Use of Genetic Programming for Automatic Synthesis of Post-2000 Patented Analog Electrical Circuits and Patentable Controllers

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Abstract

This paper describes how we used genetic programming to automatically create the design of both the structure (topology) and sizing (component values) of analog electrical circuits that duplicate the functionality of five post-2000 patented inventions. The paper also describes how we used genetic programming to automatically create the design of both the structure (topology) and tuning (parameter values) of a general-purpose controller that outperforms conventional controllers for industrially representative plants.

1 Introduction

Patents represent current research and development efforts by the engineering and scientific communities. This paper reports on a project in which we browsed patents issued since January 1, 2000 to commercial enterprises or university research institutions for analog electrical circuits. We then employed genetic programming to automatically design both the structure (topology) and sizing (component values) for circuits that duplicate the functionality of the patented inventions. Genetic programming starts from a high-level statement of a circuit's desired behavior and characteristics and only *de minimus* knowledge and platitudinous information about analog electrical circuits.

The paper also describes how we used genetic programming to automatically create the design of both the structure (topology) and tuning (parameter values) of a general-purpose controller that outperforms conventional controllers for industrially representative plants. The authors have applied for a patent on the genetically evolved controller. If a patent is granted, it will (we believe) be the first patent issued for an invention created by genetic programming.

Section 2 describes the five post-2000 patented analog electrical circuits. Section 3 describes the controller problem. Section 4 provides background on genetic programming and explains the preparatory steps for the runs of genetic programming. Section 5 presents the results.

2 The Five Patented Analog Electrical Circuits

The goal for the five problems is to automatically synthesize an analog electrical circuit that has the same functionality as the patented invention (shown in table 1). The process starts from a high-level statement of circuit's desired behavior.

Table 1 Five post-2000 patented analog electrical circuits

Invention	**Date**	**Inventor**	**Place**
Mixed analog-digital integrated circuit for variable capacitance	2000	Turgut Sefket Aytur	Lucent Technologies Inc.
Voltage-current converter	2000	Akira Ikeuchi and Naoshi Tokuda	Mitsumi Electric Co., Ltd.
Cubic function generator	2000	Stefano Cipriani and Anthony A. Takeshian	Conexant Systems, Inc.
Low-voltage high-current transistor circuit for testing a voltage source	2001	Timothy Daun-Lindberg and Michael Miller	International Business Machines Corporation
Low-voltage balun circuit	2001	Sang Gug Lee	Information and Communications University

2.1 Voltage-Current Conversion Circuit

The purpose of the voltage-current conversion circuit in U. S. patent 6,166,529 (Ikeuchi and Tokuda 2000) is to take two voltages as input and to produce a stable current whose magnitude is proportional to the difference of the voltages.

2.2 Low-Voltage Balun Circuit

The purpose of a balun (balance/unbalance) circuit is to produce two outputs, each having half the amplitude of the input, one output being in phase with the input while the other is 180 degrees out of phase with the input, with both outputs having the same DC offset. The circuit, described in U. S. patent 6,265,908 (Lee 2001), uses a power supply of only 1 Volt and is useful for contemporary low-power applications.

2.3 Cubic Signal Generator

U. S. patent 6,160,427 (Cipriani and Takeshian 2000) covers a computational circuit that produces the cube of an input signal as its output. The circuit is “compact” in that it contains a voltage drop across no more than two transistors.

2.4 Register-Controlled Variable Capacitor

U. S. patent 6,013,958 (Aytur 2000) covers a circuit that is equivalent to a capacitor whose capacitance is controlled by the value stored in a digital register.

2.5 High-Current Load Circuit

U. S. patent 6,211,726 (Daun-Lindberg and Miller 2001) covers a circuit designed to sink a time-varying amount of current in response to a control signal. Toward this end, Daun-Lindberg and Miller of IBM employed a number of FET transistors arranged in a parallel structure, each of which sinks a small amount of the desired current.

3 The General-Purpose Controller Problem

The purpose of a controller is to force, in a meritorious way, the response of a system (conventionally called the *plant*) to match a desired response (the *reference signal*). Controllers are ubiquitous in the real world. PID controllers are composed of a proportional (P), an integrative (I), and a derivative (D) block. Over 90% of all real-world controllers are PID controllers.

In 1942, Ziegler and Nichols developed a set of mathematical rules for automatically selecting the parameter values associated with the proportional, integrative, and derivative blocks of a PID controller (Ziegler and Nichols 1942). The Ziegler-Nichols tuning rules remain in widespread use today for tuning PID controllers.

In their 1995 book *PID Controllers: Theory, Design, and Tuning*, Astrom and Hagglund identified four families of plants "that are representative for the dynamics of typical industrial processes." Astrom and Hagglund developed a method for automatically tuning PID controllers for all the plants in all four of the industrially representative families of plants. The tuning rules developed by Astrom and Hagglund outperform the widely used Ziegler-Nichols tuning rules on all 16 industrially representative plants used by Astrom and Hagglund.

In this paper, we approach the problem of automatic synthesis of a controller using genetic programming. The topology is opened-ended and need not be the PID topology. In this work, we use a fitness measure containing the same elements used in Astrom and Hagglund 1995. In particular, the fitness measure attempts to optimize the integral of the time-weighted absolute error (ITAE) for a step input and disturbance rejection while simultaneously imposing constraints on maximum sensitivity and sensor noise attenuation.

In this paper, we present designs for both the topology and tuning for a parameterized general-purpose controller for the industrially representative plants belonging to the same four families of plants specified by Astrom and Hagglund. As will be seen, the automatically designed controller outperforms the controller developed by Astrom and Hagglund in their 1995 book. In addition, the automatically designed controller is general and parameterized in the sense that it contains free variables (K_u, T_u, T_r, and L). It therefore provides a solution to an entire category of problems (i.e., the control of all the plants).

4 Preparatory Steps for the Runs of Genetic Programming

We used genetic programming to breed a population of computer programs (representing either circuits or controllers) over a series of generations. Genetic programming starts with thousands of randomly created computer programs and uses the Darwinian principle of natural selection, recombination (crossover), mutation, gene duplication, gene deletion, and certain mechanisms of developmental biology to breed an improved population.

The five major preparatory steps for genetic programming entail determining

(1) the set of primitive functions for the to-be-evolved program,

(2) the set of terminals for the to-be-evolved program,

(3) the fitness measure for measuring the fitness of individuals in the population,

(4) parameters for controlling the run, and

(5) a termination criterion.

The function and terminal sets for all five problems involving the post-2000 patented analog circuits were the same. They permit the construction of any circuit composed of transistors, resistors, and capacitors. We used the commercially common `2N3904` (*npn*) and `2N3906` (*pnp*) transistor models unless the patent document specifically called for a different transistor model.

The set of primitive functions for the controller problem permits the construction of any controller composed of integrators, differentiators, gains, adders, subtractors, leads, and lags. The set of terminal accommodates any controller whose input consists of reference signal(s), plant output(s), and the output(s) of the controller itself.

Note that we did not employ any deep knowledge about circuits or controllers in choosing the function and terminal sets. The terminal and function sets contain the ingredients that genetic programming can use to build candidate structures. The terminal and function sets incorporate *de minimus* knowledge and platitudinous information of these two fields.

The control parameters and termination criterion were the same, except that we used different population sizes for some of the runs in order to approximately equalize each run's elapsed time.

For additional information about genetic programming in general and the details of the process of synthesizing circuits and controllers, see Koza, Bennett, Andre, and Keane 1999; Koza, Bennett, Andre, Keane, and Brave 1999; and Koza, Keane, Streeter, Mydlowec, Yu, and Lanza 2002.

The main difference between the runs is that a different fitness measure is used for each problem. Construction of a fitness measure requires translating the problem's high-level requirements into a precise computation. We read the patent document to find the performance that the invention was supposed to achieve. We then created a fitness measure (payoff function, objective function) reflecting the invention's asserted performance and characteristics.

4.1 Voltage-Current Conversion Circuit

We employed four time-domain input signals (fitness cases) in the fitness measure for the voltage-current conversion problem. We included a time-varying voltage source beneath the output probe point to ensure that the output current produced by the circuit was stable with respect to any subsequent circuitry to which the output of the circuit might be attached. The weight of each fitness case was defined as the reciprocal of the patented circuit's error for that fitness case, so that the patented circuit was defined to have a fitness of 1.0.

4.2 Balun Circuit

The fitness measure for this problem consisted of a (1) frequency sweep analysis designed to ensure the correct magnitude and phase at the two outputs of the circuit and (2) a Fourier analysis designed to penalize harmonic distortion.

4.3 Cubic Signal Generator

The fitness measure for this problem consisted of four time-domain fitness cases using various input signals and time scales. The compactness constraint was enforced by providing only a 2-Volt power supply.

4.4 Register-Controlled Variable Capacitor

For this problem, the fitness measure employed 16 time-domain fitness cases. The 16 fitness cases ranged over all eight possible values of a 3-bit digital register for two different analog input signals.

4.5 High-Current Load Circuit

The fitness measure for this problem consisted of two time-domain simulations, each representing a different control signal. Each fitness case was weighted by the reciprocal of the patented circuit's error on that fitness case, so that the patented circuit was defined to have a fitness of 1.0.

4.6 General-Purpose Controller

The fitness of each controller in the population is measured by means of eight separate invocations of the SPICE simulator for each plant (Quarles, Pederson, Newton, Sangiovanni-Vincentelli 1994). The fitness measure attempts to optimize the integral of the time-weighted absolute error (ITAE) for a step input and disturbance rejection while simultaneously imposing constraints on maximum sensitivity and sensor noise attenuation. The fitness of an individual controller is the sum of the detrimental contributions from each of these elements of the fitness measure. We used a total of 24 plants (from the same four families of plants that Astrom and Hagglund used in their 1995 work). Thus, there are 192 separate invocations of the SPICE simulator. We then added a 193rd element to the fitness measure concerning parsimony.

5 Results for the Five Analog Electrical Circuits

5.1 Voltage-Current Conversion Circuit

A circuit (figure 1) emerged on generation 109 of our run of this problem with a fitness of 0.619. That is, the evolved circuit has roughly 62% of the average (weighted) error of the patented circuit. The evolved circuit was subsequently tested on unseen fitness cases which were not part of the fitness measure, and outperformed the patented circuit on these new fitness cases.

5.2 Balun circuit

The best-of-run evolved circuit (figure 2) was produced in generation 84 and has a fitness of 0.429. The patented circuit had a total fitness of 1.72. That is, the evolved circuit is roughly a fourfold improvement over the patented circuit in terms of our fitness measure. The evolved circuit is superior to the patented circuit both in terms of its frequency response and its harmonic distortion.

The essential difference between Lee's invention (Lee 2001) and the prior art is a coupling capacitor located between the base and the collector of a particular transistor. The best-of-run circuit (figure 2) possesses the very feature (C302) that Lee identifies as the essence of his invention.

5.3 Cubic Signal Generator

The best-of-run evolved circuit (figure 3) was produced in generation 182 and has an average error of 4.02 millivolts. The patented circuit had an average error of 6.76 millivolts. That is, the evolved circuit has approximately 59% of the error of the patented circuit over our four fitness cases.

5.4 Register-Controlled Variable Capacitor

Over our 16 fitness cases, the patented circuit had an average error of 0.803 millivolts. In generation 95, a circuit emerged with average error of 0.808 millivolts, or approximately 100.6% of the average error of the patented circuit. During the course of this run, we harvested the smallest individuals produced on each processing node with a certain maximum level of error. Examination of these harvested individuals revealed a circuit from generation 98 (figure 4) that approximately matches the topology of the patented circuit (without infringing).

5.5 High-Current Load Circuit

On generation 114, a circuit emerged that duplicated Daun-Lindberg and Miller's parallel FET transistor structure. This circuit (figure 5) has a fitness (weighted error) of 1.82, or 182% of the weighted error for the patented circuit.

5.6 Results for the General-Purpose Controller Problem

Figure 6 shows the best-of-run genetically evolved general-purpose controller from generation 199. Genetic programming produced this controller's overall topology consisting of three adders, three subtractors, four gain blocks parameterized by a constant, two blocks parameterized by non-constant mathematical expressions containing free variables, and two lead blocks parameterized by non-constant mathematical expressions containing free variables.

This non-PID controller has two gain blocks (labeled 730 and 760) whose gain is expressed as an equation involving the four free variables that describe a particular plant, namely the plant's time constant, T_r, ultimate period, T_u, ultimate gain, K_u, dead time, L. Specifically, gain block 730 has a gain of

$$\left|\log\left|T_r - T_u + \log\left|\frac{\log\left(|L|^L\right)}{T_u + 1}\right|\right|\right| \qquad [31]$$

while gain block 760 has a gain of

$$\left|\log\left|T_r + 1\right|\right| \qquad [34]$$

This non-PID controller also has two lead blocks 740 and 750 (i.e., blocks with transfer functions of the form 1 + τs) that are parameterized by genetically evolved mathematical expressions. Lead block 740 is parameterized by:

$$\mathrm{NLM}\left(\log|L| - \left(\mathrm{abs}(L)^L\right)^2 T_u^{\,3}\left(T_u + 1\right)T_r e^L - 2T_u e^L\right) \qquad [32]$$

where NLM is a non-linear mapping such that

NLM(x) = 10^0 if $x < -100$ or $x > 100$;
$10^{-\frac{100}{19}-\frac{1}{19}x}$ if $-100 \le x < -5$;
$10^{\frac{100}{19}-\frac{1}{19}x}$ if $5 < x \le 100$; or
10^x if $-5 \le x \le 5$.

Lead block 750 is parameterized by:

$$\mathrm{NLM}\left(\log|L| - 2T_u e^L\left(2K_u\left(\log\left|K_u e^L\right| - \log|L|\right)T_u + K_u e^L\right)\right) \qquad [33]$$

This non-PID controller has internal feedback of its own output (control variable 790) back into itself. Specifically, control variable 790 is subtracted from the output of the PID controller 706 devised by Astrom and Hagglund in their 1995 book. The difference (amplified by a factor of 10 by gain block 780) becomes one of the three signals that are added together (by adder 788) to create control variable 790. Similarly, control variable 790 (amplified by a factor of 2 by gain block 770) is subtracted from the output of the Astrom-Hagglund controller 706 (amplified by a factor of 2 by gain block 720) by subtractor 734.

This best-of-run genetically evolved general-purpose controller from generation 199 can be described in terms of its transfer function, given below.

$$U = \frac{R\left(1+3E_{34}\left(1+E_{32}*s\right)\left(1+E_{33}*s\right)\right)+A\left(10+E_{34}\left(3+E_{31}+2E_{32}*s+E_{31}E_{32}*s\right)\left(1+E_{33}*s\right)\right)}{11+E_{34}\left(2+3E_{32}*s\right)\left(1+E_{33}*s\right)}$$

where U is the controller output, R is the reference signal, A is the output of the Astrom-Hagglund controller, P is the plant output (not used explicitly), E_{31} , E_{32}, E_{33}, and E_{34}, refer to equations 31, 32, 33, and 34 respectively.

Averaged over the 24 plants, the genetically evolved non-PID controller has

- 81.8% of the setpoint ITAE of the Astrom-Hagglund controller,
- 93.8% of the disturbance rejection ITAE of the Astrom-Hagglund controller,
- 98.8% of the reciprocal of minimum attenuation of the Astrom-Hagglund controller, and
- 93.4% of the maximum sensitivity, M_s, of the Astrom-Hagglund controller.

Averaged over the 18 additional plants (for cross-validation), the genetically evolved non-PID controller has

- 81.8% of the setpoint ITAE of the Astrom-Hagglund controller,
- 94.2% of the disturbance rejection ITAE of the Astrom-Hagglund controller,
- 99.7% of the reciprocal of minimum attenuation of the Astrom-Hagglund controller, and
- 92.5% of the maximum sensitivity, M_s, of the Astrom-Hagglund controller.

Thus, this best-of-run genetically evolved general-purpose controller from generation 199 is an improvement over the PID controller devised by Astrom and Hagglund in their 1995 book.

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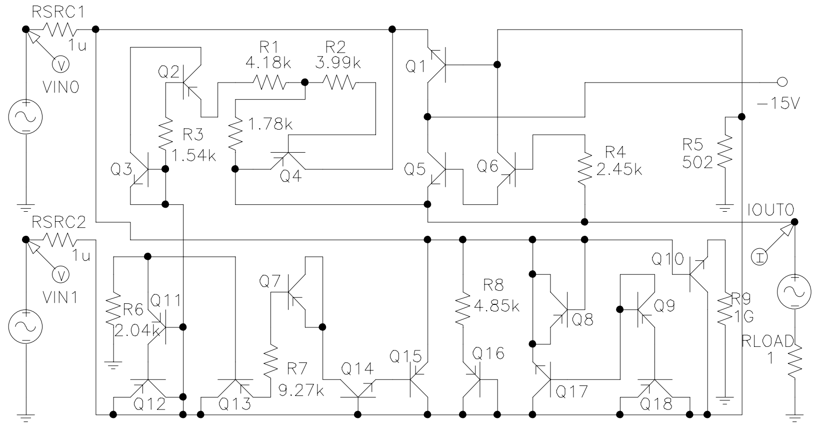

Figure 1 Best-of-run voltage-current-conversion circuit

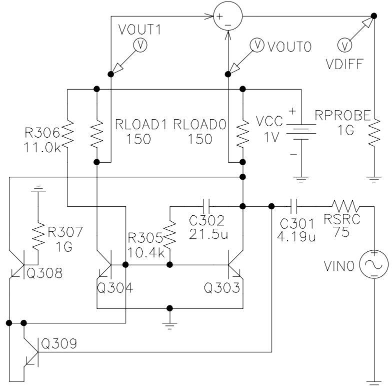

Figure 2 Best-of-run balun circuit

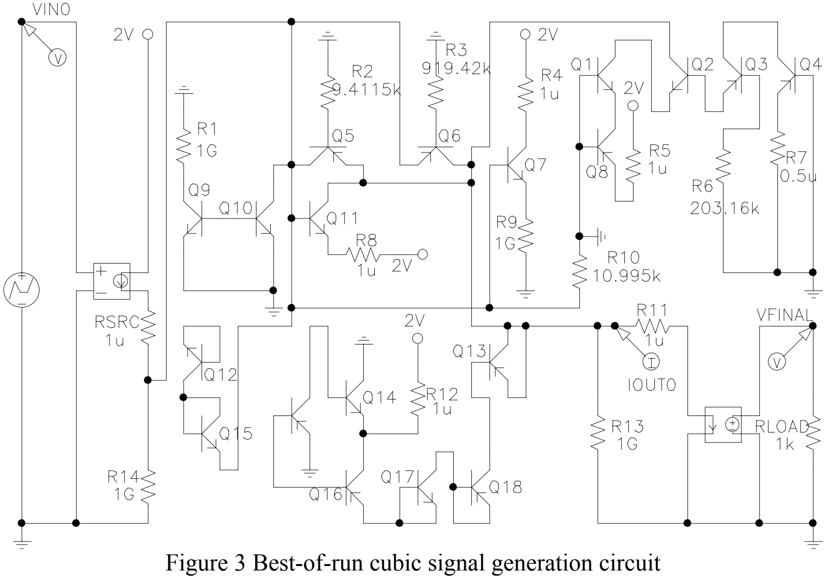

Figure 3 Best-of-run cubic signal generation circuit

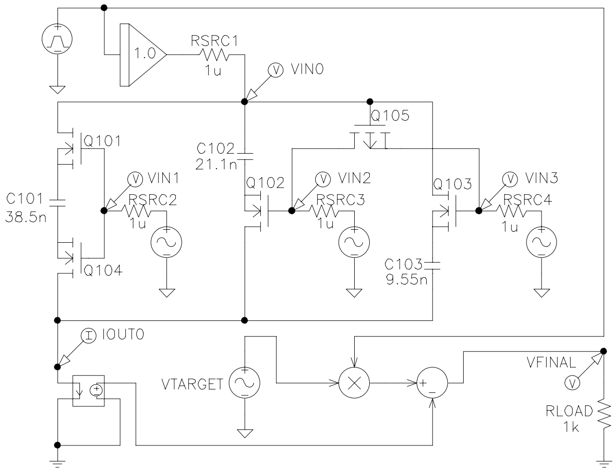

Figure 4 Evolved compliant register-controlled capacitor circuit

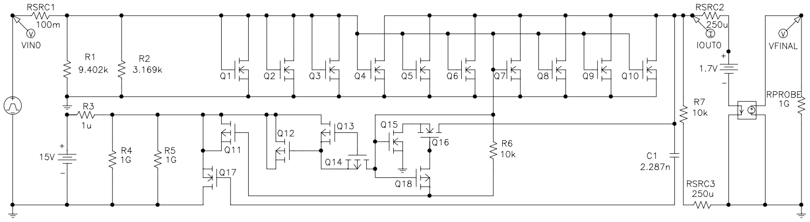

Figure 5 Best-of-run high-current load circuit

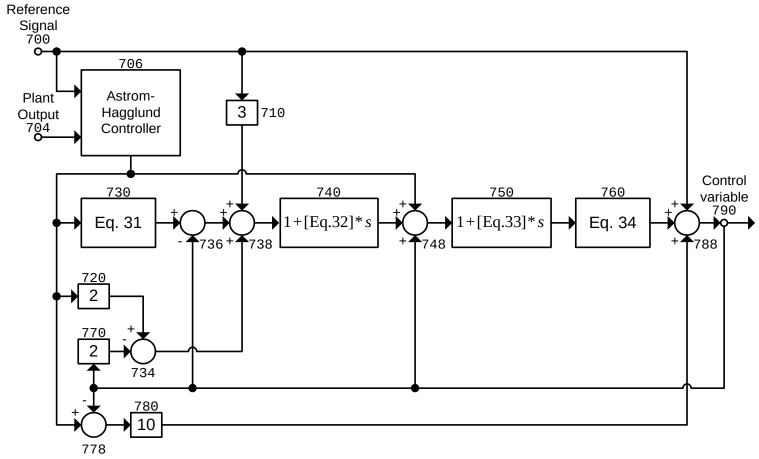

Figure 6 Best-of-run general-purpose controller