Evolutionary Strategy Using Statistical Information and Its Application to Mobile Robot Control

Kiyotaka Izumi*, Keigo Watanabe**, and M.M.A. Hashem***

*Department of Mechanical Engineering, Faculty of Science and Engineering,
**Department of Advanced Systems Control Engineering, Graduate School of Science and Engineering,
***Faculty of Engineering Systems and Technology, Graduate School of Science and Engineering,
Saga University
1-Honjomachi, Saga 840-8502, Japan
E-mail: {izumi, watanabe}@me.saga-u.ac.jp
[Received June 23, 1998; accepted November 30, 1998]

We describe an evolution strategy (ES) using the statistical information of subgroups obtained automatically by a similarity metric of individuals at each generation. Arithmetical crossover is done with an elite individual and a mean individual within each subgroup to produce offspring. Standard deviation calculated within a subgroup is used in mutation. The effectiveness of the proposed ES is first shown with tests of the 5 De Jong functions. The present ES is also applied to the acquisition of control for a terminal control problem in an omnidirectional mobile robot, in which robot control is based on fuzzy behavior-based control that combines subsumption-like architecture and fuzzy reasoning.

Keywords: Evolutionary computation, Evolution strategy, Fuzzy control, Fuzzy behavior-based control, Omnidirectional mobile robot

1. Introduction

Optimization algorithms imitating the principle of natural evolution are attractive in engineering, and include the well-known genetic algorithm (GA), genetic strategy (ES), genetic programming (GP), and evolutionary programming (EP). The major difference between ES and GA is in genetic representation, i.e., ES expresses one gene by a real number vector, instead of using binary values. Thus, GA must transform genotype to phenotype, whereas ES needs no such transformation, giving ES better precision than GA in problems of parameter optimization. Note, however, that ES has system design parameters, as does GA, in crossover and mutation; such parameters significantly affect search performance of a solution and must be suitably set from problem to problem. A simplified ES with random selection in an arithmetical crossover, for example, and Gaussian mutation with fixed standard deviation may yield a solution converging on a local minimum. Researchers are thus developing new algorithms for ES to improve its search solution.

We propose ES using statistical information of subgroups, in which a population is divided automatically into several subgroups based on the similarity of each individual, arithmetical crossover is max-mean using an elite individual and a calculated mean individual in each subgroup, and standard deviation is calculated for each objective variable within each subgroup at a generation for mutation operator. With the above concept, searching for a solution is expected to improve and tedious system design parameter setting avoided. In our proposal, the number of subgroups is the same as that of search directions. Crossover decides the search direction and mutation the search domain.

The effectiveness of our proposal is shown by optimizing the 5 De Jong functions, where convergence speed and solution precision by our method are compared to those obtained conventionally. Our method is next applied to the learning of fuzzy behavior-based control for an omnidirectional mobile robot; such control resembles the system due to subsumption architecture, but is realized by soft computing and has a competition or cooperation unit consisting of a saturation function to generate a suitable fuzzy consequent result. Simplified fuzzy reasoning is assigned to elemental behavior consisting of a single input-output relation. Mean and reciprocal values of standard deviation for a Gaussian membership function and a constant value in the conclusion part are learned by the proposed ES.

2. Conventional ES

This section reviews conventional ES (Fig.1).

2.1. Initial Population

The initial population is generated using uniform random numbers (URNs). To generate variable \( x_i \) with range \(-10 \leq x_i \leq 10\), use URN\([-10, 10]\). For variable \( x_i \) with an alternative range, use another URN. First individual \( x_i = [x_1, x_2, \ldots, x_n] \) is generated. Remaining individuals \( x_2, \ldots, x_m \) are generated the same way, with \( m \) the number of individuals.

2.2. Arithmetical Crossover

To generate child \( y_i \), uniformly arithmetical crossover – a linear combination of parents \( x_1, x_2 \) – is generally used, as follows:

\[
y_1 = \alpha x_1 + (1-\alpha)x_2 \quad (1)
\]

\[
y_2 = (1-\alpha)x_1 + \alpha x_2 \quad (2)
\]

where \( x_1, x_2 \) are selected randomly from the population,
2.3. Mutation

Mutation, a recombination operator, plays a significant role in a global search (or enhancing the diversity of a solution) and fine tuning for ESs. Smaller changes occur more often than larger ones in biological evolution, so this type of change in a child is made easily by a zero-mean Gaussian random number function, so mutation for a child is made by a zero-mean Gaussian random number, as

\[ x' = x + N(0, \sigma^2) \] ........................ (3)

where \( N(\cdot) \) is the function of a Gaussian random number vector and \( \sigma \) is the standard deviation vector of the system, \( \sigma = [\sigma_1, ..., \sigma_n] \).

2.4. Evaluation

After mutation, the cost function (fitness) of each child is evaluated for a possible solution in each generation. These evaluations are saved to create a new generation.

2.5. Alternation of Generation

Among \( m \) parents, evaluated in the previous generation, and \( m \) children, evaluated in the current generation, \( m + m \) individuals are arranged in cost function amount sequence, with the best \( m \) individuals selected for the next generation.

We call the procedure covered in Sections 2.1 to 2.5 conventional ES.

3. Evolution Strategy Using Statistical Information of Subgroups

3.1. Group Division

In our proposed ES (Fig.2), we first define \( x_{\text{max}} \) as an elite that maximizes a cost function within the \( i \)-th subgroup, especially by reordering all individuals in the fitness amount sequence. Similarity between elite individual \( x_{\text{max}} \) in the \( i \)-th subgroup and \( j \)-th individual \( x_j \) is defined by the Euclidean norm

\[ d = \|x_{\text{max}} - x_j\| \] ........................ (4)

If metric \( d \) is smaller than \( \delta \) – the specified radius of a circle (Fig.2) – then \( x_j \) is included in the \( i \)-th subgroup. Otherwise, group index number \( i \) is updated by \( i + 1 \), \( x_j \) must be substituted into \( x_{i+1, \text{max}} \) and above equation reevaluated.

Note that individuals in a subgroup number at least three if the mean is calculated excluding the elite individual in each subgroup so that the starting number of \( i \) is 1 and that of \( j \) is 4. When the number of individuals in the final group becomes less than three, they must be included in the former group, so the number of subgroups is at most \( \lceil \text{integer}(m/3) \rceil \).

3.2. Max-mean Arithmetical Crossover

We propose that the competing elite of a subgroup and the mean strength of that subgroup excluding the elite be used in crossover. This has very strong directivity to the elite (Fig.2). Of these competing subgroups, directivity toward the optimum differs \( \alpha \), so the possibility of being trapped in local minima is decreased to attain the optimum, detailed below.

Let \( \bar{x}_i \) be the mean strength of the \( i \)-th subgroup that excludes \( x_{\text{max}} \). Crossover for competing subgroup \( i \) is calculated as follows:

\[ y_1 = \alpha x_{\text{max}} + (1 - \alpha) \bar{x}_i \] ........................ (5)

\[ y_2 = (1 - \alpha) x_{\text{max}} + \alpha \bar{x}_i \] ........................ (6)

where \( \alpha \) is selected from \( \text{URN}[0,1] \).

3.3. Mutation with Directly Calculated Standard Deviation

Standard deviation \( \sigma_i \) is calculated for each objective variable within the \( i \)-th subgroup at a generation. Using normally distributed random vector \( N(0, \sigma_i^2) \) in which expectation is 0 and the standard deviation vector is \( \sigma_i = [\sigma_{i1}, \ldots, \sigma_{in}] \),
\[ \sigma_{i_1}, ..., \sigma_{i_n} \] mutation becomes
\[ x' = x + N(0, \sigma_i^2) \]
for an individual of \( i \)-th subgroup, where \( n \) is the total number of objective variables. This time-varying mutation plays an important role in searching for the optimum. Time-varying mutation calculation without using statistical subgroup information is given in a reference. \(^2\)

4. Functional Optimization

4.1. De Jong Test Functions
Functions used for analyzing ES effectiveness are common test functions known as De Jong test functions.  

**Test function 1**
Test function 1 is continuous and convex, described by
\[ \sum_{i=1}^{3} x_i^2, \text{ where } -5.12 \leq x_i \leq 5.12 \]  
When \((x_1, x_2, x_3) = (0, 0, 0)\), the global minimum is to be zero.

**Test function 2**
Test function 2 is continuous and saddle-like, described by
\[ 100(x_1^2 - x_2)^2 + (1 - x_1)^2, \text{ where } -2.048 \leq x_i \leq 2.048 \]
The function has a global minimum of 0 at \((x_1, x_2) = (1, 1)\).

**Test function 3**
Test function 3 is step-wise and decreasing, described by
\[ \sum_{i=1}^{5} \text{integer}(x_i), \text{ where } -5.12 \leq x_i \leq 5.12 \]
The function has a global minimum of -30 for all \(-5.12 \leq x_i < 5.0\).

**Test function 4**
Test function 4 is convex with a gentle slope around the minimum, described by
\[ \sum_{i=1}^{50} ax_i^2 + \text{Gauss}(0,1), \text{ where } -1.28 \leq x_i \leq 1.28 \]
The function without Gaussian noise has a global minimum of 0 at \((x_1, x_2, ..., x_{50}) = (0, 0, ..., 0)\).

**Test function 5**
Test function 5 is multimodal, described by
\[ 1 + \frac{\sum_{i=1}^{30} f_i(x_1, x_2)}{0.002 + \frac{1}{30} \sum_{i=1}^{30} f_i(x_1, x_2)} \]
where \( f(x_1, x_2) = j + \sum_{i=1}^{30} (x_i - a_i)^6 \)
where \(-65.536 \leq x_i \leq 65.536\) and

\[ [a_i] = \begin{bmatrix} -32 & -16 & 0 & 16 & 32 & -32 & -16 \\ -32 & -32 & -32 & -32 & -32 & -16 & -16 \\ ... & 0 & 16 & 32 & \vdots & 32 & 32 \end{bmatrix} \]
The function has a global minimum of 0.998 at \((x_1, x_2) = (-32, -32)\).

4.2. Simulation results
Conventional and proposed methods were applied to the above optimization problems under the condition of \( m = 60, \sigma_i = 10^{-5} \) for \( i = 1, ..., n \) in functions 1 and 2, \( \sigma_i = 0.5 \) for \( i = 1, ..., n \) in function 3, \( \sigma_i = 0.1 \) for \( i = 1, ..., n \) in functions 4 and 5, \( \delta = 10^{-2} \) for functions 1, 3, 4 and 5, and \( \delta = 10^{-3} \) for function 2, in which 20 trials with different initial populations were averaged to produce each result (Figs.3-7). In all results except for test function 4 (Fig.6), our proposal has better accuracy or faster convergence than the conventional, confirming that our ES having several directivities toward the optimum, together with time-varying variance for mutation, very effectively improves solution accuracy and convergence. For test function 4, the conventional has better convergence than our proposal, mainly because test function 4 is essentially random, so the conventional method with no strong directivity has advantages over our method in producing stronger directivity in a subgroup.

![Fig. 3. Simulation result of test function 1](image1)

![Fig. 4. Simulation result of test function 2](image2)
5. Omnidirectional Mobile Robot

5.1. Dynamic Robot Model

An omnidirectional mobile robot having a holonomic property is considered. The nonlinear dynamic equation of the robot is given in Ref.9)

\[ \dot{x} = A(x)x + B(x)u \]  \hspace{1cm} (12)

where \( x = [x, y, \phi, \dot{x}, \dot{y}, \dot{\phi}] \), \( x, y \) and \( \phi \) are the position on the absolute coordinate system, \( \phi \) is the rotational angle of the moving coordinate system for the absolute coordinate system and \( u = [u_1, u_2, u_3] \), \( u_i (i = 1, 2, 3) \) are driving input torques for each orthogonal-wheel assembly. Coefficient matrices are expressed as

\[
A(x) = \begin{bmatrix}
0 & 0 & 0 & 1 & 0
0 & 0 & 0 & 1 & 0
0 & 0 & 0 & 1 & 0
0 & 0 & a_1 & -a_2 & 0
0 & 0 & a_1 & 0 & 0
0 & 0 & 0 & 0 & a_3
\end{bmatrix}
\]

\[
B(x) = \begin{bmatrix}
 b_1 \beta_1(\phi) & b_2 \beta_2(\phi) & 2k_r \cos \phi \\
 b_1 \beta_1(\phi) & b_2 \beta_2(\phi) & 2k_r \sin \phi \\
 b_3 \beta_1(\phi) & b_3 \beta_2(\phi) & 2k_r \sin \phi \\
 b_3 \beta_1(\phi) & b_3 \beta_2(\phi) & 2k_r \cos \phi \\
 b_3 \beta_1(\phi) & b_3 \beta_2(\phi) & 2k_r \sin \phi \\
 b_3 \beta_1(\phi) & b_3 \beta_2(\phi) & 2k_r \sin \phi \\
\end{bmatrix}
\]

\[ a_1 = -3c/ (3I_w + 2Mr^2), \]
\[ a_2 = 3I_w / (3I_w + 2Mr^2), \]
\[ a_3 = -3cl^2 / (3I_w + 2Mr^2), \]
\[ b_1 = kr / (3I_w + 2Mr^2), \]
\[ b_2 = krL / (3I_w + 2Mr^2), \]
\[ \beta_1(\phi) = -\sqrt{3} \sin \phi - \cos \phi, \]
\[ \beta_2(\phi) = \sqrt{3} \sin \phi - \cos \phi, \]
\[ \beta_3(\phi) = \sqrt{3} \sin \phi - \cos \phi, \]
\[ \beta_4(\phi) = -3 \cos \phi - \sin \phi, \]

where \( L \) is the distance between any assembly and the robot center of gravity, \( c \) the viscous friction factor for the wheel, \( M \) robot mass, \( r \) wheel radius, \( I_w \) the moment of inertia of the wheel around the drive shaft, \( l \) the moment of inertia around the robot center of gravity, and \( k \) the drive gain factor.

5.2. Jacobian Matrix

Jacobian matrix \( J \) of the mobile robot satisfies the following relation:

\[
\begin{bmatrix}
 u_1 \\
 u_2 \\
 u_3 \\
\end{bmatrix} = \begin{bmatrix}
 \beta_1(\phi) & \beta_2(\phi) & 1/L \\
 \beta_3(\phi) & \beta_4(\phi) & 1/L \\
 2\cos \phi & 2\sin \phi & 1/L \\
\end{bmatrix} \begin{bmatrix}
 \dot{x} \\
 \dot{y} \\
 \dot{\phi} \\
\end{bmatrix}
\]  \hspace{1cm} (13)

\[
J^T = \frac{1}{3} \begin{bmatrix}
 \beta_1(\phi) & \beta_2(\phi) & 1/L \\
 \beta_3(\phi) & \beta_4(\phi) & 1/L \\
 2\cos \phi & 2\sin \phi & 1/L \\
\end{bmatrix}
\]  \hspace{1cm} (14)

where \( u_i \) is force required for \( x \)-directional translational motion in the absolute coordinate system, \( u_4 \) force required for \( y \)-directional translational motion in the absolute coordinate system, and \( u_6 \) torque required for rotation.

6. Fuzzy-Behavior-Based Control System

Consider a terminal control problem in which an omnidirectional mobile robot travels to a goal (Fig.8). \( \Sigma_{aa} \) is the absolute coordinate system; \( \Sigma_{ww} \) the moving coordinate system; and \( d_e \) and \( d_p \), error between the robot center of mass...
The objective point for each direction, i.e., \( d_x = x_d - x_w \) and \( d_y = y_d - y_w \), where \( x_d \) and \( y_d \) are terminal coordinates.

To solve this problem, we construct fuzzy-behavior-based control\(^{11,13,15}\) having an objective behavior group and free behavior group (Fig. 9). Note that in Refs. 11, 13, and 15, a mobile robot with two independent drive wheels as considered and conventional simple GA used to learn parameters in fuzzy reasoning, so such learning requires recombination from genotype to phenotype. In Fig. 9, \( u_x \) is the force to change the approach distance of the \( x \) direction, \( u_y \) that to change the approach distance of the \( y \) direction, \( u_v \) that to change the velocity of the \( x \) direction, \( u_r \) that to change the velocity of the \( y \) direction, \( u_t \) that to change the position of the robot, \( u_p \) that to change the \( y \) position of the robot, and \( u_\theta \) the torque to change the rotational angle \( \theta \) of the robot. Symbol \( S \) is a suppression unit implying cooperation and competition for output results of two behavioral elements. If two reasoning results are expressed as \( a \) and \( b \), the expression logic is written as

\[
c = (1 - s) a + s b, \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldot
part. If the number of labels is \( n_l \) and the number of elemental behaviors is \( m_n \), the number of learned parameters is \( 3nm_l \). The proposed ES is applied to optimally tuning the above parameters. For parameter tuning due to GA, see Ref.14).

7. Control Acquisition

7.1. Parameter Setting

The objective is assumed \( (x_d, y_d) = (2.0, 2.0) \) and the objective rotational angle \( \phi_d = \pi/2 \). The initial value of states is \( [0, 0, 0, 0, 0, 0] \). The sampling interval is 50 [ms]. In fuzzy-behavior-based control, boundary layer \( r \), used in the saturation function to make competition or cooperation of the reasoning result, is set to \( 1.0 \times 10^{-2} \).

The fitness function for objective behavior is

\[
\text{fitness} = D_{\text{end}} + |\Delta\phi|,
\]

where \( D_{\text{end}} \) is the distance between the final point of the robot and the objective point, and \( \Delta\phi \) error between the final rotational angle \( \phi_{\text{end}} \) and the objective rotational angle, i.e., \( \Delta\phi = \phi_d - \phi_{\text{end}} \). Acquiring objective behavior is equivalent to solving the minimization problem of equation (18).

ES parameters were set as follows: The number of fuzzy rules at elemental behavior is set to \( n_l = 5 \). The number of elemental behaviors is set to \( n_n = 4 \). The total number of optimized parameters is 60. The population size is set to 60. The radius for checking similarity is assumed \( \delta = 50 \).

7.2. Learning result

The resulting path (Fig.10) indicates that the mobile robot reached to the final goal. Figure 11 shows the corresponding rotational angle. The robot turns to \( \pi/2 \) with a slow time-varying angle over control duration. The control learning history is shown in Fig.12. Fitness was \( 1.51 \times 10^{-2} \) such as \( D_{\text{end}} = 7.09 \times 10^{-2} \) and \( \Delta\phi = -1.44 \times 10^{-2} \); though fitness satisfying the optimal is zero.

8. Conclusions

An ES is proposed that uses statistical information of subgroups formed automatically by a similarity metric of individuals at each generation. Arithmetical crossover was designed with an elite individual and a mean individual within each subgroup to produce offspring, standard deviation calculated in a subgroup was used for mutation. The proposed ES was applied to optimization of 5 De Jong functions. Simulation showed our proposal was superior to the conventional method, except for random function. It was also applied to control acquisition for a terminal control problem in an omnidirectional mobile robot, in which robot control was based on fuzzy-behavior-based control.

References:

Name: Kiyotaka Izumi
Affiliation: Department of Mechanical Engineering, Faculty of Science and Engineering, Saga University
Address: -Horijio-machi, Saga, 840-8502 Japan
Brief Biographical History:
- Received the Ph.D. from Saga University
- Research Associate of Saga University

Main Works:

Membership in Learned Societies:
The Robotics Society of Japan (RSJ)
The Japan Society of Mechanical Engineers (JSME)
The Society of Instrument and Control Engineers (SICE)
The Japan Society for Precision Engineering (JSPE)
Japan Society for Fuzzy Theory and Systems (SOFT)
The Institute of Electronics, Information and Communication Engineers (IEICE)

---

Name: M.M.A. Hashem
Affiliation: Faculty of Engineering Systems and Technology, Graduate School of Science and Engineering, Saga University, Japan (On deputation from Bangladesh Institute of Technology (BIT), Khulna).
Address: -Horijio-machi, Saga, 840-8502 Japan
Brief Biographical History:
- 988- B. Sc. Engineering (Electrical and Electronic) from Bangladesh Institute of Technology (BIT), Khulna.
- 988- Lecture, Dept. of Electrical and Electronic Engg., BIT, Khulna.
- 993- Master of Engineering (Computer Science) from Asian Institute of Technology (AIT), Bangkok, Thailand.
- 993- Assistant Professor, Dept. of Electrical and Electronic Engg., BIT, Khulna

Main Works:

Membership in Learned Societies:
- The Institute of Electrical and Electronics Engineers (IEEE)
- (a) IEEE Computer Society
- (b) IEEE Robotics and Automation Society
- The Institution of Engineers, Bangladesh (IEB)

---

Name: Keigo Watarabe
Affiliation: Department of Advanced Systems Control Engineering, Graduate School of Science and Engineering, Saga University
Address: -Horijio-machi, Saga, 840-8502 Japan
Brief Biographical History:
- 1980- Research Associate of Kyushu University
- 1985- Associate Professor of Shizuoka University
- 1990- Associate Professor of Saga University
- 1993- Professor of Saga University

Main Works:

Membership in Learned Societies:
- The Japan Society of Mechanical Engineers (JSME)
- The Japan Society for Precision Engineering (JSPE)
- The Japan Society for Aeronautical and Space Sciences
- The Society of Instrument and Control Engineers (SICE)
- The Institute of Systems, Control and Information Engineers (ISCIE)
- The Robotics Society of Japan (RSI)
- Japan Society for Fuzzy Theory and Systems (SOFT)
- The Institute of Electrical and Electronics Engineers (IEEE)