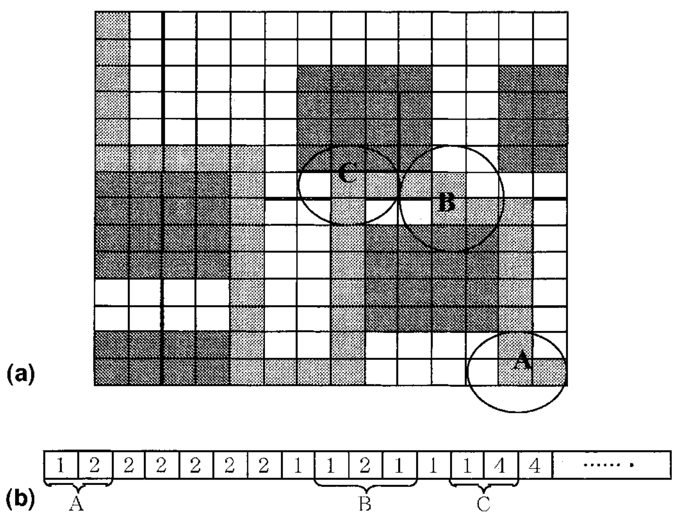

Fig. 5. (a) Route path and (b) its genotype: (■) Cells on obstacles.

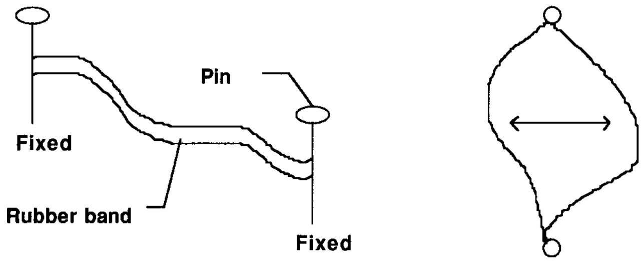

Fig. 6. Image of genotype.

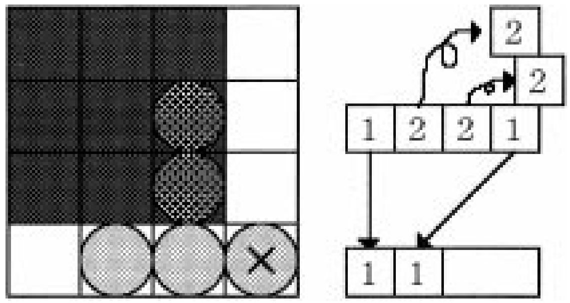

Fig. 8. A process to avoid obstacles: (■) obstacle, (●) invalid, (●) valid.

fixed with a pin in each of the terminals, and it expands smoothly.

Sometimes, genes having different lengths must be crossed over. To cover the differences in length, we act as shown in Fig. 7. Set the length of parent 1 to l_1, that of parent 2 to l_2 where $l_1 \leq l_2$. Then set one-half of l_1 to l_b. l_b is multiplied by a random number between zero and one and gives l_p. The portions between zero and l_p and between l_b and one are exchanged. Because the lengths of genes may differ from one another, an additional vector array may be inserted if the length of the generated gene is too short to connect to each end of the parent gene.

To avoid generating genes including obstacles, the potential value of each cell is checked to see if the cell is on an obstacle. If it is, a vector is repeatedly generated until the cell does not lie on an obstacle. In this way, we obtain those genes that do not contain obstacle cells in the earlier generations. As a result, a wide range of search area is considered in GA. Figure 8 shows an example of exclusive selection of vector arrays to avoid obstacles, where $\{1, 1\}$ is generated instead of $\{1, 2, 2, 1\}$. The route goes on the obstacle on the third cell if the second vector, $\boldsymbol{u}$, or 2 is applied. To avoid this, the two vectors are considered but skipped, and the following vector, $\boldsymbol{r}$ or 1 is applied.

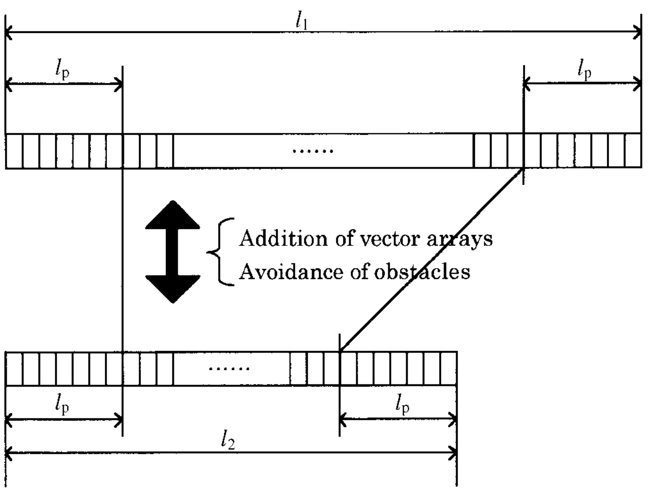

Fig. 7. Crossover for parents with different length.

From the results, two-point crossover tries to avoid obstacles, aggressively finds a new route, and can find a better route during earlier generations. On the other hand, uni-crossover can inherit characteristics from each parent at the same ratio; does not change the genotype; easily conducts crossover operations even between parents with different lengths; and can generate various kinds of vector arrays. The study mainly applies at two-point crossover operation, but uni-crossover operation is also applied as a control.

5. Introduction of tendencies in direction

5.1. *The concept and definition of tendencies in direction*

A gene goes from a starting point towards a goal point. The most important thing is that a gene must reach the goal point without fail, which means that a gene possesses the characteristics that it moves towards the goal. Otherwise, a gene randomly goes inside the search area, which is time consuming.

The concept 'zone' is defined so as to give chromosome tendencies in the direction of a route path from a current position towards the goal point. Figure 9 shows the eight zones that are defined. To determine a zone, co-ordinates of the current and goal cells are used. When the co-ordinates of the goal are (X, Y) and those of the current cell are (myx, myy), each zone is shown in Table 1.

Then, a priority vector is set to each zone. Figure 10 shows that priority vectors towards upper-right direction are preferred when a goal is in the first quadrant. In this case, $\boldsymbol{r}$ and $\boldsymbol{u}$ have higher priorities than other vectors. If the priority is set too high, however, all the chromosomes will have the same tendencies in direction and an appropriate route path will not be generated. The priority is set in a trial-and-error manner to generate chromosomes having a variety of route paths. Figure 11 shows a goal on the x-axis positive direction and $\boldsymbol{r}$ is set to have a higher priority. In this case, careful consideration is also taken so that a variety of route paths can be generated, otherwise all the route paths would only go straight in the right direction.

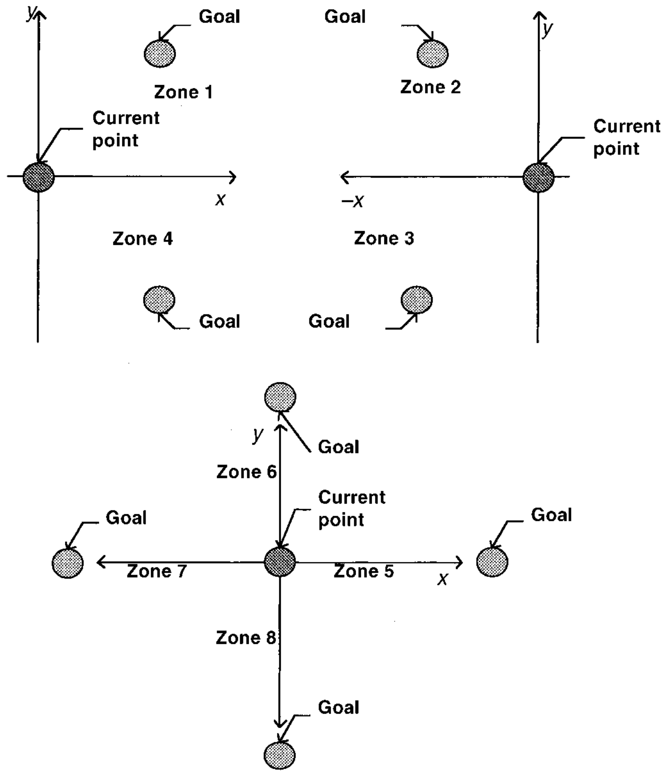

Fig. 9. Zone for the direction of goal.

Table 1. Current cell and goal in each zone

Zone	*x-axis*	*y-axis*
1	$x > myx$	$y > myy$
2	$x < myx$	$y > myy$
3	$x < myx$	$y < myy$
4	$x > myx$	$y < myy$
5	$x > myx$	$y - myy$
6	$x - myx$	$y > myy$
7	$x < myx$	$y - myy$
8	$x - myx$	$y < myy$

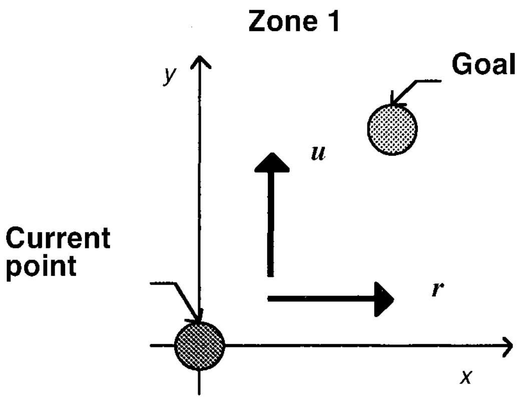

Fig. 10. Priority vector towards goal in zone 1.

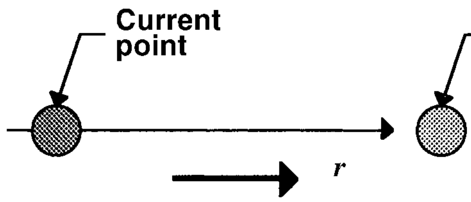

Fig. 11. Priority vector towards goal in zone 5.

5.2. *Simulation for generations of individual*

Using the concept of tendencies in direction for a pipe route, pipe routes could be made under control and give tendencies so that the paths are likely to go towards the goal point. Consequently, initial individuals are effectively generated. The method is also applicable when an additional portion is patched to cover the shortage of route path in crossover operations. Table 2 shows an example of priority values in each zone.

The use of priority vectors alone would not be a good method for generating a variety of chromosomes. This would generate those chromosomes that have the same tendencies in terms of direction so that the route paths converged by GA operations are likely to be a local optimization. Although it was difficult to find appropriate priority values, this was done in a trial-and-error manner, and the concept applied to generate initial individuals.

6. Fitness function

6.1. *Elements of the fitness function*

In general, pipe route planning is considered from various perspectives. Some typical perspectives of planning would be: (1) shorter route path length, (2) arrangement of the pipes under the same categories, (3) guarantee the maintenance spaces, and so on. This study considers the shorter length of a route path and, from this, elements of the fitness function were studied. It was also considered that the route should be as straight as possible, but no diagonal path was

Table 2. Priority ratios of unit vectors in each zone

Zone	*Unit vector*				
	1	*2*	*3*	*4*	*0*
1	40	40	10	10	0
2	10	40	40	10	0
3	10	10	40	40	0
4	40	10	10	40	0
5	50	20	10	20	0
6	20	50	20	10	0
7	10	20	50	20	0
8	20	10	20	50	0

permitted. The number of turning points in the path should be considered. The path should go along the wall in the work space surrounding or along obstacles placed in the work space as close as possible. The potential energy is set lower in these cells. Considering these elements, the fitness function is defined below.

6.2. *Definition of fitness function*

Equation 1 shows the fitness function applied in this approach:

$$f(x) = f_0 + f_1 + p_{\max} + C + W \tag{1}$$

Equation 2 accumulates the number of cells and gives the length of a route path.

$$f_0 = \sum_{k=1}^{N} x_i \tag{2}$$

The length of the route path is evaluated in Equation 2, but it is not enough to cover a variety of route paths. For example, Figure 12 shows different routes having the same fitness value. Because the shape of the route is different in these two paths, the functions given in Equation 3, which accumulates the total potential values for the route, and in Equation 4, which considers the maximum value of potential energy in the cells of the route were applied:

$$f_1 = \sum_{i=0}^{N} p_i \tag{3}$$

$$f_3 = p_{\max} \tag{4}$$

Every time the direction of a route is changed, a certain weight is added, such as C in Equation 1. If a route path is on any obstacle, or the path contains cells including obstacles, a large weight is added as shown in Equation 5:

$$W = p_{\text{obstacle}} \times A \tag{5}$$

7. Approach to pipe route planning

7.1. *Conditions for pipe route planning*

Although pipe route planning depends upon various kinds of factors, as mentioned before, the study emphasizes the minimum length of a route path and determines the conditions as follows.

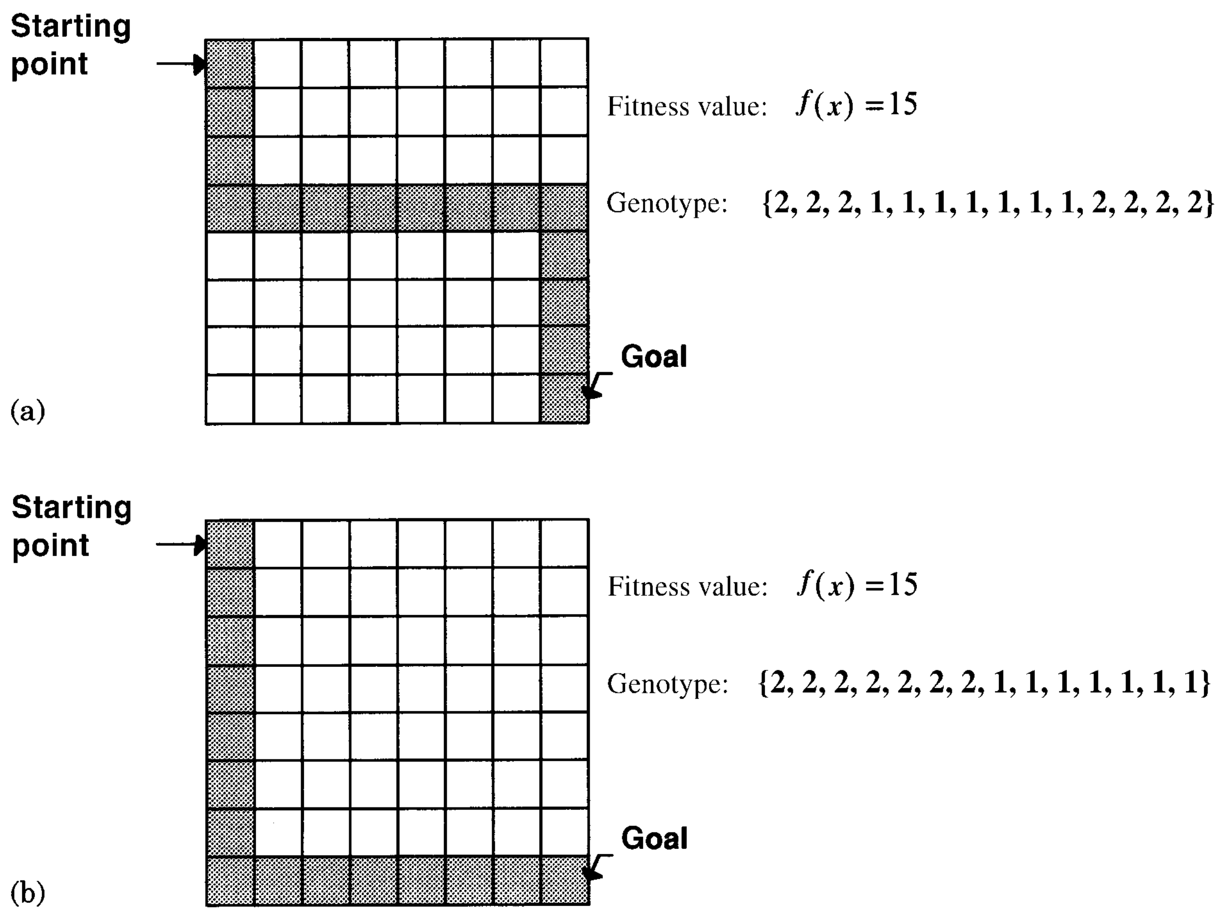

Fig. 12. Different route paths with the same fitness value.

No significant problem was observed in the genotype based on vector representation, so the definition was applied without any modification. As for potential energy values in the work space, four classes of categories were defined. Cells on obstacles, cells surrounded by spaces, cells around obstacles and cells around the wall, classified as P_0, P_1, P_2 and P_3, respectively. Conditions were different between pipings indoor and pipings outdoor; the study focused on pipings indoor and set up the potentials, $P_0 > P_1 > P_3 > P_2$. Table 3 shows an example of potential values.

As for crossover methods, extended two-points crossover and uni-crossover were applied.

Figure 13 shows the method of selection in two-point crossover operation. Individuals generated by two-point crossover are sorted by the fitness function value, the top 50% of them were randomly processed two-point crossover operations to generate offsprings, and the bottom 50% were untouched and exchanged with the offsprings. Figure 14 shows the method of selection in uni-crossover operation. Individuals generated by uni-crossover were sorted by the fitness function value: the top 70% were extracted, 85.7% out of the 70% were randomly selected to be processed crossover operation, and the bottom 30% were untouched and exchanged with them. In both crossover methods, the fitness function, Equation 1, was applied.

Table 3. An example of potential energy values

	P_0	P_1	P_2	P_3
Indoor pipings	100	4	2	0
Outdoor pipings	100	4	0	2

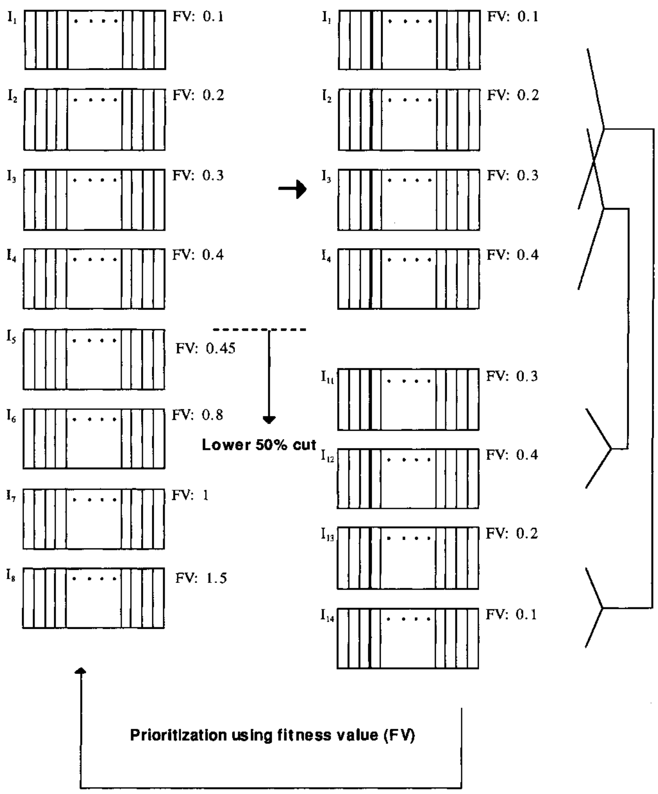

Fig. 13. Method of selection in two-point crossover.

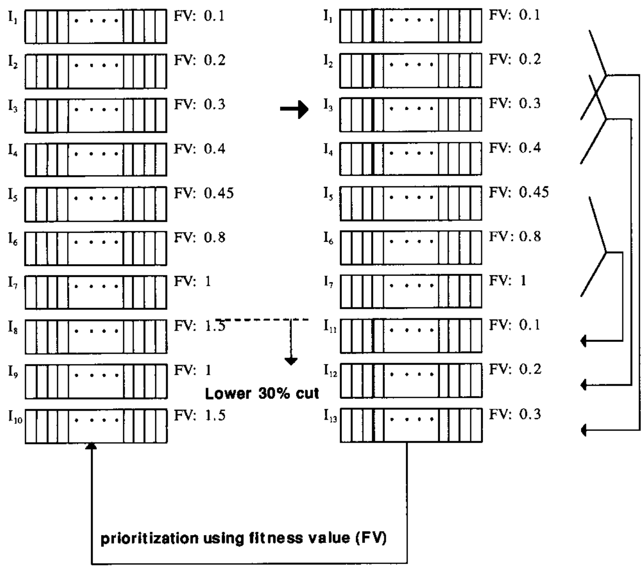

Fig. 14. Method of selection in uni-crossover.

Based on the genotype, crossover method, selection method and fitness function, various parameters were studied to determine appropriate values and settings.

7.2. *Reconsideration of generation method for initial individuals*

Using a starting point and a goal point, initial individuals are randomly generated before the GA procedure. The zone defined in Section 5 is used here. Figure 15 shows the procedure for generation of initial individuals.

At first, a current cell zone is determined using starting and goal point co-ordinates. A roulette based on the priority vector ratio in the zone is set up, an arbitrary point on the roulette is determined using a random number generator between zero and one, and the first gene is selected. A current point is forwarded using the selected vector, and the co-ordinates of the updated current cell are obtained. Then the current zone is set up based on the updated current cell and the goal cell. The same procedure is repeated until the current point reaches the goal cell. In this way, initial individuals are generated.

In the meantime, to find the most appropriate route, the initial route should be as random as possible in the working area. Without considering obstacles, routes are generated only by the specified cells for the starting and destination points. But most of the routes in the initial individuals have tendencies to go straight to the goal point. The routes using these initial individuals did avoid obstacles and reached the goal point in the end. Judging from the route path length,

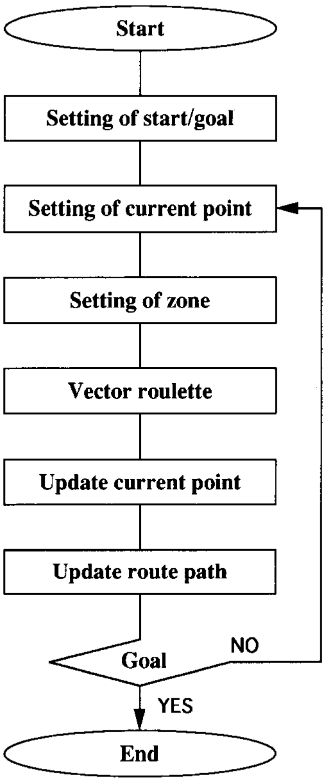

Fig. 15. Procedure of initial individuals generation.

the number of turnovers and overall observations, the most appropriate route is not always found. The next section describes the approach used to solve this problem.

7.3. *Introduction of intermediate points*

Most of the routes in the initial individuals have the tendency to go straight to the goal point as shown in Fig. 16. To generate initial individuals more randomly, intermediate points were defined to be passed in the route and applied in this approach.

Figure 17 shows how to set up an intermediate point. Making a bisector cutting through the line that connects the starting cell and the destination cell, an arbitrary cell on the bisector is selected. Making an arbitrary line passing through the bisector cell from the starting cell to the destination cell, initial individuals are generated referring to this line. Because the arbitrary cell is randomly selected, the route paths cover the overall working space.

7.4. *Evaluation of the crossover method*

Using the initial individuals generated in the method mentioned in Section 7.2, simulation of piping route path planning was carried out. The following results were observed:

(1) uni-crossover converges individuals at earlier generations,
(2) uni-crossover does not always exclude those individuals that include obstacle cells, and
(3) two-point crossover is superior to uni-crossover.

Although two-point crossover generated appropriate route paths, some of them seem to be locally optimized route paths. To avoid this, the dynamic selection ratio, based on the minimum fitness value, average fitness value and the number of cells on obstacles, was applied. The first selection ratio of 40% is used until all the individuals become obstacle free. Then the ratio is set down to 3% to study all the possible routes. When the convergence status becomes a certain level, the ratio is set back up to 40%. If the difference between the average fitness value and the minimum fitness value is below five, it is assumed that the convergence is going to terminate. In this way, those individuals

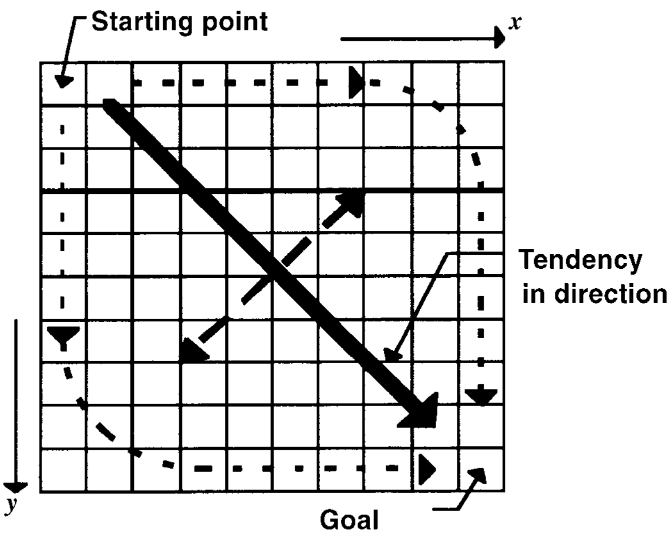

Fig. 16. Expansion of initial route path.

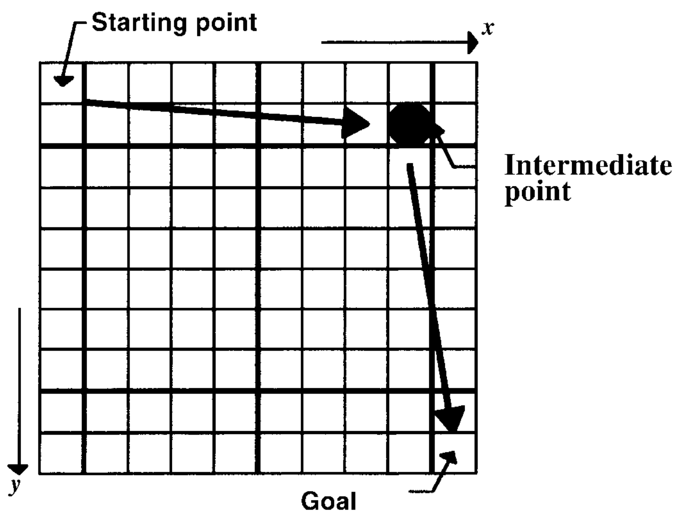

Fig. 17. Setting of intermediate point.

including obstacles are excluded in the earlier generation: time is taken to try and find the most appropriate route path without converging to a locally optimized route. When individuals are likely to converge to an appropriate route path, the convergence speed is accelerated. In addition to the distinction using the fitness value, a certain number is subtracted from the fitness value to distinguish each individual more effectively, as shown in Table 4.

7.5. *Conversion of co-ordinates*

The above-mentioned process is described based on a specific direction. In reality, one has to deal with various directions. A route path may be in any direction: down–right, down–left, up–left or up–right. Because it is not effective to consider each direction separately, a temporary co-ordinate system is introduced into which actual route co-ordinates are mapped to conduct GA operations. Combining rotation at 90° and parallel transfer operation, any route can be converted to temporary co-ordinates. As shown in Fig. 18, a route is mapped to temporary co-ordinates, given GA operations to optimize the path, and returned to the original co-ordinate system.

7.6. *Route adjustment using a subgoal*

Routes generated based on the starting and goal points are not always appropriate in terms of pipe route planning. For example, even if a path is not the shortest of all the candidate routes, it might be an appropriate path because it goes through a certain point. The importance of subgoal setting in GA route planning, as shown in Fig. 19, has been realized. Once a subgoal is set up in addition to the starting and goal points, the first portion of the route connecting the starting and subgoal points is automized and generated. When the portion is generated, the remaining portion is designed and added to the first portion. More than one subgoal can be specified. In this way, a designer can specify the points to be passed en route, which will support the designer's thought in finding the appropriate route.

Table 4. Range and subtraction values

Range	$2 < x < 5$	$4 < x < 7$	$6 < x$
Subtraction value	−1	−7	−13

8. Conclusions

The paper describes the method used to conduct pipe route planning using GAs. The definition of genes to deal with a pipe route, the concept of spatial potential energy, the method to generate initial individuals, the zone concept in route path generation using GAs, evaluation of crossover

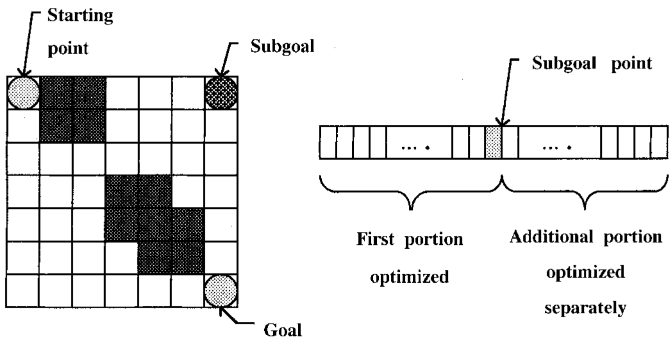

Fig. 19. Route path planning using a subgoal.

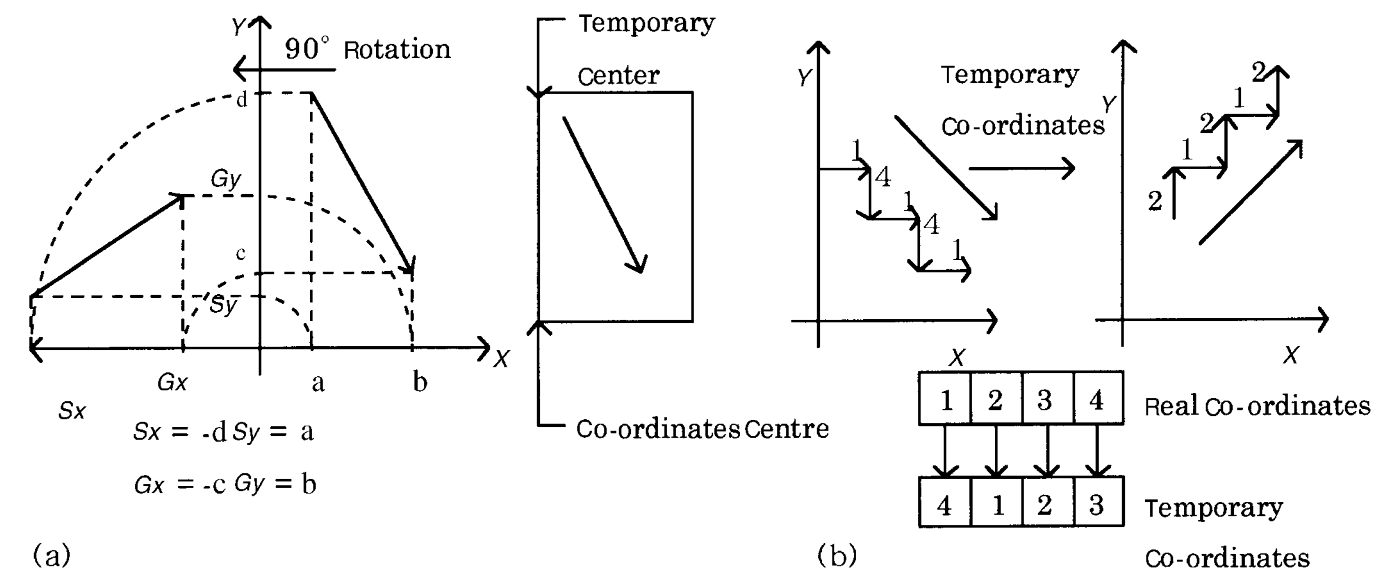

Fig. 18. Co-ordinate conversion.

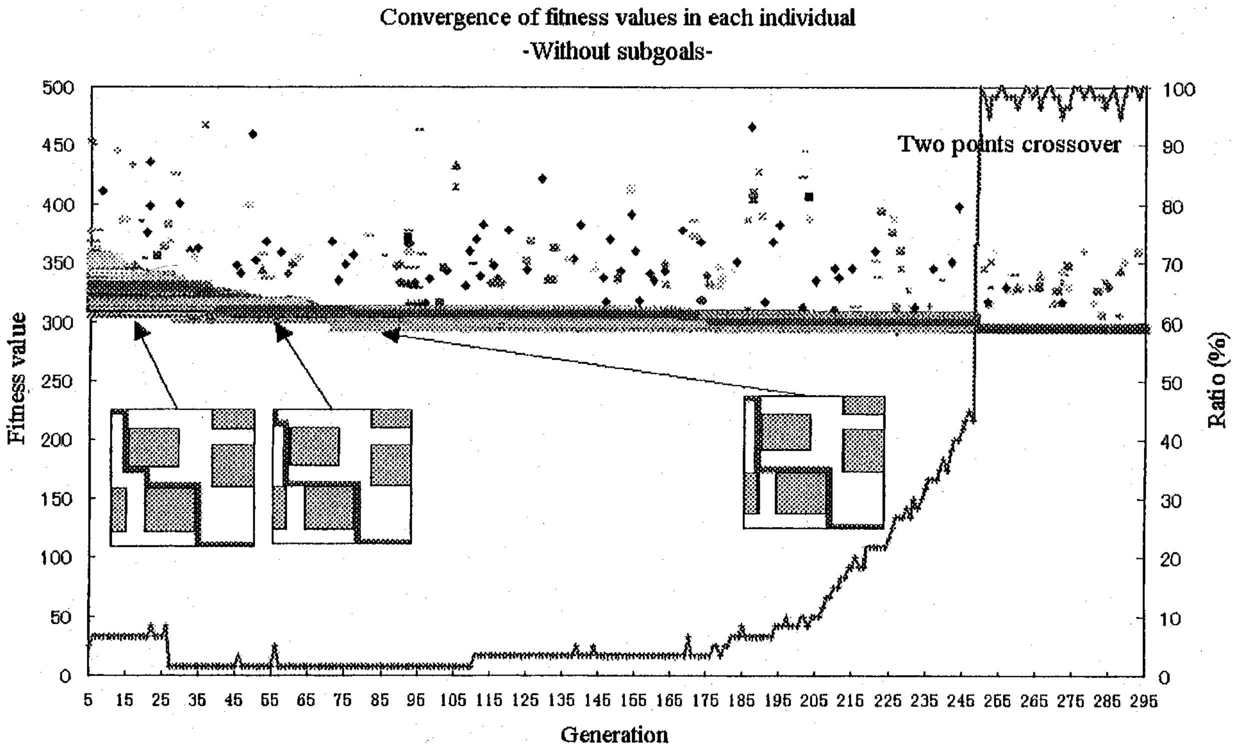

Fig. 20. Convergence of fitness values in each individual.

methods, definition and application of fitness functions are described.

A prototype system has been developed to conduct pipe route planning using GAs and evaluate the results of simulation to show the validity of this approach. Figure 20 is a result of route path generation simulation and shows convergence of fitness values in each individual. The vertical axis on the left-hand side shows fitness values for each individual, which is shown as points on the graph, where the horizontal axis shows the generations. The vertical axis on the right-hand side shows the ratio of individuals with the lowest fitness value out of the total individuals. Some of the routes with the lowest fitness value, or the most appropriate route at the specified generation are also shown on the graph. The figure shows that the individuals converge to the appropriate route after the 245th generation.

The following will be studied in future work: higher performance of processes to cope with interactive designing more effectively, consideration of more complicated conditions, pipe route planning in three-dimensional spaces, and integration with computer-aided design (CAD) systems.

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