Proceedings of the 2003 IEEE/RSJ
Intl. Conference on Intelligent Robots and Systems
Las Vegas, Nevada · October 2003

Co-evolution of Morphology and Walking Pattern of Biped Humanoid Robot using Evolutionary Computation -Evolutionary Designing Method and its Evaluation-

Ken Endo
Future Robotics Technology Center
Chiba Institute of Technology
2-17-1, Tsudanuma, Narashino, Chiba
Keio University
Japan

Takashi Maeno
Keio University
3-13-1 Hiyoshi, Kohoku-ku, Yokohama
Japan

Hiroaki Kitano
Kitano Symbiotic Systems Project
M31 6A 6-31-15, Jingumae, Shibuya-ku
Tokyo, 150-0001
Sony CSL
Keio University
Japan

***Abstract*— In this paper, evolutionary designing method of a bi-ped walking robot is proposed and evaluated in comparison with traditional manner. Usually, the structure and control system of robot have been designed separately. Therefore, the structure is given in advance when the control system is developed. This results in a great deal of trial-and-errors. On the other hand, evolutionary designing method carries out these operations simultaneously. Two calculations are conducted of which morphologies are changed (evolutionary designing method) and not changed (traditional manner) during the evolution.**

As a result, almost the same number of pareto optimal solutions are emerged. However, solutions generated with evolutionary designing method obtain higher fitnesses than the others. This means that evolutionary designing method could be powerful and efficient method for the real robot.

I. INTRODUCTION

Traditionally, robot systems have been utilized in factories for high-precision routine operations. In recent years, a lot of robots have been developed which are directly related to human lives such as Sony's AIBO. Especially, human-like robots, or humanoids, are of particular interests because of its visual appearance and less need to modify environment since robots have the same degree of freedom as humans to fit into our living space. Numbers of humanoid robots have been developed aiming at possible deployment for office and home [1],[2]. However, all of these humanoids require expensive components and extensive time in order to design and implement them.

There are several interesting issues about humanoid robot. First, one of the challenges is to identify methods to control such robots to walk and behave in a stable manner by overcoming lack of torque and non-trivial backrush, because only cheap servo modules for radio-controlled toys are used to lower the cost. Assuming the current structural design of PINO[3], the use of traditional ZMP-compensation method did not fits well as it requires sufficient torque and precision to stably control the robot[4]. A new control method needs to be discovered to control the robots to walk in a stable manner.

Second, the current structural designs are not proven to be optimal, and it will never be proven to be optimal because control methods are generally designed assuming specific hardware. What we wish to attain is to optimize both morphology and control at the same time, so that it is optimized for the walking behavior, instead of optimizing the walking behavior for a given hardware. This is important for open evolution of robotics system, such as OpenPINO.

Our position is to learn from evolution of living systems on how they have developed morphology and control systems at the same time. Optimum structures of robots can be designed when the suitable components and locomotions for the robots are selected appropriately through evolution.

An artificial life is one of the answers. Sims [5] generated robots that can walk, jump and swim in computer simulation. He also generated virtual creatures which compete with each other to obtain one resource [6]. However, all of them do not consider how to construct practical robots.

On the other hand, evolutionary method has been tried to apply them to practical robots. Lipson [7] adopted the rapid prototyping to produce the creatures that were generated in three-dimensional virtual space. Hornby [8] made use of L-system in order to evolve three-dimensional robot, and implement real robots referring to the solutions of this calculation. However, all of them are far from practical robots. Although Paul [9] coevolutes morphlogy and walking pattern of biped walking robot, characteristics of materials are not considered clearly.

Until now, we have developed the method for designing the morphology and walking pattern of biped walking robots [10]. In this paper, we compare and evaluate the

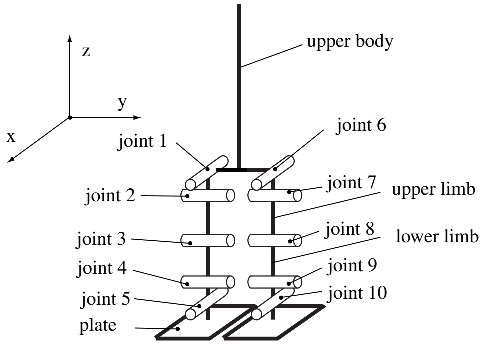


Fig. 1. model of robot of the first step

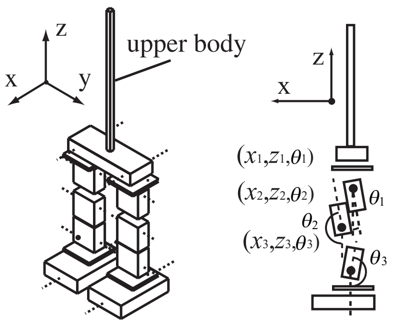


Fig. 2. model of robot of the second step

solution of our method with one that was generated under the condition that morphology is given in advance, or traditional manner.

II. Evolutionary Designing Method

In this section, we explain the morphology, controller and so on which are dealt with in the evolutionary designing method.

A. Morphology

Humanoid robots are composed of large numbers of components such as sensors, actuators and so on. It is difficult to consider the optimal choice for all of them simultaneously. Moreover, it is also difficult to obtain biped walking because it is an advanced locomotion. In order to develop the basic method for generating both of morphology and controller, at first, the simple models are needed for the dynamic simulation. Therefore, two step GA is adopted for this method. For the first step, simple model is used to obtain basic walking pattern, and for the second step, a more detailed model is used to obtain the detailed structure of robot and its suitable walking pattern.

The multi-link model of robot as shown in Fig. 1 is used at the first step. This three-dimensional robot is composed of 11 links for body and legs, and two plates for each foot. The length of five links for upper body, upper and lower limbs change during the evolution, though the total length of all links is constant. Joints are numbered as joint 1 to 10 as shown in Fig. 1. Driving torque of each joint

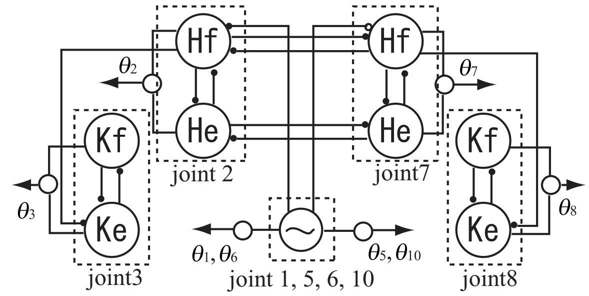


Fig. 3. controller

can be changed from -2.45 Nm to 2.45 Nm reflecting the real robots. The joint 3 and 8 have a range of motions between 0 and $\pi/2$ and the other joints move between $-\pi/2$ and $\pi/2$, respectively. Densities of the leg links and the upper body are 3.14kg/m and 4.55kg/m, respectively, and the length of one leg is 0.28m. These parameters are constant though the lengths of upper body, upper and lower limbs of the robot change in the process of GA. The basic locomotion of biped walking is emerged with this simple model.

At the second step, we assume that the robot is composed of the servo modules S5301 with metal gears from Futaba, which can be obtained easily. This three-dimensional robot is composed of 6 servo modules, as shown in Fig. 2. the geometry of each modules (x_i, z_i, θ_i) as shown in Fig. 2 is emerged during the evolution, with the height of hip is constant at 0.28m. In fact, there are some robots composed of similar servo modules such as morph [11]. Morph is a humanoid robot which has high-range of motion, and can perform acrobatic behavior. Arrangement of servo modules of morph is well considered so that they do not disturb any motion. However, it has taken a long time to develop this robot. With our method, such a long time is not needed for the best arrangement of servo modules.

The characteristics of servo modules are considered in the dynamic simulation so that the generated robot is close to the real robot. Moreover, the system identification is conducted in advance and these parameters are used in the dynamic simulation because these modules have the PD control system inside. Driving torque of each joint can be changed from -2.45 Nm to 2.45 Nm. The detailed model of morphology can be obtained with this model.

B. Controller

A lot of research has been comducted about generating the locomotion of artificial lives or robots using neural network and evolutionary computation[12][13]. However, these methods result in too large size of chromosomes to generate valid solution considering both morphology and locomotion simultaneously. Moreover we have to take the velocity of all joints and external force from the ground in account in order to control the robots. In the biomechanics field, pattern generators are often used for generating the walking pattern of humans because the bi-ped walking is a periodical and symmetrical motion, and the structure of the control system can be decided in advance. Until now, many studies of neural oscillators have been conducted. The control system composed of neural oscillators can generate the rhythm for the bi-ped walking. Unlike the recurrent neural network, the length of chromosome are not so long. However, any application for the real robots has not been accomplished. Our goal is to propose the designing method that can generate detail structure and controller of bi-ped humanoid robot.

The structure of control system is decided according to the basic locomotion of bi-ped walking as shown in Fig. 3. Hf and He are neurons for the hip joints. Kf and Ke are neuron for knees. The action of each neuron is expressed as follows,

$$\begin{aligned} T_i \dot{u}_i &= -u_i - \sum_{ij} w_{ij} y(u_j) - \beta y(v_i) \\ &\quad + U_0 + \sum_k FB_k \qquad (1) \\ T'_i \dot{v} &= -v_i - y_i \qquad (2) \\ y(x_i) &= \frac{1}{1+e^{-\tau(x_i)}} \qquad (3) \end{aligned}$$

where FB_k is a feedback signal from the body of robot such as the angle of each joint or external force of the feet, u_i is the inner state of the ith neuron, v_i is the variable representing the degree of the adaptation or self-inhibition effect of the ith neuron, U_0 is an external input with a constant rate, w is the connecting weight, and T_i and T'_i are time constants of the inner state and the adaptation effect, respectively. The neuron at the center of Fig. 3 is for joint 1, 5, 6, and 10, which generates a sine wave. In the white circle in Fig. 3, the desired trajectory of each joint is given by the following equation,

$$\theta_k = p_k(y(u_{k1}) - y(u_{k2})) \qquad (4)$$

where, θ_k is the desired trajectory and p_k is the gain for the joint k. The desired trajectory of joint is given from the output of neurons. Thus, the driving torque of each joint is given by controlling the angle of joints to desired trajectory with the PD control. The gains of PD controller and maximum driving torque are given from the system identification of servo modules. The plates of each leg are kept parallel to the ground. This method is often used for bi-ped humanoid robot in order to make the problem simple.

C. Simulation

The environment which robots walk on is a flat ground. When the dynamic simulation starts, the posture of the robot is in the state of the initial position as show in Fig. 4.

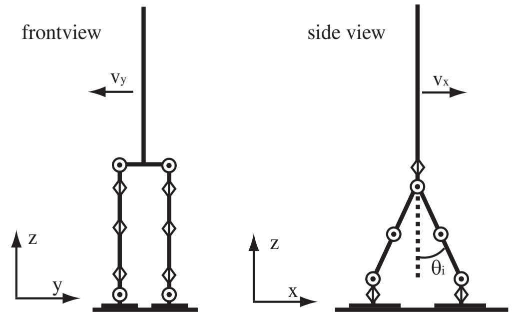


Fig. 4. initial state

Initial angle of θ_i and velocity v_x,v_y are decoded from chromosomes. When the dynamic simulation begins, the controller starts to work and generate driving torque at the each joint. The only robots with controller that generates the rhythm for walking can keep walking. If the knee, hip and other parts of the robot's body get in contact with the ground or the motion of robot continues to stay at the same place for 0.5 s, simulation is finished and next one begins in order to avoid wasting the time.

Dynamic simulation is conducted for 5s per a robot. the movement of robots resulting from their interaction with the environment. Motions of the robot are calculated by the forth order Runge-Kutta method. One time step is 0.1ms. Contact response with the ground of the links is calculated with a hybrid model using spring and damper under the influence of friction and gravity. The friction is large enough so that the robots do not slip while they are walking.

D. Evolutionary Computation

GA is a method for optimization based on the evolution of creatures. GA has been used for various complicated problems[14]. In this paper, a fixed length genetic algorithm is used to evolve the controllers and morphologies. Each chromosome includes the information of initial angle, velocity, length of each link and weights of each neuron in control systems. Here, we use the GA which deals with real number from 0 to 1. Robots with low-fitness are eliminated by selection, and new robots are produced using crossover and mutation. Then, their morphologies and controller are generated from generation to generation, and finally, converges to a reasonably optimal solution.

Crossover is the operation to create new children in the next generation from parents selected due to their fitness. Here, BLX-α [15] is used as the crossover for real number GA. BLX-α is useful to generate the walking pattern because this crossover can explore the best solution more certainly in the middle or latter of calculation, that is to say, this method can adjust the walking pattern in detail.

Each factor in the chromosomes is decided as follows:

$$
\begin{aligned}
c_{1i,2i} &= u(min(p_{1i}, p_{2i}) \\
&\quad -\alpha I_i, max(p_{1i}, p_{2i}) + \alpha I_i) \qquad (5) \\
I_i &= |p_{1i} - p_{2i}| \qquad (6)
\end{aligned}
$$

where $p_1 = (p_{11} \cdots p_{1n})$ and $p_2 = (p_{21} \cdots p_{2n})$ are parents, $c_1 = (c_{11} \cdots c_{1n})$ and $c_2 = (c_{21} \cdots c_{2n})$ are children, and $u(x, y)$ is the uniform deviates from x to y. Here α is set to 0.05. In this way, the length of total chromosomes does not change. Selection is operated due to finesses of the robots. The larger the fitness is, the easier the robot is selected. Mutation is the operation to change the part of some chromosomes of robots selected randomly. When mutation occurs to c_i, the new factor c_n is given as follows:

$$c_n = c_i + \frac{rand_g}{10} \qquad (7)$$

where $rand_g$ donates the gaussian deviates. This operation also works without changing the total length of chromosomes. With these operations, the only robots with large fitness can survive.

Moreover we use the elite preservation strategy at the same time. These method and condition is used at the first and second step.The parameters of GA is as shown in Table 1.

Through the first step of evolution, only walking distance of all robots are evaluated. As the fitness function of the first step,

$$fitness_1 = l_g \qquad (8)$$

is used, where l_g is the distance of the center of mass of robots from the initial point. With this function, robots are evaluated simply by the distance that robot walks.

At the second step, robot design is taken as multi optimal problem and two fitness functions are used. One is the same function as the first step, equation (8), and the other is

$$fitness_2 = \frac{l_g}{\int \dot{\theta}_{upper} dt} \qquad (9)$$

where, $\dot{\theta}_{upper}$ donates the anglar velocity of the upper body against the absolute coordinate.

TABLE I

GA PARAMETERS

population size	200
generation	300
crossover ratio	0.8
mutation ratio	0.05

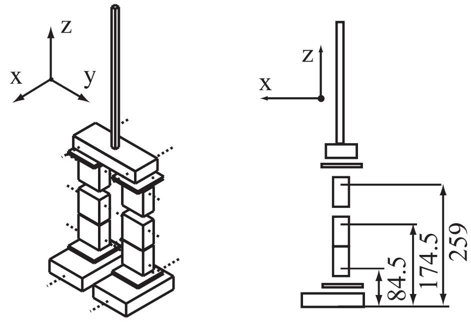
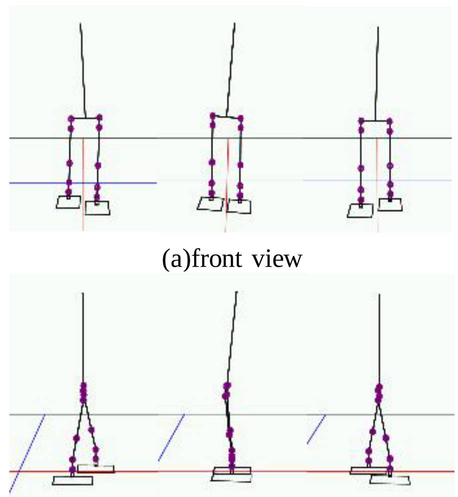


Fig. 5. fixed model of morphology



(a)front view

(b)side view

Fig. 6. walking pattern of the best robot

III. EVALUATION

Commonly, structures and controller of robots are designed separately. If the morphology and locomotion are designed simultaneously like creatures, much better solutions can be explored in a much wider solution space than the traditional manner. In this paper, two calculations are conducted of which morphologies are changed (Evolutionary designing method) and not changed (traditional manner) during the evolution respectively. The structure of PINO is used as a fixed morphology as shown in Fig.5. Each calculation is conducted under the same condition except for morphology.

IV. RESULTS AND DISCUSSIONS

A. Results of Non-Fixed Model

The calculation for non-fixed morphology has conducted. At the end of the first step, morphology and walking pattern as shown in Fig.6 is emerged. The basic walking pattern is emerged in which the robot lifts one leg up, brings it forward and lifts another leg up when the swing leg gets in contact with the ground. This robot

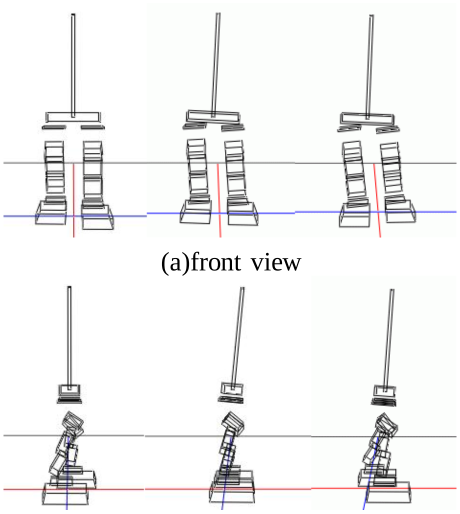


Fig. 7. walking pattern of the not-fixed model

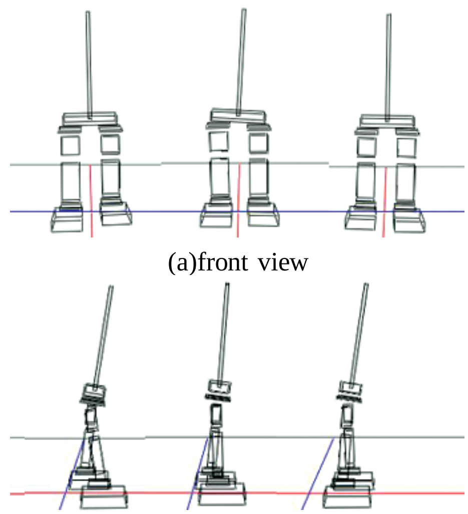


Fig. 8. walking pattern of fixed model

always walks with knees kept straight. This combination is the best solution for these models because morphology and walking pattern are designed simultaneously, though this manner is very different from humans'. This robot is included in the first population of the second step.

The walking pattern and morphology as shown in Fig.7 is generated after the second step GA. In the first step, the basic biped walking pattern is generated. In this step, both the detailed model of morphology and waling pattern for it are generated simultaneously. Therefore, this result is a valid solution if we assume the robot is composed of the servo modules. It took a very long time for the best arrangement of servo modules for morph because the design of the robot mainly depends on the experience of the designer. With our method, the optimal arrangement for the fitness function can be obtained easily and quickly.

B. Results of Fixed Model

The calculation for fixed morphology is conducted under the same condition as not-fixed model. Similar link robot is emerged, and included in the first generation of the second step. After the second step, walking pattern of preferred solution as shown in Fig.8 is emerged. This robot also walk with knees kept straight as well similar to the result of the not-fixed model.

C. Discussions

Both walking patterns are similar to each other, for both robots walks with knees kept straight. There are three possible reasons. The first reason is because robot has low compliance at all joints because of PD controller. Humans have high compliant joints and make use of this compliance to walk passively. Therefore, humans walk efficiently with the swinging leg bended. Secondly, this robot walks only on the flat ground through the evolution. If the ground has some slope, or if he shape is not flat, robots cannot walk with this manner. This is the problem on the environment that robots walk on in the dynamic simulation. Finally, the other evaluations such as efficiency of walking and so on, are not considered through the evolution process. In the future, these problems should be cleared.

All pareto optimal solutions at the final generation of both calculations are shown in Fig.9. In this paper, walking distance and stability of upper body are evaluated as showin in equation (8) and (9). The non-fixed model are superior to the fixed model in two evaluations. This means that this method can generate much better robots than PINO. In fact, PINO, at first, is designed by beginner and a lot of times of trial-and-errors are needed, because it needs high technology to develop the biped walking robots. Moreover, PINO is composed of off-the-shelf components. Therefore, it is more difficult to develop PINO than usual biped walking robots composed of expensive materials. In other words, arrangement of components is important to control PINO. Our method can be useful for the design of robots, especially robots with rigid conditions like PINO because it optimizes control system as well as morphology. It means that evolutionary designing method could be a powerful method for any real robot.

Moreover, this method can be applied to any types of robots. In the future, we'll develop libraries of various components for robots, and implements the real robots.

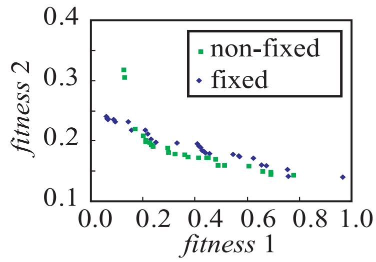


Fig. 9. pareto optimal solutions

V. Conclusions

In this paper, a method for co-evolving morphology and controller of bi-ped humanoid robots is suggested and evaluated in comparison with traditional method. We propose an evolutionary designing method that enables that co-evolution of morphology and control. Moreover, the detailed structure and walking pattern are obtained using the model considering the characteristics of the servo modules. Finally, it is confirmed that evolutionary designing method could be one method for the real robot.

VI. Acknowledgements

The dynamic simulation is supported by M. Ogino in Osaka University. We appreciate him, the members of fuRo(Future Robotics Technology Center), and Biorobotics laboratory in Keio University.

VII. REFERENCES

[1] Inaba, M., Kanehiro, F., Kagami, S. and Inoue, H., ”Two-armed Bipedal Robot that can Walk, Roll Over and Stand up”, *Proceeding of International Conference on Intelligent Robots and Systems*, 1995.

[2] A. Takanishi, M. Ishida, Y. Yamazaki and I. Kato, ”The Realization of Dynamic Walking by the Biped Walking Robot”, *Proceeding of IEEE International Conference on Robotics and Automation*, CDROM, pp. 159-166, 1985.

[3] Fuminori Yamasaki, Takahiro Miyashita, Tatsuya Matsui and Hiroaki Kitano, ” PINO the Humanoid : A basic architecture”, *Proceeding of The Fourth International Workshop on Robocup*, 2000.

[4] M. Vukobratović, B. Borovac and D. Šurdilović, ”Zero-Moment Point - Propoer Interpretation and New Apprications”, *Proceeding of IEEE/RAS International Conference on Humanoid Robots*, pp.237-252, 2001.

[5] Karl Sims, ””Evolving Virtual Creatures”, Computer Graphics Proceedings”, *Computer Graphics Proceedings*, pp.12-22, 1994.

[6] Karl Sims, ”Evolving 3D Morphology and Behavior by Competition”, *Artificial Life IV*, pp.28-39, 1994.

[7] H. Lipson and J. B. Plollack, ”Automatic design and manufacture of robotic lifeforms”, *Nature*, Vol.406, no. No.6799, pp. 974-978, 2000.

[8] G. S. Hornby and J. B. Pollack, ”Body-brain Coevolution using L-system as a Generative Encoding”, *In Genetic and Evolutionary Computation Conference*, 2001.

[9] Chandana Paul and Josh C. Bongard, ”The Road Less Travelled: Morphology in the Optimization of Biped Robot Locomotion”, *Proceeding of IEEE/RAS International Conference on Intelligent Robots and Systems*, 2001.

[10] Ken Endo, Takashi Maeno and Hiroaki Kitano, ”Co-evolution of Morphology and Walking Pattern of Biped Humanoid Robot using Evolutionary Computation -Consideration of characteristic of the servomotors-”, *Proceeding of IEEE/RSJ International Conference on Intelligent Robots and Systems*, pp.2678-2683, 2002.

[11] Takayuki Furuta, Yu Okumura, Tetsuo Tawara and Hiroaki Kitano, ”’morph’:A Small-size Humanoid Platform for Behavior Coordination Research”, *Proceeding of IEEE/RAS International Conference on Humanoid Robots*, pp.165-171, 2001.

[12] Fukuda, T., Komata, Y., Arakawa, T., ”Stabilization Control of Biped Locomotion Robot based learning with GAs having Self-adaptive Mutation and Recurrent Neural Networks”, *Proceeding of International Conference on Robotics and Automation*, pp.217-222, 1997.

[13] Cao, M., Kawamura, A., ”A Design Method of Neural Oscillatory Networks for Generation of Humanoid Biped walking Patterns”, *Proceeding of International Conference on Robotics and Automation*, pp.2357-2362, 1998.

[14] Hiroaki Kitano, ”Designing neural networks using genetic algorithms with graph generation system”, *Complex System*, pp.454-461, 1990.

[15] Eshleman, L. J. and Schaffer, J. D., ”Real-Coded Genetic Algorithms and Interval-Schemata”, *Foundations of Genetic Algorithms 2*, pp.187-202, 1993.