2 System Architecure

In the anlalog circuit evolution by EHW, the topology and values of circuit components are adjusted through genetic operations. GA will evaluate each circuit and find the closest response with avalilable components.

The system of Evolutionary Analog Circuit is shown in Fig.1.

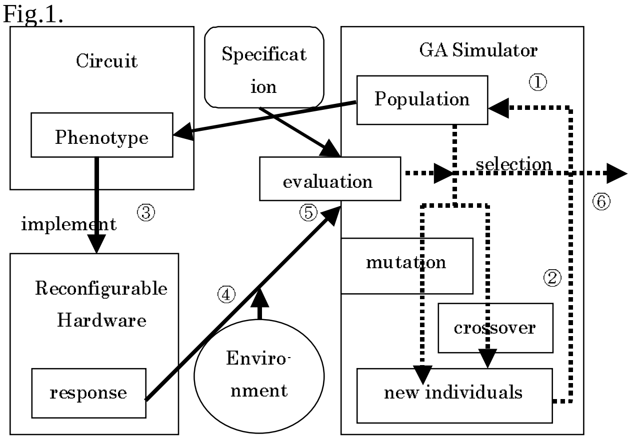


Fig.1:Structure of Evolutionary Analog Circuit

It consists of reconfigurable hardwares and GA simulator. Hardwares are resistors and capacitors with programmable value and layout. The evolution proceeds as follows:

1. Initial population is prepared.
2. Circuits are modified using genetic operation.
3. The phenotype is implemented on the hardware.
4. Response with noise is observed.
5. Response is evaluated based on the specification.
6. Inferior individuals are excluded from the population.
7. Return to 2.

These are basic steps for genetic algorithms. Through the repetition of adjustment and feedback, the precise specification can be achieved.

3 GA Simulator

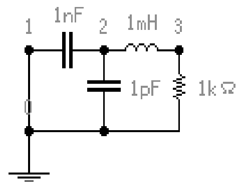
This section describes the details of the GA simulator.

3.1 Chromosome Implementation

Our chromosome is a component-list representation. This chromosome consisits of genes which represent circuit components and are variable in length. The phenotype and the genotype are shown in Fig.2.

The components are described with type, value, and location. In describing the location of a component, we have used MessyGA method which was proposed by Goldberg to prevent GA from falling into a local solution[2]. Zebulum also used this representation in the synthesis of active filters.[10]

Each gene holds an allele for type, location and value parameter. The location is described by a pair of integers, representing a pair of nodes that the component is connected to. Alleles for components' types are R, C, L, N, and O which represent resisitors, capacitors reactances, connected nodes, and open nodes, respectively.



N,0,1,0	C,1,2,1nF	R,0,3,1kΩ	L,2,3,1mH	C,0,2,1pF

Fig.2:Chromosome Implementation

3.2 Fitness

Each individual is evaluated on the deviation between the ideal and actual response by frequency. The fitness function is defined as below.

$$fitness = \frac{1}{K}\sum_{f}^{K}\left|F_f - R_f\right|^2 \cdots \textbf{eq. 1}$$

This fitness is the mean of squared deviation between ideal gain F_f and obtained gain R_f at frequency f. The chromosomes with lower fitness are selected to reproduce according to the roullette wheel selection. We also used Evolutionary Strategy breeding of ($\mu + \lambda$)-ES.

3.3 Structure and Parameter Evolution

GA features the strong global search and quick convergence to a quasi-optimal solution. On the other hand, the stochastic search of GA can be inefficient from the quasi-optimal to the optimal solution.

Evolving an electric circuit from the scrach requires two different tasks, i.e., finding the rough layout of the circuit and adjusting precisely to the specification. The first task requires efficient topology search and the second requires fine tuning of the parameters.

Though both the structure and parameters of the components are configurable in our component-list representation, it is inefficient to evolve them simultaneously.

At the earlier stage of the evolution, the parameter adjustment has relatively smaller affect on the circuit response and is less important compared to the topology alternation. Meanwhile, at the final stage of the evolution where a precise adjustment is required, modifying the topogy changes the response so drastically that it may degrade the search. Thus, we have divided the evolution into two stages. At the first stage, the main objective is to acquire a proper topology and parameters will be fixed to pre-settled values. At the second stage, the objective is to realize a precise specification using the acquired layout as a fixed structure.

At the first stage or the structural stage, chromosomes shown in Fig.2 are used. At the second stage, or the parameter stage, arrays of s_i values are used as our chromosomes. The value of component s_i is adjusted according to eq.2. The s_i's are real numbers ranging from 1 to –1. Range of modification is kept small for the applicability in reconfigurable analog components of EHW.

$$Adjval = Val \times 10^{s_i} \cdots \textbf{eq. 2}$$

Limiting the variables at each stage also results in better fitness, faster convergence, and less memory consumption. Section 5.2 describes the experimental results using this method.

3.4 Selective Pressure on Circuit Size

One of the problems in Genetic Programming and GA with variable-length chromosome is the development of introns. At a certain point in the evolution, introns bloat up to huge amount and makes the search awfully inefficient. Details on the effect of introns are described in [7].

In electric circuits, they appear as a set of components connected to the ground or a node. These introns are fatal to EHW application because it results in consuming a large amount of hardware resources.

There can be several measures to eliminate the introns. A method of multi-criteria evolution is used for the digital circuit evolution by Kalganova[5]. We have chosen to simply put a selective pressure on the circuit size. The fitness is adjusted as shown in eq.3, where E is the evaluation of the response and P is the penalty for the circuit size. P is defined as shown in eq.4, where N is the number of components in the circuit and represents the size factor, and T is the modulus to control the intensity of the pressure.

$$fitness = E + P \cdots \textbf{eq. 3}$$

$$P = N \cdot T \cdots \textbf{eq. 4}$$

Since introns have no effect on the circuit response, circuits with introns are subject to the elimination by the size factor.

This selective pressure can be impeditive to GA search when applied too excessively or too early. Eliminating introns too much causes crossover operation to be semantically destructive, and there are also dangers of abandoning diversity and deleting useful schema at the early stage of the evolution.

The intensity of the pressure is controled using the modulus T, by properly setting the order of P and E in eq.3. At the early stage of evolution, the term E should be predominant. As the evolution proceeds and the value of E decreases, the selective pressure P should gain influence. Therefore unnecessary large circuits are eliminated or modified to the proper size.

The T value has to be set according to the priority of the circuit size and required accuracy. We have used an empirical value for the following experiments described in section 7.

4 Robustnes Against Variance

The design methods for various passive filters are well established. Yet, analog filters used in many devices are hard to manufacture. As we mentioned before, this is because the components' values vary from the one specified in the designing process.

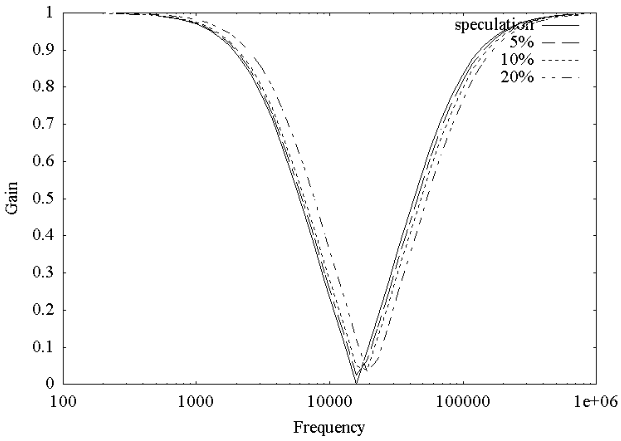


Fig. 3:Ideal and Actual Response of the Band Elimination Filter

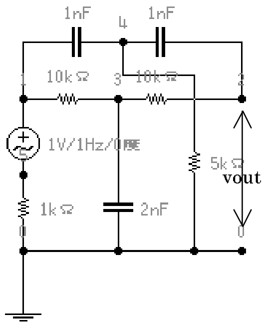


Fig. 4:Band Elimination Circuit Design

The solid line in Fig. 3 shows the response of a band-eliminator filter designed as Fig. 4. However, when the circuit is manufactured from real components, because the components' values differ from the specification, the response would not be identical to the solid line.

Actual analog components like resistors and capacitors could contain errors up to 20% of the specified value. The dotted and broken lines in Fig. 3 show the response when each component in circuit of Fig. 4 randomly contained errors within 20%, 10%, and 5% of the designed values, respectively.

The difference caused by these errors is fatal in manufactureing precise analog devices. Therefore, we conducted a filter synthesis experiment under such a condition that components' values are not exactly as specified. This is to show how Evolutionary Analog Circuit can accomodate with preliminary errors.

4.1 Specification & Result

The goal response is the band eliminating response shown as a solid line in Fig. 3. The central frequency of the stop band is 16kHz. The components used to compose this circuit are shown in Table 2

As in the real world, each component's value is not exact and contains error up to certain maximum. We set the maximum errors to 5, 10, and 20% and conducted 5 runs. The result is shown in Table1. The fitness of the sample circuit shown in Fig.4 is also given in the left column. It should be adequate in the noiseless condition.

Noise	Sample circuit	200th generation	400th generation
5%	0.000242971	1.73174e-05	2.53538e-08
10%	0.00121551	1.54782e-05	1.48567e-07
20%	0.00521907	2.17895e-05	1.35741e-07

Table 1:Fitness of Band Elimination Filter

In EHW, the circuit is evaluated and modified based on its whole response, and not by the value of each component. Thus, the errors of the components are absorbed through the modification of topology and parameter applied to the components as a whole.

5 Comparison with Other Representation Schemes

In this section, we show several filter syntheses using list chromosomes along with other representation schemes. To compare the results, we used the similar objective function and GA parameters.

5.1 Specification

The experiment described here is based on "Synthesis of an Asymmetric Bandpass Filter" in Chap.31 of [4].

The objective is to acquire an asymmetric bandpass filter, which is difficult to design because of its stringent and highly asymmetric specification[4].

The ideal and allowable characteristics are defined as shown in Fig.3. The solid line labeled *ideal* indicates the bounds of ideal characteristics and the broken line labeled *allowable* indicates the allowable range. The circuit behavior is observed at 101 frequencies in the interval between 10kHz and 200kHz in equal increments on a logarithm scale. The fitness is defined as in eq.5

$$F = \sum_{0}^{100} \left[W_i \left(d\left(f_i \right) \right) \cdot d\left(f_i \right) \right] \cdots \textbf{eq. 5}$$

Weight W_i is calculated from the difference between the response and the goal response at each observation point. The fitness is derived from the total product of the weight W_i and the difference d. W_i in the pass-band is 10 if allowable, 100 if else. In the stop-band, W_i is set to 1 if allowable, 10 if not. Detailed description is found in [4]. The GA parameters are shown in Table 2.

	Population	Generation	Crossover rate	Mutation rate
List-based	2000	400	0.99	0.001
GP**[4]**	640000	200	0.9	0.01

Table 2:GA Parameters

5.2 Result

The acquired response is shown in Fig. 5. The best response at the 400th generation is shown by the broken line labeled *acquired*. The dotted line labeled as *GP* indicates the response of the circuit obtained in [4].

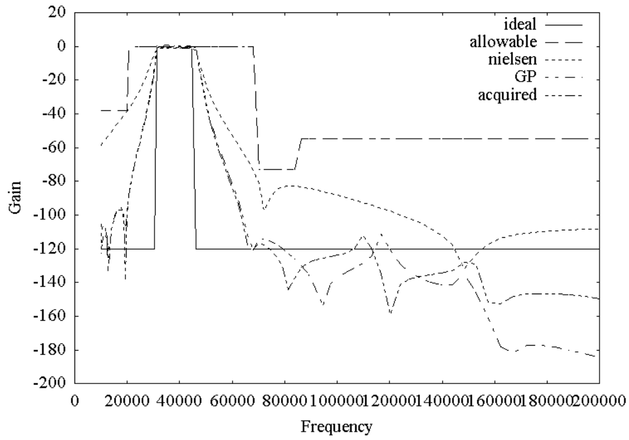


Fig. 5:Acquired Asymmetric Bandpass Filter Response

The fitness of the best individuals was 2037.47 with the *acquired* and 2024.0 with the *GP*. Meanwhile, the dotted line of the label *Nielson* shows the response of a human designed prototype circuit. As can be seen in Fig. 5, the acquired response satisfies the allowable condition in every region, and obtained better response than the Nielson's heuristic method. In comparison with GP, we were able to obtain very close response at the pass-band, and equally acceptable characteristic in the cut-off region as well.

5.3 Specification

Next experiment is conducted according to [6]. The objective is to acquire an ideal low-pass filter shown in Fig. 6. The pass-band ranges from 1Hz to 1300Hz and the stop-band is from 1300Hz to 100kHz, thus the cut-off frequency is 1300Hz.

The fitness is defined as given in eq.6. $d(f_i)$ is the difference between the goal gain $V_{goal}(f_i)$ and the actual gain $V_{out}(fi)$ at $F+1$ sample frequencies defined as eq.7. The weighted function W is defined by eq.8. The value of W_θ is set to 0.02 in this experiment. For details refer to [6].

$$Fitness = \sum_{i=0}^{F} W\left(d\left(f_i\right), f_i\right) \cdot d\left(f_i\right) \cdots \textbf{eq. 6}$$

$$d\left(f_i\right) = \left|V_{goal}\left(f_i\right) - V_{out}\left(f_i\right)\right| \cdots \textbf{eq. 7}$$

$$W\left(d\left(f_i\right), f_i\right) = \begin{Bmatrix} 1 & for & d\left(f_i\right) \le W_\theta \\ 10 & for & d\left(f_i\right) > W_\theta \end{Bmatrix} \cdots \textbf{eq. 8}$$

$V_{goal}(fi)$ is 1V in the pass-band and 0V in the stop-band. Fitness was calculated from the total of 78 sample frequencies, i.e., 50 from the pass-band and 28 from stop-band. We used a population of 500 individuals, and 200 generations for each run as in [6]. Crossover ratio, mutation ratio, and replacement ratio are the same as shown in Table 2.

5.4 Result

Fig. 6 shows the response of the best individual at 200th generation. The deviation from the specification remained within W_θ (=0.02V), and its fitness was 1.97615 while the fitness of the best individual obtained in [6] was 2.278. The phenotype of the best individual is shown in Fig. 7.

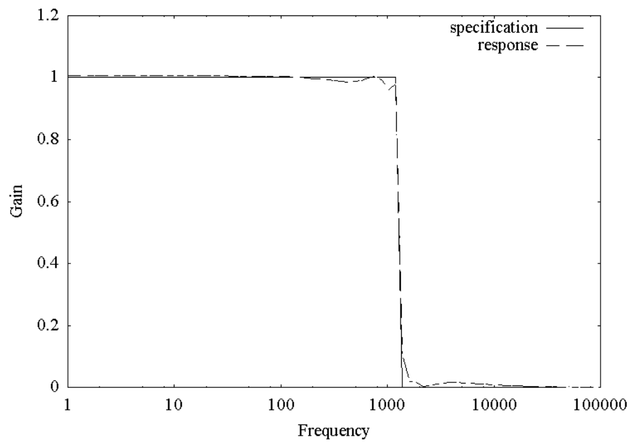


Fig. 6:Specification and Acquired Response of Ideal Lowpass Filter

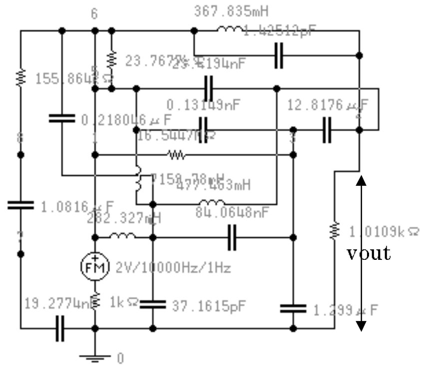


Fig. 7:Aquired Lowpass Filter Circuit

6 Multi-stage Evolution

The experiment in this section shows the effect of dividing the evolution into the structural and parameter stages.

6.1 Specification

The target response is an ideal high-pass filter depicted as a solid line in Fig. 8. The cut-off frequency is at 30kHz, and 14 observation points were taken at an interval of a geometric ratio ranging from 100kHz to 1MHz. In the structure evolution phase, the settled values were used as shown in Table 3. GA parameters are shown in Table 2.

Element type	Values
Resistances	10kΩ,1MΩ
Condensers	1nF,1pF
Coils	100 μ H,10mH

Table 3:Circuit Components Specification

6.2 Result

Fig. 9 shows the fitness of the best individual. This fitness is averaged over 3 runs. The broken line labeled *single step* denotes one-stage evolution, in which the topology and the parameters were simultaneously evolved. And dotted line labeled *2step* indicates that of the multi-stage evolution. The arrow shows where the parameter evolution started. The responses acquired by two methods are shown in Fig. 8.

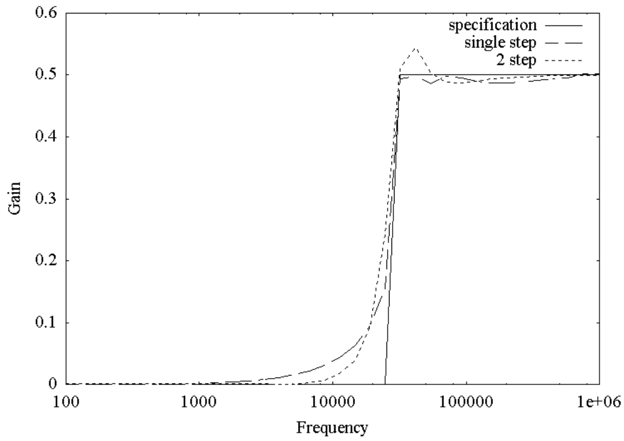


Fig. 8:Specification and Acquired Response of High-pass Filter

The response of the single-step evolution is given as the broken line labeled *single step,* whereas that of the two-stage evolution is provided by the dotted line labled as *2 step.* The achieved fitness was 0.00113213 for the multi-stage and 0.001955815 for the one-stage. It is perceived from Fig. 9 that while the simultaneous evolution converged after 100 generations, the multi-stage evolution resumed the search by entering the parameter evolution.

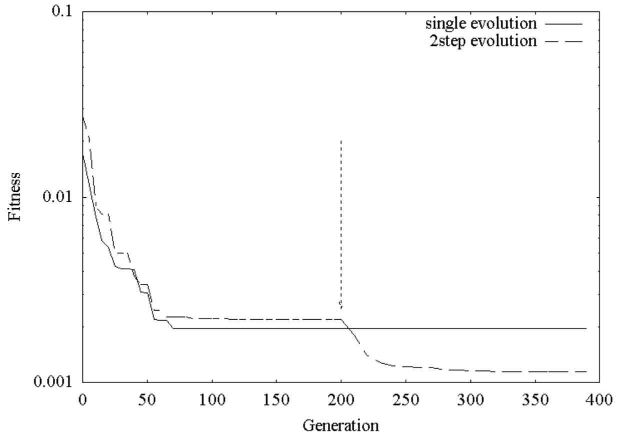


Fig. 9:Fitness by Generation for Highpass Filter Evolution

7 Selective Pressure on the Circuit Size

7.1 Specification

We have simulated a circuit evolution using the selective pressure described in section 3.4. The objective response is the bandpass filter shown in Fig. 10.

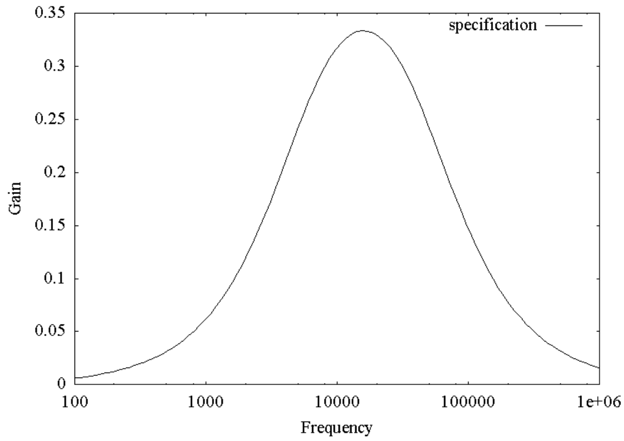


Fig. 10:Objective Bandpass Filter Response

Fitness definition was adjusted as in eq.3, and T modulous was set to be 10^{-6}. We have conducted 5 runs with a population of 500 and 200 genererations. Other parameters followed that of Table 2. Only the topology was modified in the course of evolution as the circuit size was fixed in the parameter evolution.

7.2 Result

The responses of the best individuals at the 40th and 150th generations for a typical trial are shown in Fig. 11. The phenotypes are shown in Fig. 14 and Fig. 15. The fitness value at the final generation was 6.20766e-11. The fitness and circuit size with generations are shown in Fig. 12 and Fig. 13.

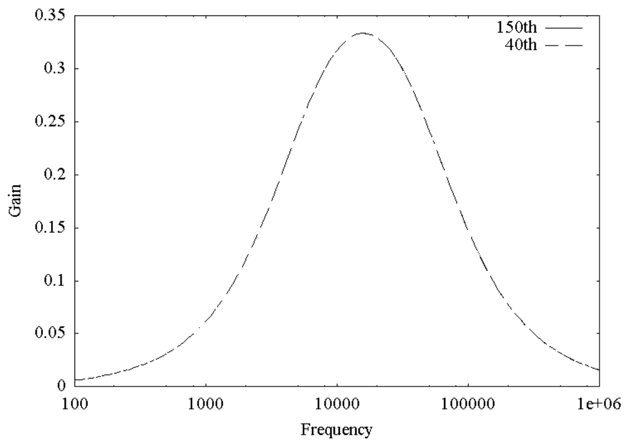


Fig. 11:Response of the Best Individuals at Generations 40 and 150

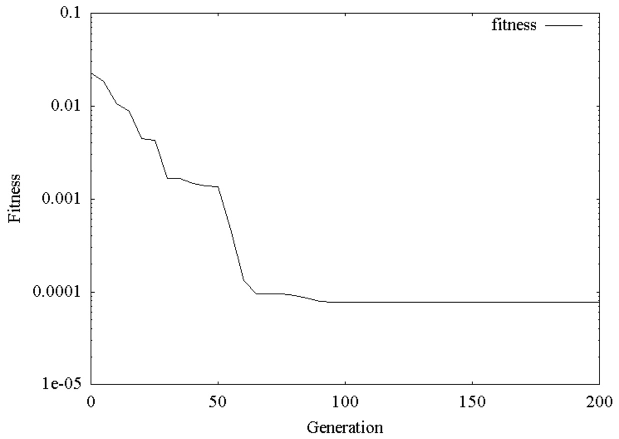


Fig. 12:Fitness by generation

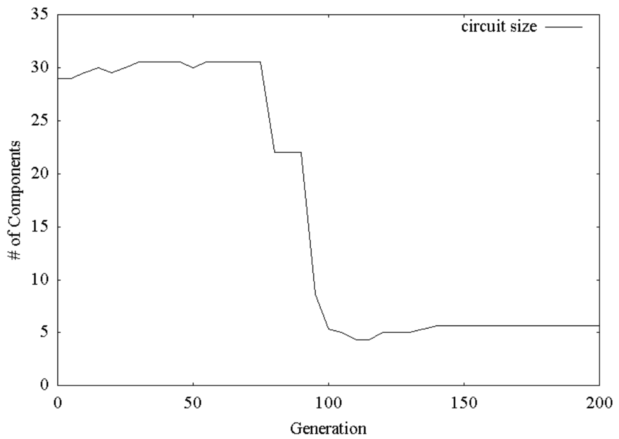


Fig. 13:Circuit Size by Generation

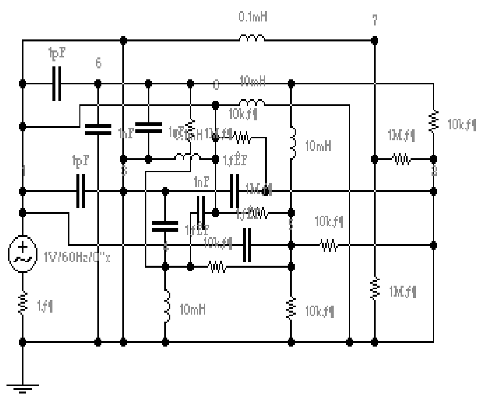


Fig. 14:Best Individual at Generation 40

It can be seen from Fig. 12 that by the 40th generation, the response fullfilled the specification. At generation 40, while the influence of the pressure was inconsiderable, electrical introns were existent as shown in Fig. 14. However, as the evolution proceeded, those portions were removed as seen in Fig. 15. Fig. 12 and Fig. 13 show that the adaption at the earlier stage of the evolution was done by aquiring the proper circuit and at the later stage, by getting rid of the unnecessary components.

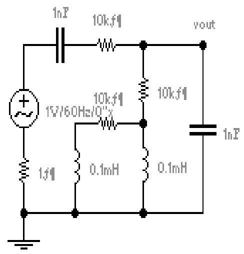


Fig. 15:Best Individual at Generation 150

8 Discussion

8.1 Robustness Against Variation

As shown in the experiment in section 4, EHW method works on the variance problem because GA evaluates only the response of the whole circuit and the variance of each component is absorbed through the layout and value modification. However, this robustness is achieved only for the preliminary variance. We will work on the extension to cope with the robustness against aging in our future research.

8.2 Comparison with Other Representation

Generally, GP has the advantage in finding the topology and structure. However, in finding a circuit structure for a fairly difficult filter shown in section 5.1, the list representation was capable of achieving a near-equivalent fitness. Meanwhile, using the GA, the amount of calculation can be kept small in terms of the popoulation size and the number of generations. In addition, the memory consumption becomes lower because of the simpler chromosome implementation. Therefore, we can confirm that the GA with our list representation has the adequecy in the circuit design.

8.3 Multi-stage Evolution

At the multiple stage evolution, the first stage, or the structural evolution, causes dynamic change in the response and fitness, while at the later stage, i.e., the parameter evolution, the response changes to a smaller degree to adapt to more stringent specification with higher accuracy.

Considering the simultaneous evolution of topology and value of the components, at the earlier stage when the fitness improves rapidly in primary convergence, the effect of modifying parameters is so small. In the later stage, the topology modification affects the response too drastically to make the gradual progress possible, and newly created circuits do not survive.

This multi-stage evolution also contributes to reducing the memory consumption by limiting the variables at each stage.

8.4 Pressurizing Circuit Size

In the experiment of section 7, the value of *T*, i.e., the relative order between *P* and *E* in eq.3, was calculated by hand. Considering that P is an integer and the required accuracy is about 10^{-6}, setting the T value to be 10^{-6} seemes to be reasonable in order for the response to be undistinguishable from the specification to the human eyes. Fig. 12 and Fig. 13 show that at the earlier stage of the evolution, the fitness is improved by acquiring better response, and at the later stage, the size factor mainly contributes to the fitness improvement. Thus, we can conclude that this pressurizing method has worked to remove introns and make the GA search more efficient. However, the automatic derivation of the *T* value remains to be seen in coming work.

In additon, this circuit reduction scheme seems to contribute to quickening the evolution and achieving better fitness value. We expect to verify this with future experiments.

9 Conclusion

In this study, we have proposed methods shown below for the implementation of Evolutionary Analog Circuit.

- Component list representation of a circuit.
- Multi-stage evolution
- Selective pressure on the circuit size

We have shown experiments using these methods to confirm its effectiveness in analog EHW system. The equipment of the GA system with a reconfigurable hardware is to be promoted as a prospect for the future work.

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Bibliography

[1] D. Keymeulen, H. Sakanashi, M. Murakawa, I. Kajitani, E. Takahashi, K. Toda, M. Salami, N.Kajihara, and N. Otsu, "Real-World Applications of Analog and Digital Evolvable Hardware", IEEE Transactions on Evolutionary Computation, Vol.3, No.3, 1999

[2] Goldberg, D.E. and Deb, K. and Karpupta, H. and Harik, G. "Rapid, Accurate Optimization of Difficult Problem using Fast Messy Genetic Algorithms", Proc. 5th Int. Joint Conf. On Genetic Algorithms(ICGA93), 1993

[3] J.R.Koza and F.H.Bennett III and D. Andre and M.A. Keane and F.Dunlap, "Automated Synthesis of Analog Electrical Circuit by Means of Genetic Programming", IEEE Transactions on Evolutionary Computation, Vol.1, No.2, 1997

[4] John R. Koza and Forrest H. Bennett III and David Andre and Martin A. Keane, "Genetic Programming III", Morgan Kaufmann Publishers Inc., 1999

[5] M. Iwata, I. Kajitani, H. Yamada, H. Iba, and T. Higuchi, "A Pattern Recognition System using Evolvable Hardware", Parallel Problem Solving from Nature - PPSN IV, Lecture Notes in Computer Science 1141, pp.761-770, Springer-Verlag, 1996.

[6] Masaya Koyabu, Hajime Murao, Shinzo Kitamura, "Automatic Design of Electrical Circuit by Genetic Algorithm", SICE 24th Sympodium of Intelligent Systems, Mar. 1997, in Japanese

[7] Melanie Mitchell, "An introduction to genetic algorithms", 1996

[8] Murakawa, Masahiro and Yoshizawa, Shuji and Adachi, Toshio and Suzuki, Shiro and Takasuka, Kaoru and Higuchi, Tetsuya, "Analogue EHW Chip for Intermediate Frequency Filter", Proceedings of the Second International Conference on Evolvable Systems, 1998

[9] R. Zebulum, M. Pacheco and M. Vellasco, "Analog Circuit Evolution in Intrinsic and Extrinsic Mode", Proceedings of Second International Conference of Evolvable Systems, vol.1478 p.154-165,1998

[10] R. Zebulum, M. Pacheco and M. Vellasco, "Artificial Evolution of Active Filters: A Case Study", The First NASA/DOD Workshop on Evolvable Hardware, 1999

[11] Shin Ando, Hitoshi Iba, Mitsuru Ishizuka, "Evolvable Analog Circuit using Variable Length Chromosomes", 56th IPSJ National Conference, in Japanese, 1999

[12] Ival Nielson, " A C-T filter compiler-From specification to layout," Analog Integrated Circuits and Signal Processing, 7(1):21-33

[13] J.D.Lohn, S.P.Colombano, "A Circuit Representation Technique for Auomated Circuit Design", IEEE Trans. on Evolutionary Computation, Sept. 1999, Vol.3 Num.3 p.205

[14] J.D.Lohn, S.P.Colombano, "Automated Analog Circuit Synthesis using a Linear Representation," Proc. of the Second Int'l Conf. on Evolvable Systems: From Biology to Hardware, Springer-Verlag, Berlin, 1998, pp.125-133.

[15] Stuart J. Flockton, Kevin Sheehan, "A System for Intrinsic Evolution of Linear and Non-linear Filters," The First NASA/DOD Workshop on Evolvable Hardware, 1999

[16] Tatiana Kalganova, Julian F. Miller and Terence C. Fogarty, "Some Aspects of an Evolvable Hardware Approach for Multiple-Valued Combinational Circuit Design", Proc. of the Second Int'l Conf. on Evolvable Systems: From Biology to Hardware, Springer-Verlag, Berlin, 1998